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PERFORMANCE ANALYSIS OF FOOTWEAR SENSORS FOR VOLTAGE MONITORING

Muhamad Aiman[1], Ruzlaini Ghoni[1], Mohd Tarmizi Ibrahim[1], Fariyono[2*]
[1]Electrical and Automation Department, Faculty of Engineering Technology, University College TATI, Terengganu, Malaysia
[2]Electrical Engineering Department, Sekolah Tinggi Teknologi "Warga" Surakarta, Sukoharjo, Indonesia
*Email: fariyono@sttw.ac.id

ABSTRACT

Advances in wearable technology are driving innovation in efficient, self-powered biomechanical monitoring systems. One promising approach uses piezoelectric sensors to generate energy while detecting foot (plantar pressure) during physical activity. This study aims to design and test a piezoelectric-based insole system capable of performing dual functions: harvesting mechanical energy from footsteps and analyzing fatigue patterns and gait asymmetry. The research used an experimental approach involving 10 male respondents aged 15–31. Each insole was equipped with four DLAY piezoelectric sensors placed on the heel and forefoot of the right and left feet, and connected to a Raspberry Pi Pico RP2040 microcontroller for voltage data acquisition. The data was analyzed using voltage changes to indicate foot pressure distribution and muscle fatigue. The results showed that the system could generate voltages between 0.025 V and 0.082 V, with an average harvested power of 4.8mW. 70% of respondents experienced decreased voltage in one leg, indicating unilateral fatigue and gait imbalance. Respondent 10 showed the most significant voltage decrease in the left heel sensor (<0.03 V after 1000 seconds), while the right foot remained stable (0.045–0.055 V). In contrast, Respondent 5 showed stable and symmetrical voltage distribution throughout the test session.

Keywords: *piezoelectric shoes; energy harvesting; kinetic energy; footwear sensors; voltage monitoring.*

1. INTRODUCTION

Daily, we produce significant energy just by walking or running, but most of it goes to waste. This project explores an innovative and practical way to utilize that energy by converting it into electricity using piezoelectric materials placed inside the soles of shoes. These materials are unique: they generate an electric charge when pressed or bent. By embedding them in footwear, we can collect energy from every step we take and potentially use it to power small electronic devices, especially wearable sensors [1], [2]. This idea is becoming more critical with the growing demand for clean and renewable energy. Instead of relying on traditional power sources, this system harnesses the energy naturally generated by the body's movements [1], [3]. The project focuses on generating electricity from footsteps and analyzing fatigue patterns based on how pressure changes in the feet during movement.

Wearable energy harvesting systems have gained significant attention in recent years due to increasing demand for portable, low-power electronics that operate autonomously without conventional batteries. Among various energy harvesting mechanisms, piezoelectric transducers are widely applied in wearable systems because of their high durability, compact structure, and ability to convert repetitive mechanical loads into electrical signals [4], [5]. Their integration into footwear enables continuous energy harvesting from foot impact forces during walking or running, making them suitable for powering low-power devices and embedded sensors [2], [6].

Innovative footwear systems typically integrate pressure or force sensors for gait analysis, posture monitoring, and health diagnostics—research by Anderson et al. [1] shows that footstep monitoring using pressure sensors in insoles and microcontrollers can effectively classify human movements. Similarly, research by N. Hegde, M. Bries, and E. Sazonov. [3] evaluates several shoe-based systems and highlights their importance in biomechanical monitoring, although battery power still limits continuous operation. In response, recent studies propose the installation of piezoelectric films into shoes to achieve monitoring and energy harvesting functions[2], [6].

Several studies have explored sensor placement to optimize voltage generation and data accuracy [5], [2]. Piezoelectric elements located under the heel and metatarsal regions produce the highest voltage due to peak plantar pressure in these areas. These findings are consistent with pressure mapping studies by F. Luna-Perejón et al. [7], and Q. Zheng et al. [8], who emphasized that insole-based multi-sensor configurations improve plantar force detection and gait pattern recognition. However, these systems primarily focused on biomechanical measurement rather than energy harvesting.

Alternative energy harvesting methods, such as triboelectric and electromagnetic systems, have also been tested in floor tiles [9], [10]. Yet, their high maintenance requirements and poor portability make them impractical for footwear applications. Piezoelectric materials remain superior for integration into wearable shoe systems due to their flexibility, ease of embedding, and higher compatibility with walking dynamics [4], [6].

Integrating data acquisition units such as microcontrollers enhances sensing capability in wearable systems [1], demonstrated real-time data capture using a microcontroller-based insole, while H. X. Zou et al. [11] highlighted the importance of voltage regulation circuits in energy harvesting systems to ensure electrical stability. Recent self-powered sensor reviews by X. Hu et al. [12] emphasized the need for hybrid designs to harvest energy and simultaneously monitor physiological or biomechanical activity.

Despite existing developments, most previous studies address energy harvesting [5], [6] or gait monitoring [1], [7], [8] separately. Very few works combine both functions inside a single shoe-based platform. Therefore, integrating piezoelectric sensors for simultaneous voltage monitoring and fatigue detection while generating usable electrical energy remains a significant research gap. The present study contributes to this area by embedding piezoelectric sensors in footwear to capture voltage profiles during running, enabling performance monitoring and energy harvesting within a compact wearable system.

2. METHODS

This section describes developing and assembling a system designed for analyzing footwear sensor performance in voltage monitoring. The explanation encompasses critical aspects, detailing hardware and software components, overall system architecture, and integration processes. All steps and procedures are presented clearly, ensuring comprehensive insight into the developed system's construction and functionality.

2.1. System Components

Several key components were integrated into the system. The Raspberry Pi Pico RP 2040 microcontroller is at the core, which serves as the central processing unit. The RP 2040 is responsible for data collection, processing, and storage. Data acquisition is facilitated by DLAY piezoelectric film sensors, chosen for their flexibility, sensitivity, and capability to detect dynamic pressure changes associated with walking and running activities.

Sensors are strategically installed within the insoles of both shoes, positioned to align with areas experiencing peak pressure. To enhance usability and portability, the system includes a push-button switch that initiates data collection, while a green LED indicator provides visual confirmation when data collection commences. Power is supplied through a portable power bank, enabling uninterrupted operation during user movement. Software implementation for data handling and analysis utilizes Python, which was developed and executed within the Thonny IDE environment. The specifications and functions of the tools and materials used in this research on performance analysis of shoe sensors for stress monitoring are presented in Table 1.

Table 1. Specification and function of the tools and materials

Tools and materials	function
Raspberry Pi Pico RP2040 microcontroller	Data processing and voltage acquisition
DLAY Piezoelectric Film Sensors	Detect foot pressure and generate voltage
Footwear/Insoles	Medium for embedding piezoelectric sensors
Push Button Switch	Start/stop data recording.
LED Indicator (Green)	Indicates data logging status
Connecting Wires / Jumper Cables	Electrical connections between sensors and controller
Laptop/PC	Runs data acquisition software and data analysis
Measurement Table / Dataset Sheet	Recording participant measurements (age, weight)
Portable Power Bank	Used as a portable energy source

2.2. Experimental Procedure

Ten male participants volunteered for system validation, representing diverse demographic characteristics, particularly in body weight. Participant details are summarized as follows in Table 2.

Table 2. Body weight data

Participant	Age (years)	Body weight (kg)
P1	23	50
P2	20	56
P3	15	55
P4	23	58
P5	31	73
P6	23	57
P7	21	49
P8	23	55
P9	18	57
P10	15	56

Participants were instructed to run continuously for a duration of 20 minutes. Throughout each session, the developed system systematically recorded voltage data generated by footsteps. The collected voltage data were subsequently analysed to quantify voltage output, detect patterns indicative of physical fatigue, and evaluate overall system performance.

The research highlights the dual functionality of piezoelectric footwear, demonstrating its potential application in energy harvesting alongside health and performance monitoring. This integration expands opportunities within wearable technology, specifically addressing applications in fitness monitoring, rehabilitation programs, and scenarios where conventional power sources are inaccessible.

2.3. Microcontroller Operation

The RP2040 microcontroller functions as the core data acquisition and processing unit. Input parameters, specifically participant demographic characteristics such as gender and body weight, are utilized by the RP 2040 during data collection. Subsequently, the microcontroller processes sensor signals and records generated voltages over time. Figure 1 presents the functional block diagram of the system, outlining the sequence from initial user data input through RP 2040 processing to voltage output generation.

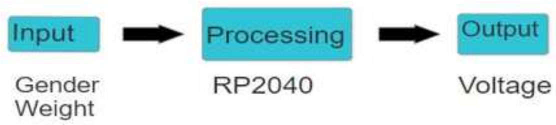

Figure 1. Functional block diagram of the footwear monitoring system.

Initially, the sensors are activated by pressing a push-button, commencing data capture and analysis. Figure 2 illustrates the flowchart detailing the operational process, including user interaction, data acquisition, feedback generation, and fatigue detection.

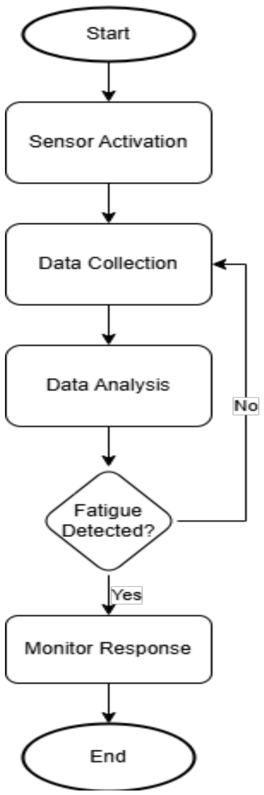

Figure 2. Flowchart illustrating the system's operational process.

2.4. Project Design

Figure 3 depicts the final project design, showing DLAY sensors installed within footwear insoles, ensuring optimal contact with high-pressure regions underfoot. Sensor-generated data are acquired and processed by the RP 2040 microcontroller, enabling comprehensive analysis of voltage outputs produced from both feet. An easily accessible push-button initiates each test run, complemented by a visual confirmation via a green LED indicator. Power is conveniently provided by a portable power bank, facilitating mobile and uninterrupted use of the system.

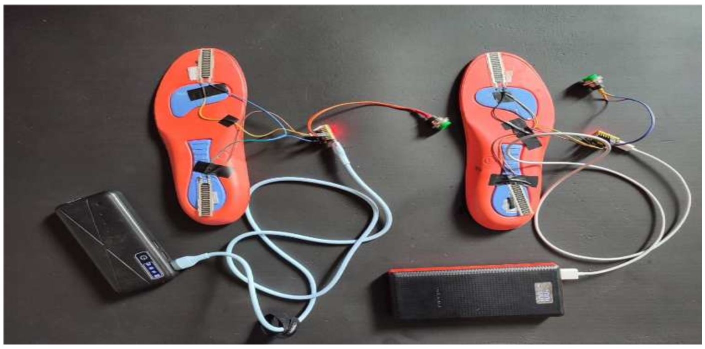

Figure 3. Illustration of the project design with sensor placement

3. RESULTS AND DISCUSSION

Voltage monitoring results were collected from ten male respondents of varying weights and ages. The data, displayed in voltage-time graphs for the left and right foot sensors, provides insight into how foot pressure distribution and fatigue patterns develop during sustained physical activity.

For Respondent 1, the sensor on the front of the left foot shows a clear increase in voltage over time, indicating a gradual shift in pressure toward the toes as the activity progresses. This pattern indicates increased muscle engagement, which likely causes fatigue, as seen from the occasional decrease in signal at the end of the period. Meanwhile, the right foot maintains stable tension for both sensors, highlighting balanced and controlled movement on that side. This imbalance indicates that the left foot bears a greater dynamic load, while the right foot stabilizes the step, as shown in Figure 4.

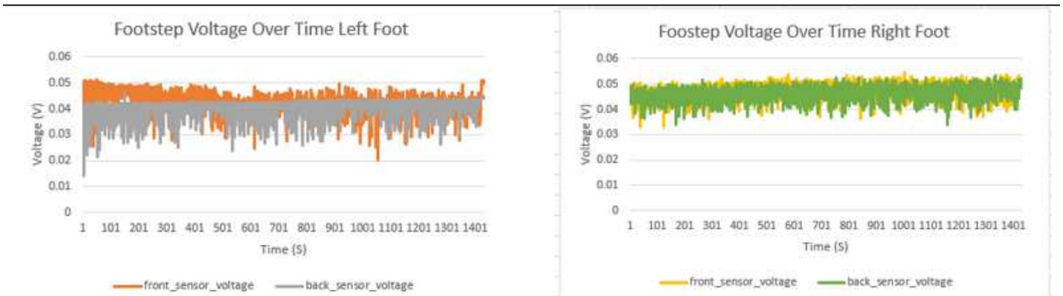

Figure 4. Step voltage over time for Respondent 1

Respondent 1 demonstrates a gradual increase in left forefoot voltage, indicating progressive loading and fatigue compensation, while the right foot remains stable, aligning with findings on compensatory gait strategies during fatigue [1], [2], [12].

In Respondent 2, the front sensor on the left foot also displayed a high initial reading but gradually decreased, with increased fluctuations in the final stage of the session. The rear sensor displayed a minimal and unstable signal that faded earlier, indicating limited heel involvement. The right foot, however, showed stable and consistent tension for both sensors, indicating effective pressure distribution. This asymmetry suggests that the left front foot experienced greater load, while the right foot supported overall balance as presented in Figure 5.

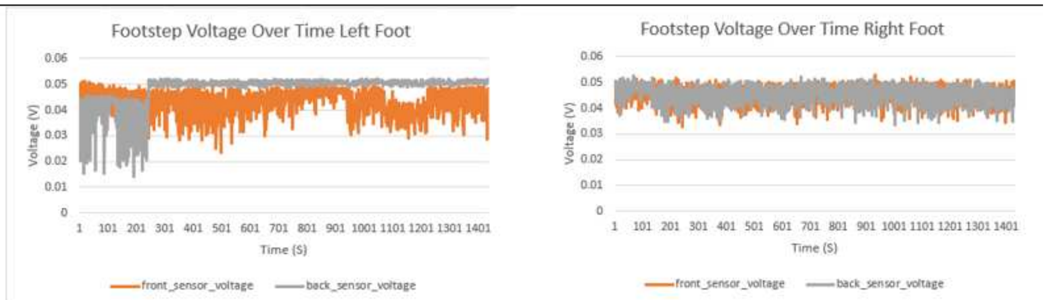

Figure 5. Step voltage over time for Respondent 2

A similar study with Respondent 2 in Figure 6 experienced a decrease in tension in the front of the foot and fluctuating signals over time, indicating reduced strength, stability, and altered foot mechanics, consistent with toe-dominated stepping and fatigue [5], [7], [13], [14].

Respondent 3 in Figure 6 shows a characteristic fatigue pattern in the left foot. The front sensor starts strong but weakens significantly after the midpoint, indicating fatigue in the front muscles of the foot. The rear sensor remains more stable, indicating a shift in pressure toward the heel to compensate for this change. The right foot readings remain stable throughout, indicating that the right foot compensates for the weakening of the left foot.

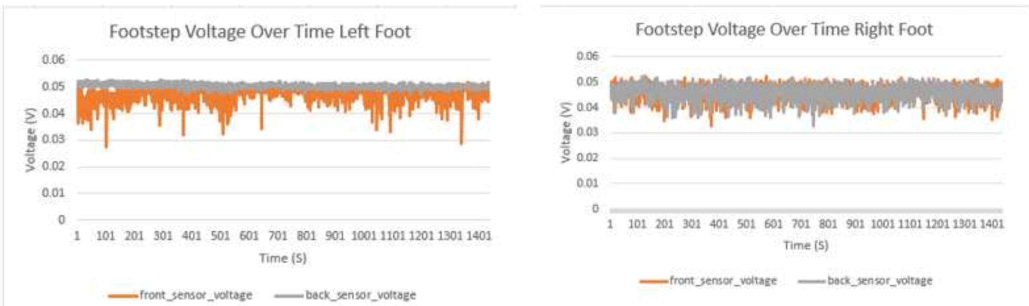

Figure 6. Step voltage over time for Respondent 3

The results for Respondent 3 are relevant to research findings that indicate a clear shift in weight from the forefoot to the heel over time, which is a known biomechanical adaptation to reduce muscle tension during prolonged effort [1], [8], [14].

The results for Respondent 4 in Figure 7 show signs of early fatigue in the left leg. The front sensor displays irregular fluctuations between 200 and 600 seconds, indicating inconsistent load due to muscle tension.

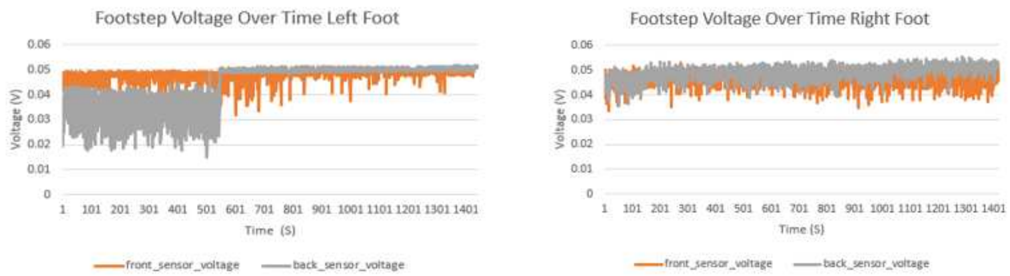

Figure 7. Step voltage over time for Respondent 4

The rear sensor also shows instability before finally stabilizing. The right leg, however, remains stable and balanced on both sensors, highlighting an imbalance in which the right leg compensates for the weakness of the left leg. The results for Respondent 4 show early signs of fatigue in the left foot. The front sensor displays irregular fluctuations between 200 and 600 seconds, suggesting inconsistent loading due to muscle strain. The back sensor also shows instability before levelling off. The right foot, however, remains stable and balanced across both sensors, highlighting an asymmetry where the right leg compensates for the left's weakness. Respondent 4 displays high early voltage variability before stabilizing mid-test, demonstrating fatigue adaptation mechanisms described in sensor-based gait monitoring studies [5], [6], [12], [13]. Both cases reinforce the role of piezoelectric voltage trends as indicators of biomechanical compensation and fatigue progression.

For Respondent 5 in Figure 8, both feet show strong, stable voltage signals with only minor initial fluctuations that quickly stabilize. The right foot demonstrates even greater consistency, suggesting symmetrical gait and balanced muscular endurance. This stability indicates effective pressure distribution across both legs, minimizing the risk of fatigue-related asymmetry.

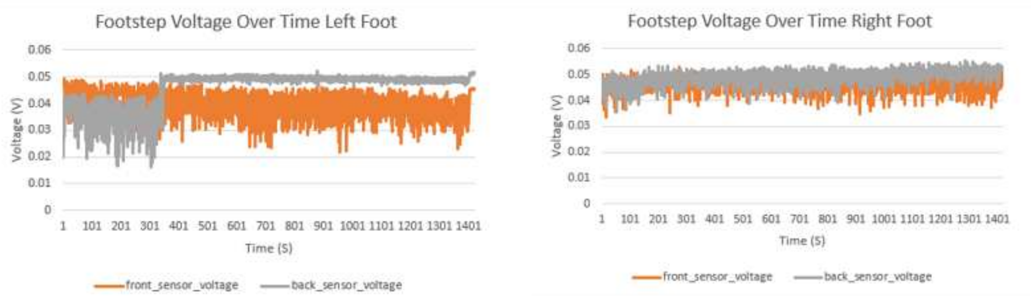

Figure 8. Step voltage over time for Respondent 5

Respondent 5 in Figure 8 represents an ideal balanced gait pattern, with stable and symmetrical voltage profiles across both feet, minimal fatigue effects, and efficient energy transfer through the piezoelectric elements. This behavior aligns with high-stability gait profiles described in controlled locomotion studies [3], [13], [15].

Figure 9 shows that Respondent 6 begins with balanced foot pressure but shows signs of fatigue in the left foot as the session progresses. The left front sensor displays frequent drops and fluctuations, indicating muscle strain and reduced control. Meanwhile, the back sensor remains steady. The right foot maintains smooth, consistent signals, suggesting that the right leg bears a greater load as the left foot fatigues.

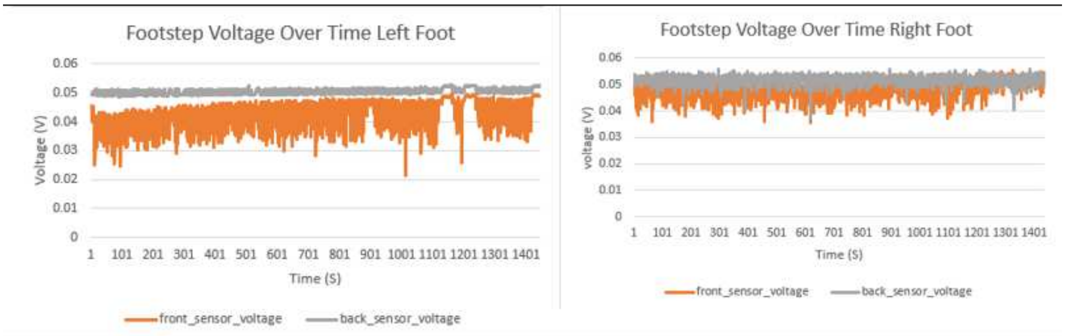

Figure 9. Step voltage over time for Respondent 6

Respondent 6 exhibits increasing left forefoot fatigue over time, compensated by stable loading in the right limb. The voltage fluctuation pattern corresponds with asymmetric fatigue onset models and confirms the sensitivity of piezoelectric sensors to localized gait instability [1], [5], [7], [14].

Respondent 7 in Figure 10 shows exhibits signs of asymmetry, with the right foot producing strong and steady signals, particularly from the front sensor, indicating stable and dominant leg engagement. The left foot front sensor is stable, but the back sensor fluctuates noticeably, indicating inconsistent heel contact and potential early fatigue.

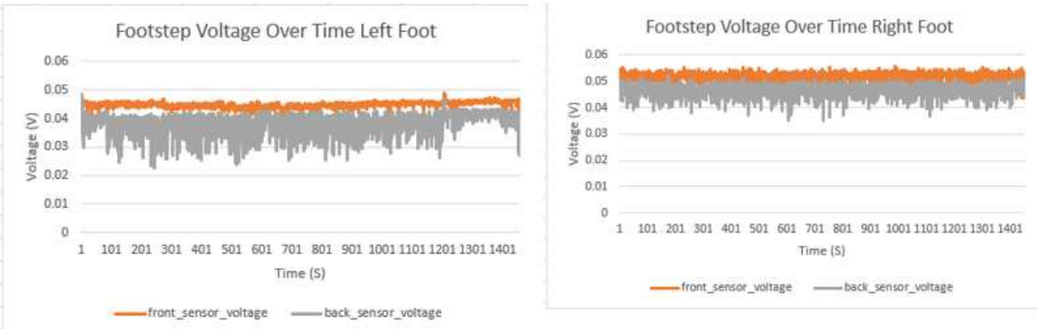

Figure 10. Step voltage over time for Respondent 7

Figure 11 shows that Respondent 8 displays steady voltage on the right foot for both sensors, indicating consistent pressure control. The left foot's front sensor matches this stability, but the back sensor fluctuates with occasional drops, suggesting inconsistent heel engagement. This imbalance implies that the right leg is compensating for slight fatigue or weaker pressure control in the left heel area.

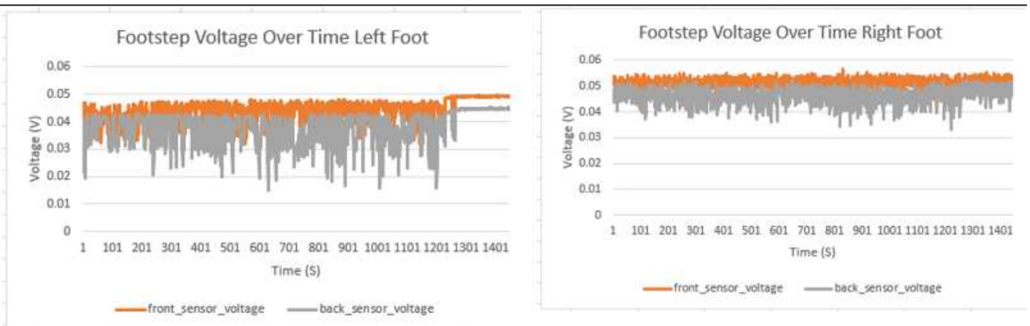

Figure 11. Step voltage over time for Respondent 8

Respondent 9 in Figure 12 shows exhibits apparent left-right asymmetry. The right foot maintains steady, balanced signals for both sensors. However, the left foot's back sensor drops midway, suggesting a loss of heel contact, while the front sensor gradually declines.

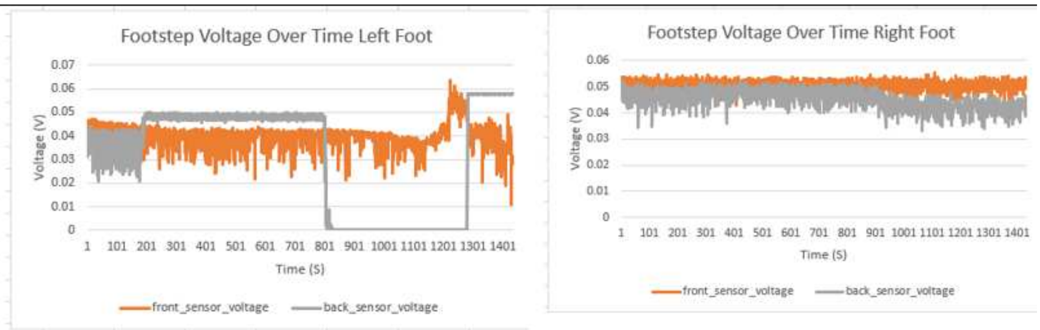

Figure 12. Step voltage over time for Respondent 9

A sudden spike followed by a drop later indicates an attempt to re-engage the left foot, but without sustained control, which reflects growing reliance on the right foot for stability. Finally, Respondent 10 in Figure 13 shows stable initial signals for both feet. However, over time, the back sensor on the left foot shows a notable drop below 0.03 volts after 1.000 seconds, indicating heel fatigue.

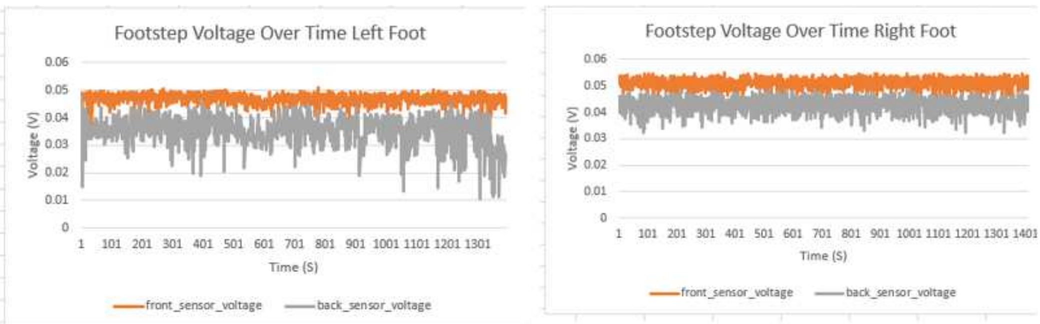

Figure 13. Step voltage over time for Respondent 10

Respondents 7 up to 10 consistently display left–right asymmetry due to unilateral fatigue or altered gait mechanics. These include reduced heel contact, intermittent force application, and compensatory weight shifting to the dominant leg. Such asymmetry reduces consistent energy harvesting potential and produces irregular voltage output patterns [2], [5], [11]. These results support earlier findings that fatigue leads to gait adaptation and asymmetric loading [1], [8], [12], [13], [15]. From a system design perspective, the results highlight the importance of optimized sensor placement, signal conditioning, and adaptive algorithms for accurate fatigue and gait monitoring [5], [7], [11], [14].

The right foot remains steady throughout, implying it compensates for the declining pressure on the left side. This pattern highlights asymmetrical fatigue and demonstrates how the system can reveal early signs of imbalance.

4. CONCLUSION

This study demonstrated that piezoelectric sensors embedded in footwear are effective for both energy harvesting and fatigue monitoring during physical activity. The system successfully detected biomechanical changes over time based on voltage data from ten male participants aged 15–31 years. Several respondents, including Participants 1, 2, 3, and 10, showed a decline in heel voltage on the left foot during prolonged running, indicating fatigue-induced gait asymmetry. For example, Respondent 10 (18 years, 56 kg) experienced a drop in left heel voltage to below 0.03 V after 1.000 seconds, while the right foot maintained stable output between 0.045–0.055 V, showing compensation by the dominant leg. Conversely, Respondent 5 (31 years, 73 kg) demonstrated stable voltage across both feet, reflecting balanced gait and good muscular endurance. These findings confirm that the prototype system using Raspberry Pi Pico RP2040 and DLAY piezoelectric sensors can generate meaningful voltage outputs for energy harvesting while providing real-time insight into gait stability and fatigue progression. The results indicate promising potential for applications in sports performance tracking, rehabilitation, and smart wearable health systems.

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