

Design, Fabrication, and Experimental Characterisation of a Low-Cost Piezoelectric Pavement Tile for Footstep Energy Harvesting: An Indoor Pilot Study at a University in Somalia

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Abstract

Pedestrian traffic provides a small but persistent mechanical input that can be converted into electrical signals for distributed sensing. This study designed, fabricated, and experimentally characterized a low-cost piezoelectric pavement tile using components available in Mogadishu, Somalia. The 24×16.5 cm prototype contains ten PZT-5A ceramic discs connected in parallel beneath a rigid acrylic plate and a 10 mm expanded polyethylene foam layer. The array feeds a four-diode bridge rectifier, a 10 μ F capacitor, and an Arduino UNO used for voltage acquisition and relay control. Controlled indoor tests produced two independently acquired datasets. In the qualitative loading series, conditioned voltage increased from 0 mV at no load to 25–50 mV under a full footstep; eight repeated firm-footstep trials yielded 24.6 ± 1.8 mV (CV = 7.5%). In the participant series, one-foot loads of 245.25, 343.35, and 490.50 N produced capacitor voltages of 0.20, 0.35, and 0.50 V. Corresponding recovered energies were 0.200–1.250 μ J, average powers 0.500–3.125 μ W, and estimated system-level efficiencies 5.44×10^{-5} – 1.02×10^{-4} %. Current was below instrument resolution, so energy and power were derived from capacitor voltage. The two voltage series differed by approximately one order of magnitude and were therefore analysed separately. The prototype reliably detected footsteps but did not provide useful load power, identifying event sensing rather than energy supply as its realistic application.

Keywords: Piezoelectric energy harvesting, Footstep energy harvesting, Pavement tile, PZT-5A, Energy conversion efficiency, Low-power sensing, Proof-of-concept prototype, Somalia

1. Introduction

Growing electricity demand and decarbonization targets continue to expand interest in renewable and distributed energy technologies [1], [2]. Alongside utility-scale generation, ambient energy harvesting has developed as a complementary approach for low-power devices embedded in buildings and infrastructure [3], [4]. Its value lies less in bulk electricity production than in reducing wiring and battery maintenance for distributed sensing nodes.

Human locomotion is attractive in this context because foot traffic is repetitive, spatially concentrated, and available wherever occupancy monitoring is useful. Walking transfers repeated mechanical impulses to floors that are otherwise dissipated as heat and deformation

[5], [6]. Shoe-mounted devices can achieve stronger mechanical coupling but require user participation, whereas floor-mounted harvesters remain fixed, shared, and unobtrusive [7]. Piezoelectric ceramics convert mechanical stress directly into electrical charge through the direct piezoelectric effect [8], [9]. Their constitutive behaviour is well established [10], [11]; the principal engineering problem in a floor tile is therefore not the material mechanism itself but the load path and interface circuit. Mechanical compliance determines how much footstep work reaches the ceramic, while rectification, impedance matching, and storage determine how much generated charge becomes recoverable electrical energy.

Published pavement harvesters broadly fall into two design families. Low-cost systems use direct compression with little or no mechanical amplification. Disc-based tiles in this class generally report outputs from sub-milliwatt to a few milliwatts per step, with ceramic fragility and uneven load transfer recurring concerns [12]–[16]. Their advantages are simple fabrication, low component count, and compatibility with basic workshop facilities.

Higher-output designs add mechanical amplification, stacked transducers, or active power-conditioning circuits. Frequency up-conversion, stacked, and spring-mounted architectures increase transducer excitation at a given external force [17]–[19], while voltage doublers, booster converters, impedance-matching networks, and maximum-power-point tracking reduce electrical losses [20]–[23]. Related road and impact harvesters show the same dependence on mechanical coupling and interface design [24]–[26]. Product-oriented studies likewise emphasise that tile geometry, transducer arrangement, durability, and conditioning electronics must be evaluated together rather than as isolated components [27]. The large output spread across reported devices is therefore mainly architectural. High source impedance and rectifier forward-voltage losses are especially important at low signal amplitudes [28], [29].

A parallel strand of research treats the harvested signal primarily as information. Recent footstep systems have been proposed for smart infrastructure, pedestrian monitoring, and battery-free or intermittently powered sensing [30]–[36]. In such applications, repeatable event detection can be more useful than the absolute energy recovered from each step. This distinction is important when evaluating deliberately simple, unamplified prototypes.

The deployment context also matters. Energy-access constraints, financing costs, and dependence on off-grid or backup generation remain significant across parts of Sub-Saharan Africa [37]–[49]. Somalia has a fragmented electricity system, high tariffs, and substantial institutional dependence on local generation [50]. A locally fabricated, self-signalling floor sensor therefore has a different research value from a device assessed only as a source of electrical power.

Two gaps motivate the present work. Quantitative footstep-harvesting data from Somali institutions are absent from the published record, and many low-cost demonstrations report voltage or power without an explicit mechanical-energy baseline or transparent treatment of assumptions. This study therefore develops a locally reproducible pavement tile, documents its mechanical and electrical architecture, quantifies load-dependent voltage, repeatability, recovered energy, power, and system-level efficiency, and distinguishes measured quantities from calculated and assumed values. Tests were conducted in a Hornuud University hallway as a controlled indoor pilot environment rather than as a field deployment.

2. Materials and methods

2.1 Theoretical framework

The prototype operates through the direct piezoelectric effect. For a linear piezoelectric material under small-signal conditions, electric displacement D depends on mechanical stress T , the piezoelectric charge constant d , permittivity ϵ , and electric field E :

$$D = dT + \varepsilon E \quad (1)$$

Under near open-circuit harvesting conditions, generated charge is approximated as proportional to applied force:

$$Q = d \cdot F \quad (2)$$

and the corresponding voltage across a transducer of capacitance C is:

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

Equations 1–3 separate the principal design variables. Mechanical construction controls the force and strain delivered to the ceramic, whereas the transducer constants are fixed once the PZT element is selected. Downstream, recovered energy is highly sensitive to voltage because capacitor energy varies with V^2 , and the high source impedance of piezoelectric ceramics makes interface impedance and rectifier losses critical. These considerations guided the load-transfer structure and electrical conditioning used here.

Table 1. Nomenclature. The symbol d carries two conventional meanings in this field, and the equation number is given where ambiguity could arise.

Symbol	Quantity	Unit
D	Electric displacement	C/m^2
T	Mechanical stress	Pa
d (Eqs. 1, 2)	Piezoelectric charge constant	C/N
ε	Permittivity of the material	F/m
E	Electric field	V/m
Q	Generated electric charge	C
C	Capacitance of the filter capacitor	F
V	Measured output voltage at the capacitor terminals	V
m	Participant body mass	kg
g	Standard gravitational acceleration (9.81)	m/s^2
W	Participant body weight	N
F	Effective one-foot force	N
d (Eq. 6)	Vertical displacement of the tile surface	m
E_m	Mechanical input energy per loading event	J
E_e	Electrical energy recovered on the capacitor	J
P	Average electrical power per loading event	W
t	Pulse duration assumed in the power calculation	s
η	System-level energy conversion efficiency	%

2.2 Prototype architecture

The tile comprises four functional stages (Figure 1): a mechanical load-transfer structure, a ten-disc piezoelectric array, a rectifier/filter storage stage, and an Arduino-based measurement and indication stage. The top structure distributes the footstep, the array converts strain into charge, the bridge and capacitor condition the bidirectional signal, and the microcontroller detects the event and controls the relay.

Component selection prioritised local availability in Mogadishu, followed by mechanical suitability and cost. This constraint explains choices that are practical but electrically suboptimal, particularly the use of general-purpose 1N4007 diodes rather than low-

drop Schottky devices and adhesive bonding rather than a machined fixture. The prototype was intended as a reproducible local baseline, not as an output-maximised tile.

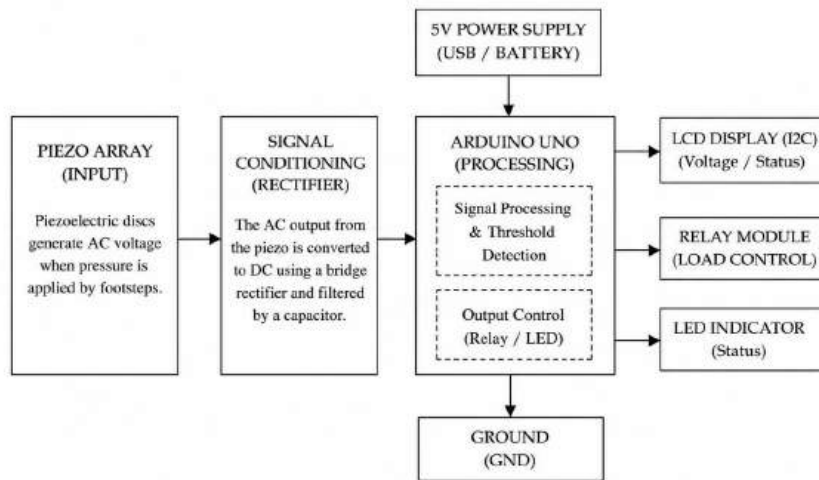


Figure 1. System block diagram showing the piezoelectric array as input stage, the bridge-rectifier and filter-capacitor conditioning stage, the Arduino UNO processing stage, and the LCD, relay, and indicator output stage.

2.3 Materials and components

Table 2 lists the complete component set and its role in the assembled system. The specification is retained in full so that the prototype can be reconstructed and so that electrical and mechanical limitations can be traced to particular components.

Table 2. Components used in the fabricated prototype.

Component	Qty	Function in the assembled system
Acrylic sheet, 24 cm × 16.5 cm	1	Rigid top plate; distributes footstep load across the array
PMMA substrate sheet	1	Mounting substrate for the disc array
PZT-5A piezoelectric ceramic disc	10	Electromechanical transduction; wired in parallel
EPE foam sheet, 10 mm	1	Cushioning base layer; permits controlled vertical deflection
A3 cardboard sheet	6	Structural casing and pressure platform
AKFIX 705 adhesive	1	Bonding of casing and foam layers
1N4007 diode	4	Full-wave bridge rectification of the alternating array output
Electrolytic capacitor, 10 μ F / 25 V	1	Ripple filtering and the storage element used in Eq. 7
Arduino UNO	1	10-bit ADC voltage measurement on pin A1; relay control on pin D7
I ² C LCD, 16 × 2	1	Live voltage display during testing; SDA to A4, SCL to A5
5 V relay module	1	Switches the electrically separate 9 V indicator circuit
RGB LED strip (9 V, 600 mA)	1	Visual indication of a detected event; externally supplied

9 V battery	2	One supplies the Arduino via VIN; one supplies the LED strip
Digital multimeter, DT830D	1	Voltage measurement at the capacitor terminals
Digital weighing scale	1	Participant body mass measurement
Breadboard, jumper and connecting wire	1 set	Circuit assembly

2.4 Fabrication

The 24×16.5 cm acrylic top plate provides stiffness and spreads footstep load over the transducer array. Ten PZT-5A ceramic discs were bonded to a PMMA substrate beneath the plate and connected in parallel, with common positive and negative terminals. Parallel connection sums charge and improves current capacity while keeping terminal voltage close to that of a single disc; it also avoids complete array failure if one element becomes open-circuit. A 10 mm expanded polyethylene foam layer beneath the array cushions the brittle discs and permits limited vertical travel. This protection carries an energy penalty because part of the applied work is absorbed by the foam before reaching the ceramic. The assembly was enclosed in a cardboard casing bonded with adhesive. Figure 2 shows the disc arrangement and completed prototype.

The design therefore deliberately balances survivability, local manufacturability, and energy transfer. The same compliant interfaces that protect the ceramic also reduce strain transfer, a trade-off considered when interpreting the measured output.

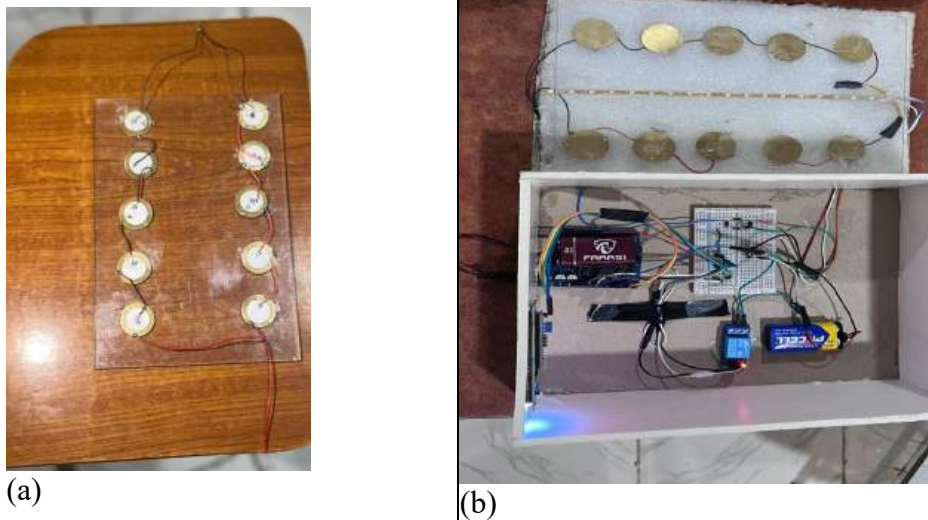


Figure 2. Prototype fabrication. (a) Ten PZT-5A piezoelectric ceramic discs wired in parallel on the substrate before final assembly. (b) Completed prototype showing the disc tile at top and the electronic housing containing the Arduino UNO, breadboard rectifier circuit, relay module, and LED strip.

2.5 Electrical conditioning and storage

The piezoelectric array feeds a full-wave bridge rectifier assembled from four 1N4007 diodes. Because disc polarity reverses between compression and release, rectification is required before the signal can be sampled by the microcontroller. Two diode drops are present in each conducting path, which is a substantial penalty when the generated signal is only tens or hundreds of millivolts.

A $10 \mu\text{F}$, 25 V electrolytic capacitor is connected across the rectifier output. It smooths the rectified pulse for measurement and serves as the storage element used to calculate recovered electrical energy. The reported electrical energy is therefore the energy present on

the capacitor after rectification, not the gross energy generated by the ceramic. An Arduino UNO samples the conditioned voltage through its 10-bit ADC over 0–5 V, giving a nominal step of about 4.9 mV, and displays the result on a 16×2 I²C LCD. A 5 V relay controlled from digital pin D7 switches a separate 9 V circuit supplying an RGB LED strip. The harvested signal triggers the relay; it does not power the indicator. Piezoelectric harvesting, voltage sensing, relay actuation, and externally supplied visual indication are consequently treated as distinct outcomes throughout the analysis.

2.6 Experimental environment and instrumentation

Testing was conducted on a flat, rigid indoor floor in a Hormuud University hallway, with the tile and conditioning circuit held stationary. The environment provided controlled pedestrian-type loading while excluding weather and contamination effects. It is treated as a pilot test environment, not as evidence of long-term field performance. Figures 3–5 document the workflow, prototype under loading, and test circuit.



Figure 3. Experimental workflow followed for prototype testing and data analysis.

Participant mass was measured with a digital scale. Capacitor voltage for the quantitative series was recorded with a DT830D multimeter connected directly across the filter capacitor, independently of the Arduino display path. Current could not be resolved: the instrument floor is approximately 200 μ A, well above the expected nanoampere-to-microampere current. No current value was assumed; recovered energy and average power were derived from capacitor voltage as described in Section 2.8.



Figure 4. Assembled prototype under footstep loading in the Hormuud University hallway test environment, showing a live voltage reading on the Arduino-driven LCD.

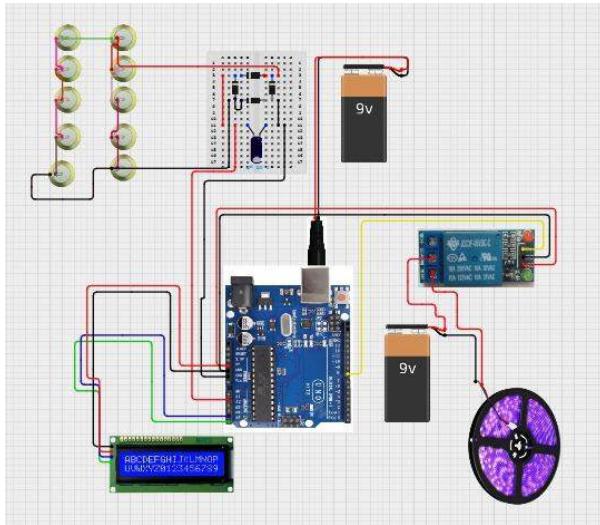


Figure 5. Experimental setup showing the piezoelectric tile, the breadboard rectifier and Arduino measurement circuit, the relay module, and the indicator used during controlled indoor testing. The 2.40 mV display visible in Figure 4 was recorded during a preliminary continuity check and is not part of the analysed dataset. This distinction avoids mixing setup documentation with formal measurements.

2.7 Loading and testing procedure

Two datasets were collected in separate sessions and under different measurement arrangements. The qualitative series comprised no load, light footstep, firm footstep, full footstep engaging multiple discs, and load release. Its purpose was to establish direction of response, threshold switching, and return to baseline. The firm-footstep condition was repeated eight times to assess short-term repeatability; voltages were read through the Arduino display path.

The quantitative participant series comprised three individuals of 50, 70, and 100 kg, each contributing one single-foot trial. Body mass, tile displacement, and peak capacitor voltage were recorded, with voltage measured by the DT830D. Participants removed footwear and the system was allowed to return to zero between trials. Participation was voluntary and non-invasive, no identifying information other than body mass was recorded, and voltages remained within safe extra-low-voltage limits. Stepping frequency was not controlled and cumulative walking was not assessed. The experiments therefore support per-event characterisation only; no inference is made about cadence effects, accumulated energy, or continuous pedestrian traffic.

2.8 Data reduction and calculations

Participant body weight was calculated from measured mass as

$$W = mg \quad (4)$$

with $g = 9.81 \text{ m/s}^2$. Because direct force measurement was unavailable, effective one-foot force was estimated as

$$F = 0.5 W \quad (5)$$

The factor 0.5 is an engineering approximation applied consistently across participants, not a physiological assertion. Actual stance-phase force can exceed half body weight; this assumption is therefore the dominant systematic uncertainty in force, mechanical energy, and

efficiency. Mechanical input energy per event was estimated from the product of effective force and measured vertical displacement:

$$Em = F \times d \quad (6)$$

This rectangular work approximation treats force as constant through the compression stroke. The true foam-supported force–displacement relation was not measured and is expected to be nonlinear. Recovered electrical energy on the filter capacitor was calculated from peak measured voltage:

$$Ee = \frac{1}{2} CV^2 \quad (7)$$

where the nominal capacitance was 10 μF (1.0×10^{-5} F). Because capacitance was not independently measured, its tolerance propagates directly into energy, power, and efficiency. Average electrical power was obtained from

$$P = Ee / t \quad (8)$$

using a common pulse duration of 0.40 s based on observed charge–discharge behaviour. The value was not measured per trial and therefore scales the absolute power estimates uniformly. System-level energy conversion efficiency was calculated as

$$\eta = (Ee / Em) \times 100 \% \quad (9)$$

Table 3 identifies each variable as measured, calculated, nominal, standard, or assumed. This classification is central to interpretation: mass, displacement, and voltage were measured; force and mechanical energy depend on the one-foot approximation; electrical energy derives from capacitor voltage; power additionally depends on the assumed pulse duration; and current was not measured.

Table 3. Classification of every quantity used in the data reduction as measured, calculated, or assumed, with its provenance.

Quantity	Symbol	Classification	Provenance
Participant body mass	m	Measured	Digital weighing scale, immediately before each trial
Tile vertical displacement	d	Measured	Manual measurement under applied load, in millimetres
Capacitor voltage (participant series)	V	Measured	DT830D multimeter at the capacitor terminals
Conditioned voltage (loading series)	V	Measured	Arduino 10-bit ADC, displayed on the LCD
Filter capacitance	C	Nominal value	Manufacturer rating of 10 μF ; not independently measured
Gravitational acceleration	g	Standard constant	9.81 m/s ²
One-foot force fraction	0.5	Assumed	Engineering approximation; no load cell available
Body weight	W	Calculated	Equation 4
Effective one-foot force	F	Calculated (assumption-dependent)	Equation 5, inherits the 0.5 factor
Mechanical input energy	Em	Calculated (assumption-dependent)	Equation 6, constant-force approximation

Electrical energy recovered	E_e	Calculated	Equation 7, from measured V and nominal C
Pulse duration	t	Assumed	0.40 s, from observed charge and discharge behaviour; not measured per trial
Average electrical power	P	Calculated (assumption-dependent)	Equation 8, inherits the assumed t
Energy conversion efficiency	η	Estimated	Equation 9, inherits all assumptions above
Current	I	Not measured	Below the approximately 200 μ A resolution of the available instrument

3. Results

3.1 Prototype response

The prototype remained functional throughout testing. Every active loading event produced a measurable voltage, the Arduino detected each event, the relay switched correctly, and no false trigger occurred during no-load intervals. No disc fracture, delamination, or visible structural failure was observed. These observations demonstrate short-term functionality only and do not establish durability.

3.2 Load-dependent voltage response

Table 4 and Figure 6 summarise the qualitative load response. Voltage increased monotonically from 0 mV at baseline to 8–15 mV under a light footstep, 18–30 mV under a firm footstep, and 25–50 mV under a full footstep engaging several discs. Removal of the load returned the output to zero and deactivated the relay and indicator.

Table 4. Voltage, relay state, and indicator state across the five loading conditions of the qualitative series. Voltages were read through the Arduino ADC and displayed on the LCD.

Test	Condition	Voltage (mV)	Relay	Indicator
1	No load (baseline)	0	Not activated	Off
2	Light footstep	8 - 15	Activated	On
3	Firm footstep	18 - 30	Activated	On
4	Full footstep (multiple discs)	25 - 50	Activated	On (brighter)
5	Load released	Returns to 0	Deactivated	Off

The higher full-footstep response may reflect both greater force per disc and engagement of more discs. Because the parallel array sums charge from active elements, the present experiment cannot separate these effects. The result nevertheless establishes a clear load-dependent electrical response and a stable zero baseline.

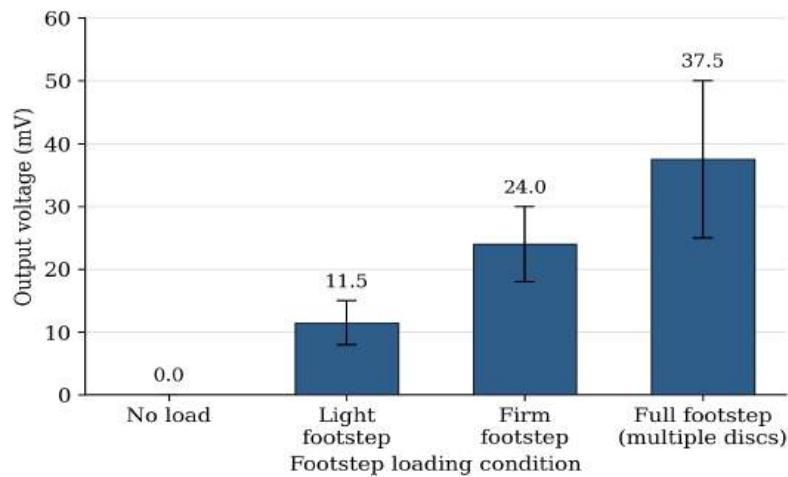


Figure 6. Output voltage against footstep loading condition. Bars show the midpoint of each recorded range; error bars span the full range given in Table 4.

3.3 Repeatability

Eight repeated firm-footstep trials produced 22, 25, 24, 28, 23, 26, 24, and 25 mV (Table 5; Figure 7), giving a mean of 24.6 mV, sample standard deviation of 1.8 mV, and coefficient of variation of 7.5%. No monotonic drift was evident. The observed scatter includes variation in manual loading, foot placement, and ADC quantisation. Since the 4.9 mV ADC step is larger than the calculated standard deviation, the 7.5% coefficient should be treated as an upper-bound estimate of short-term system variability rather than a precise measure of transducer repeatability.

Table 5. Output voltage across eight repeated trials of the firm-footstep condition. Mean 24.6 mV; standard deviation 1.8 mV; coefficient of variation 7.5 %.

Trial	1	2	3	4	5	6	7	8	Mean
Voltage (mV)	22	25	24	28	23	26	24	25	24.6

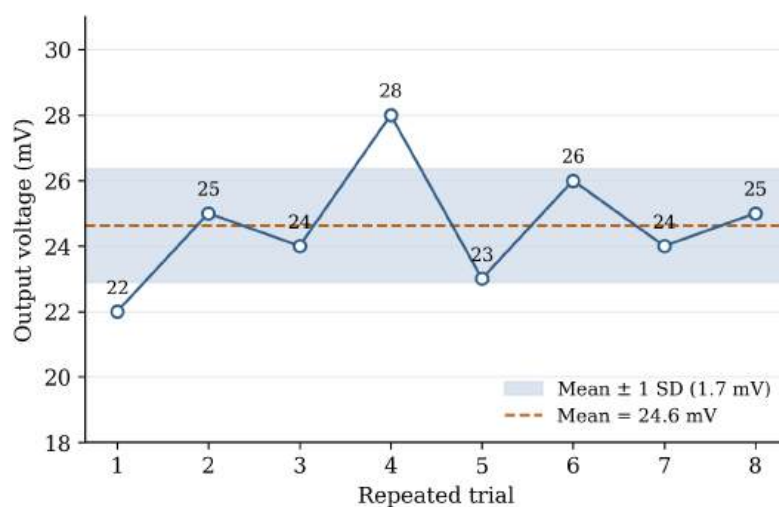


Figure 7. Output voltage across eight repeated trials of the firm-footstep condition, with the trial mean and the one standard deviation band.

3.4 Mechanical input and electrical output

Table 6 combines the measured participant quantities with values derived from Equations 4–9. Effective force increased from 245.25 to 490.50 N as participant mass rose from 50 to 100 kg, while measured tile displacement increased from 1.5 to 2.5 mm. Mechanical input energy therefore rose from 0.3679 to 1.2263 J. Capacitor voltage increased from 0.20 to 0.50 V across the same loading range. Table 6. Measured and derived quantities for the three participants under one-foot loading. Mass, displacement, and voltage were measured; force, mechanical energy, electrical energy, power, and efficiency were calculated using Equations 4 to 9.

Classification of each quantity is given in Table 3.

	Mass	Force F	Displ. d	Em	Voltage	Ee	Power P	Efficiency η
	(kg)	(N)	(mm)	(J)	(V)	(μ J)	(μ W)	(%)
P1	50	245.25	1.5	0.3679	0.20	0.200	0.500	5.44×10^{-5}
P2	70	343.35	2.0	0.6867	0.35	0.613	1.531	8.92×10^{-5}
P3	100	490.50	2.5	1.2263	0.50	1.250	3.125	1.02×10^{-4}

Displacement increased less than proportionally with force, consistent with progressive stiffening of the foam-supported laminate. Voltage increased by a factor of 2.5 while estimated force doubled, indicating a monotonic but non-proportional response. With only three participant trials, no functional relationship is fitted.

3.5 Power and estimated efficiency

From Equation 7, recovered capacitor energy increased from 0.200 to 1.250 μ J. Using the assumed 0.40 s pulse duration, average power rose from 0.500 to 3.125 μ W. Estimated system-level efficiency increased from $5.44 \times 10^{-5}\%$ at 245.25 N to $1.02 \times 10^{-4}\%$ at 490.50 N (Figure 8). The increase follows from the squared voltage term in capacitor energy, which grew faster over the tested range than the estimated mechanical input. These efficiencies describe the complete fabricated assembly from estimated footstep work to energy stored on the capacitor. They are not intrinsic PZT-5A conversion efficiencies. Absolute values inherit the assumed one-foot force, constant-force work approximation, nominal capacitor value, and limited sample size; their relative ordering is more defensible than their precise magnitude.

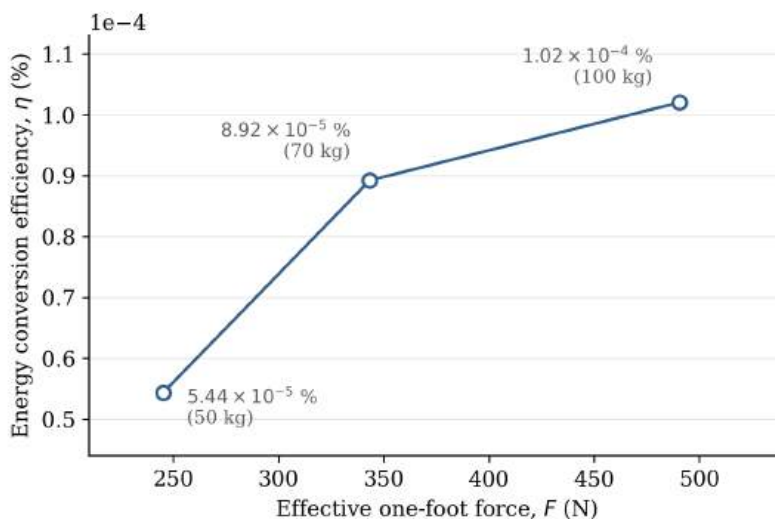


Figure 8. System-level energy conversion efficiency against effective one-foot force, from the three participant trials in Table 6. Participant body mass is annotated at each point.

3.6 Comparison with existing studies

Table 7 compares the prototype with selected direct-compression and mechanically or electrically enhanced systems. Numerical comparisons must be interpreted cautiously because tile area, transducer geometry, loading protocol, conditioning circuitry, and reported metrics differ among studies. The present device lies at the low-output end, with 0.500–3.125 μW , whereas direct-compression literature generally reaches sub-milliwatt to low-milliwatt levels and amplified or circuit-optimised designs extend substantially higher. Selim et al. [20], [21] reported a maximum useful output of 246 mW, rising to 249.6 mW with a voltage doubler versus 189.6 mW with a bridge rectifier. Their tile is about 4.65 times larger in active area and uses fourteen rather than ten transducers, so scale alone cannot explain the much larger output. The comparison instead points to mechanical strain transfer and power-conditioning design as the dominant differences.

Table 7. The present prototype compared with non-amplified systems (Group A) and mechanically amplified or circuit-optimised systems (Group B).

Study	Voltage	Power	Efficiency	Configuration
Group A. Non-amplified, low-cost systems				
Present study	0.20 - 0.50 V	0.500 - 3.125 μW	5.44×10^{-5} to $1.02 \times 10^{-4} \%$	10 PZT-5A discs in parallel; diode bridge and 10 μF capacitor; 240×165 mm
Fan et al. (2017) [7]	not reported	0.03 - 0.35 mW	not reported	Shoe-mounted cantilever, magnetic coupling
Withana (2023) [14]	not reported	1 - 5 mW per step	not reported	Rod-tap and wheel-tap striking mechanism
Yingyong et al. (2021) [12]	not reported	1 - 3 mW per step	not reported	Modular tile, PZT discs, direct compression
Fauzi & Noh (2022) [13]	not reported	< 2 mW per step	not reported	Sensor-based floor tile, no amplification
Sandoval Rodriguez et al. (2023) [15]	not reported	not reported	not reported	27 mm discs, 1300×750 mm platform, 75 - 85 kg participants
Esekhaigbe et al. (2025) [16]	9 - 20 V pre-reg.; 5 V reg.	not reported	not reported	Discs with battery storage,

				grid-unstable regions
Group B. Mechanically amplified or circuit-optimised systems				
Asadi et al. (2023) [17]	not reported	1 - 5 mW per step	not reported	Electromagnetic frequency up-converted floor tile (Halbach array)
Sharma et al. (2022) [18]	not reported	up to 8 mW (lab)	not reported	Stacked PZT tile (review)
Sirigireddy et al. (2022) [19]	up to 69 V peak to peak	3.95 mW avg. at 490 N	not reported	Stacked, spring-mounted disc array
Selim et al. (2024) [20]	33.7 V open circuit	246 mW max. useful; 249.6 mW with voltage doubler, 189.6 mW with plain bridge	not reported	14 patches of 35 mm; 455 × 405 mm tile; ≈ USD 10.2 per tile
Dadi et al. (2025) [22]	up to 9 V	≈ 1 mW	68.2 %	11 discs, DC-DC booster and RFID
Potdar et al. (2025) [23]	not reported	1.04 mW	68 %	Optimised transducer matrix with MPPT

Entries marked “not reported” indicate quantities the source does not report; no values have been inferred. Efficiencies reported by Dadi et al. [22] and Potdar et al. [23] are defined at the power-conditioning stage and are not directly comparable with the system-level figure computed here.

4. Discussion

4.1 Load dependence

Both datasets show a monotonic increase in voltage with applied load, consistent with piezoelectric charge generation. The participant series is not proportional: estimated force doubled while voltage rose 2.5-fold. Greater displacement at higher load increased strain, and the fixed forward-voltage loss of the diode bridge consumes a larger fraction of weak signals than strong ones. Either mechanism can produce super-proportional terminal voltage without implying nonlinear ceramic behaviour. Three points are insufficient to distinguish mechanisms or fit a response law; they support only the direction of the load effect.

4.2 Mechanical behaviour

Mechanical response was bounded, with displacement rising from 1.5 to 2.5 mm as force increased from 245.25 to 490.50 N. The sub-proportional displacement is consistent with foam stiffening. Energy losses occur across the same load path: the EPE cushion protects brittle discs but absorbs work, adhesive joints add compliance, and the cardboard casing contributes further deformation. Foot pressure is also non-uniform, so only part of the ten-disc array is likely to

experience strong strain during a step. The higher response when multiple discs were engaged supports this interpretation.

4.3 Electrical output

The microwatt output can be traced to identifiable losses. Direct compression provides limited strain compared with spring-assisted or stacked arrangements [17]–[19]. More critically, the 1N4007 bridge imposes two forward drops in each conduction path; for sub-volt piezoelectric signals this can remove a substantial fraction of the available voltage, and the resulting energy penalty is amplified by the V^2 dependence of capacitor energy. The device also presents a strong source-load impedance mismatch [28], [29], while the 10 μF capacitor records per-event charge rather than accumulating energy over successive steps. These losses act together and explain why the prototype sits far below optimized systems.

4.4 Voltage measurement discrepancy

The qualitative and participant voltage datasets differ by approximately one order of magnitude: 8–50 mV through the Arduino display path versus 0.20–0.50 V measured directly at the capacitor. The records do not identify a single cause, so the datasets are not pooled. Plausible contributors include different instrument input impedances, ADC quantisation at low amplitude, different loading profiles, firmware scaling, and session-to-session circuit variation. Quantitative energy and efficiency calculations therefore use only the multimeter measurements. Resolution requires simultaneous acquisition from the Arduino and a calibrated logger or oscilloscope at the same node under identical loading.

4.5 Interpretation of the efficiency estimate

The estimated efficiency of 5.44×10^{-5} – $1.02 \times 10^{-4}\%$ is a system-level ratio between energy stored on the capacitor and estimated work applied to the whole tile. It includes upstream losses in foam, adhesive, casing, and load distribution as well as downstream rectifier and impedance losses; it must not be interpreted as PZT-5A material efficiency. The dominant uncertainty is the 0.5 body-weight force approximation. The constant-force work model tends to overestimate input for a stiffening structure, while the nominal capacitor tolerance scales the numerator directly. The 0.40 s pulse assumption affects power but not efficiency. Accordingly, absolute efficiencies are order-of-magnitude estimates; the observed increase with load is indicative rather than statistically characterised.

4.6 Repeatability

Short-term repeatability is relevant because the realistic application is event detection. A 7.5% coefficient of variation across eight firm-footstep trials provides adequate separation from the zero baseline for threshold sensing, but it should not be extrapolated to long-term stability. Manual force, foot placement, and ADC resolution are confounded in the statistic, and repeatability was not measured across sessions, loading conditions, participants, or extended cycling.

4.7 Comparison with previous studies

Table 7 is best read in terms of design choices rather than as a ranking. Compared with unamplified tiles [12]–[16], the present output is lower, suggesting substantial headroom even without mechanical amplification. The contrast becomes clearer under comparable force: Sirigireddy et al. [19] reported 3.95 mW average and up to 69 V peak-to-peak at about 490 N using a stacked, spring-mounted array, whereas the present prototype produced 3.125 μW at 490.50 N. Selim et al. [20], [21] further quantified the benefit of interface design, reporting roughly 30% higher power with a voltage doubler than with a plain bridge. Efficiencies near 68% reported for conditioning stages [22], [23] are not directly comparable with the

mechanical-to-capacitor system efficiency used here. The performance gap is therefore consistent with known differences in strain amplification, rectification, impedance matching, and storage.

4.8 Sensing versus energy supply

The results distinguish energy harvesting from useful power supply. Mechanical loading generated measurable energy in every active trial, and the conditioned signal was detected reliably enough to actuate a relay without false no-load events. However, 0.500–3.125 μW per event is several orders of magnitude below practical load requirements, no accumulation across successive footsteps was tested, and the LED indicator was powered from a separate battery. The defensible application is therefore event sensing—occupancy detection, footstep counting, pedestrian-flow monitoring, or smart-floor triggering—where the harvested signal carries information rather than sustained energy [32]–[34].

4.9 Relevance to the Somali context

The Somali significance of the prototype is experimental rather than electrical. The measured output cannot support a claim that piezoelectric pavement could contribute materially to national or institutional electricity supply. Its value is that a working harvester was fabricated and quantitatively characterised at a Somali university using locally procurable components, establishing a documented baseline where none previously existed. In institutions facing costly or unreliable supply [50], a self-signalling floor element could ultimately have value for occupancy or load-management sensing, but economic viability would require multi-tile testing under real traffic and service-life conditions.

4.10 Design improvement pathways

Improvement should proceed in an order that preserves experimental interpretability. Instrumentation comes first: a calibrated load cell, nanoampere-capable current measurement, oscilloscope-based pulse timing, simultaneous voltage logging, and measured capacitance would remove the largest uncertainties. Electrical improvements should then reduce rectifier and impedance losses through Schottky diodes, voltage-doubling or synchronous interfaces, impedance matching, and storage capable of accumulating successive events [20], [28], [29]. Mechanical development can follow through spring assistance or stacked structures [17], [19], stiffer fixtures, alternative series/parallel interconnections, and disc placement informed by foot-pressure distribution. A subsequent validation programme should include repeated trials for a larger participant sample, controlled cadence, multi-tile corridor testing, and extended cyclic loading.

5. Limitations

The study is intentionally small in scale. Three participants contributed one quantitative trial each, and repeatability was evaluated with eight trials of one loading condition in one session; the data establish direction and order of magnitude but do not support population inference or significance testing. Effective one-foot force was estimated as 50% of body weight because no load cell was available, making force the dominant systematic uncertainty. Mechanical work was approximated as $F d$ without a measured force–displacement curve. Current was below the approximately 200 μA resolution of the available meter, so electrical energy and power were derived from capacitor voltage rather than independently verified current. Additional uncertainty arises from the nominal 10 μF capacitance, manually measured displacement, and the assumed 0.40 s pulse duration. The two voltage datasets show an unresolved order-of-magnitude offset and are therefore kept separate. Stepping frequency, cumulative energy, durability, environmental exposure, multi-tile operation, and uncontrolled pedestrian traffic

were not tested. The battery-powered LED demonstrates relay triggering only. Finally, the reported efficiency is a system-level estimate for the complete prototype, not the intrinsic conversion efficiency of PZT-5A. Table 8 summarises these uncertainties and their propagation.

Table 8. Principal sources of measurement and sampling uncertainty, and their effect on the reported quantities.

Source of uncertainty	Effect on the reported results
Force estimated as 50 % of body weight; no load cell	Scales mechanical energy and efficiency directly. Dominant systematic term.
Constant-force work approximation in Eq. 6	Over-estimates mechanical input for a stiffening structure; biases efficiency downward.
Nominal 10 μ F capacitance, not measured	Scales recovered energy, power and efficiency linearly; tolerance typically about 20 %.
Voltage read via DT830D and 10-bit ADC	Limits precision of the recorded peak, which propagates through the squared term in Eq. 7.
Current below the ≈ 200 μ A instrument resolution	Power and efficiency derived from voltage; current never independently verified.
Displacement measured manually during a dynamic event	Introduces reading uncertainty into E_m in Eq. 6.
Pulse duration fixed at 0.40 s for all trials	Uniform scaling factor on all reported power values; not measured per trial.
Order-of-magnitude offset between the two voltage datasets	Unresolved; the two series are reported separately and never pooled.
Sample of three participants, one trial each	Limits generalisability; results are indicative rather than statistically representative.

6. Conclusion

A low-cost 24×16.5 cm piezoelectric pavement tile containing ten parallel PZT-5A discs was fabricated from locally available components and tested under controlled indoor footstep loading at Hormuud University. The prototype produced a clean load-dependent signal with no false no-load triggering. A full footstep generated 25–50 mV through the Arduino path, while eight repeated firm-footstep trials yielded 24.6 ± 1.8 mV ($CV = 7.5\%$). In the independent participant series, 245.25–490.50 N one-foot loads produced 0.20–0.50 V at the capacitor, corresponding to 0.200–1.250 μ J recovered energy, 0.500–3.125 μ W average power, and estimated system-level efficiency of 5.44×10^{-5} – $1.02 \times 10^{-4}\%$.

The output is too small for practical electrical supply but sufficiently repeatable for event detection. Its principal limitations—unamplified load transfer, foam and structural compliance, diode losses, impedance mismatch, uncertain force, unresolved voltage-path differences, and limited instrumentation—also define a clear improvement route. The study therefore establishes a documented low-cost baseline for piezoelectric footstep sensing in a Somali institutional setting, with transparent separation of measured, calculated, and assumed quantities. Future work should prioritise calibrated force and current measurement, simultaneous voltage logging, improved power conditioning, mechanical amplification, larger repeated samples, and multi-tile durability testing.

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Conflict of Interest

The authors declare no conflict of interest.

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