Footsteps to Energy: A Sustainable Power Solution*

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Abstract

With the increasing global demand for renewable energy and the need to reduce carbon footprints, innovative solutions for electricity generation have become critical. This research focuses on a Mechanical Footstep Electricity Generation System designed to harness human kinetic energy in densely populated urban areas where energy scarcity poses environmental and social challenges. The system, measuring 300 mm × 300 mm × 280 mm, utilizes a combination of rack and pinion mechanisms, springs, spur gears, flywheels, and dynamos to efficiently convert the mechanical energy from footsteps into electrical power. The methodology includes a detailed system design and cost analysis of key components, emphasizing its economic feasibility. Results show that a 60 kg person can generate approximately 0.455 watts per step, with total output varying based on the weight and number of steps taken. This research provides a practical, environmentally friendly solution to enhance energy access in areas with high human mobility, contributing to the broader goal of sustainable urban development.

Keywords: Electricity consumption; Foot traffic; Rack and pinion; Electricity production

1 Introduction

In recent years, electricity has evolved into a basic human requirement. Wherever and in every activity, electricity is needed (Löfquist, 2020). It is utilized for domestic purposes as well as in all other areas, such as industrial, transportation, commercial, etc. Global energy demand has increased since 2017 due to the demographic revolution, rise in the middle-income group, computerization, economic development, and high mobility rate (Anon., 2018). There are several sources from which electricity can be generated to meet the global energy demand; the key sources include but are not limited to fossil fuels such as natural gas, coal, petroleum, and nuclear energy. Eventually, power generation from fossil fuels will continue to dominate since they still form a substantial percentage of the global energy mix (Anon., 2018). Yet, relying heavily on fossil fuels results in greenhouse gas emissions that contaminate the environment, contribute to global warming, and raise other health issues (Kipkoech *et al.*, 2022). The most advantageous, cost-effective, and smart approaches to combat global warming are generally thought to increase energy efficiency and reduce global energy consumption. Renewable technologies including solar energy, wind energy, hydropower, kinetic energy, and geothermal energy are being developed to meet the growing global energy demand (Elstad, 2022). Solar energy is the most prevalent and trustworthy energy source out of the bunch, but it has a high initial installation cost and is not always readily available, especially during rainy seasons (Yeboah *et al*., 2024). This research aims to propose an alternative approach by harnessing the kinetic energy of human footsteps to generate electricity, presenting a low-cost solution for limited applications.

The originality of this research lies in addressing the problem of energy wastage during human locomotion, an underexplored energy source that can be harnessed for electricity generation. This study bridges a critical gap in the existing literature by investigating how the untapped kinetic energy from footsteps can be efficiently harvested and utilized.

The question is: Has it occurred to us that electricity can be produced with our footsteps? Walking has been the most common form of exercise throughout human history. As individuals walk, energy is lost to the ground or the road surface in the form of impact, vibrations, and sound due to the transfer of weight during each step (Pavankalyan, 2021; Iqba, 2018). Kinetic energy is wasted as heat energy during human movement (Munaswamy *et al*., 2018). This energy could be collected and converted into usable electricity. Given the global increase in human population, the number of people constantly walking on footpaths and in cities has surged, resulting in a continuous generation of energy through footstep mechanisms. This energy can be captured and utilized to power urban infrastructure such as traffic lights and streetlights. This work was motivated by the need for sustainable and eco-friendly technology that helps meet the increasing global energy demand by generating electricity from human locomotion, particularly through footsteps.

A footstep electricity generator employs a variety of design mechanisms (Ang *et al.,* 2019). A considerable amount of research has presented several conceptual design mechanisms for generating foot power (Iqba, 2018; Ang *et al.,* 2019). Some of the findings propose changes to the

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different design approaches in footstep power generation (Wagh *et al*., 2018). The mechanisms that constitute the most typical design approaches in footstep power generation are piezoelectric-based electricity generation and the traditional mechanical footstep electricity generation mechanisms. When a piezoelectric device detects a disturbance in its surroundings caused by mechanical stresses (vibrations), it generates an electric voltage (Edmison, 2002). In the midst of electrical and mechanical swings, piezoelectricity provides an appropriate transducer effect. When mechanical stress is applied to a piezoelectric material, it generates an electric charge (direct piezoelectric effect). Conversely, if an electric field is applied to the piezoelectric transducer, it induces mechanical strain within the material (inverse piezoelectric effect). A greater number of piezoelectric footstep electricity generators have been developed; however, despite their popularity, they still have some drawbacks, such as the technology's impracticability under stationary conditions and power capacity limitations (Ye *et al.*, 2009; Nyan, 2015; Nitashree *et al.*, 2015). Furthermore, the piezoelectric effect may generate very small electricity. Another issue with the piezoelectric transducer is the selection of the appropriate ferroelectric material, which controls the efficiency of converting kinetic energy to electrical energy (Nitashree *et al.,* 2015).

A mechanical footstep power generator offers an alternative to piezoelectric-based power generators, providing the potential to generate more electricity through diverse configurations. Instead of relying on a piezoelectric transducer, mechanical footstep power generators utilize specially designed mechanisms to convert human movement into electrical energy (Ang *et al*., 2019). Various components are employed in different designs. For instance, Iqbal (2018) developed a system demonstrating electricity generation from human locomotion, incorporating a turbine, nozzle, water reservoir, pipe, DC generator, and valve. Here, pressure applied to the reservoir causes water to flow through the nozzle and turn the turbine, producing electricity. Dhimar (2017) designed a "footstep power generation platform" using springs, racks, pinions, bearings, chain drives, gear wheels, flywheels, and shafts. In this system, electricity is generated from the pressure of human footsteps and stored in batteries.

While these systems typically rely on conventional mechanical components, some research explores non-conventional approaches. Munaswamy *et al.* (2018) employed a non-conventional method by generating electricity from footsteps using a rack and pinion arrangement coupled with an alternator and chain drive system. Agham *et al*. (2021) developed a low-cost footstep power generation system using the same configuration. Similarly, Wagh *et al.* (2018) converted the up-and-down motion of footsteps into rotational motion using a rack and pinion mechanism, which is then converted into electricity via a dynamo.

These mechanical systems are valued for their simplicity, cost-effectiveness, and minimal transmission losses (Tom *et al*., 2013a). Recent work by Ohiemi *et al*. (2021) presented a prototype system using connecting rods, gears, bearings, a U-shaped shaft, and an electrical generator. Tom *et al*. (2013b) designed a system using a rack and pinion arrangement coupled with a dynamo, gear mechanism, and slider. Pressing the slider during foot movement compresses a spring, which pushes back the slider attached to the dynamo to generate electricity. Ang *et al*. (2019) proposed a simple and affordable design based on a rack and pinion mechanism, incorporating components such as shafts, spur gears, bearings, a dynamo, and a battery.

However, some designs, such as those using bearings (Saeed *et al*., 2019), encounter challenges like noise, low shock resistance, and excessive heat generation. Magdum *et al*. (2017) used a crankshaft, gear, and flywheel in their footstep electricity generator. Although effective, using wooden upper and bottom plates along with springs raises concerns about durability, as wood is prone to dampness and decay.

While substantial research has delved into mechanical footstep electricity generation, many existing designs exhibit complexities due to the incorporation of additional components. This complexity raises concerns about the systems' bulkiness and potential compromises to their durability and performance (Ohiemi *et al*., 2021; Saeed *et al*., 2019; Magdum *et al*., 2017). Furthermore, there is a notable gap in the current literature regarding the optimization of such systems for various user behaviors and environmental conditions. In light of these limitations, there is a conspicuous need to address research gaps that revolve around the development of systems capable of adapting to diverse environmental conditions and accommodating various user behaviors.

Moreover, existing studies predominantly concentrate on the weight of individuals as a fundamental variable in footstep electricity generation. While this variable is pivotal, further exploration is required to understand the intricate interplay of factors like the number of steps, spring stiffness, and tensile strength in relation to power output. These factors, when examined collectively, could offer a more comprehensive understanding of the system's capabilities.

Another limitation of current systems is the noise they generate during operation, which can be problematic in urban environments. Additionally, the choice of materials for various system components significantly influences both efficiency and durability, a facet that necessitates rigorous investigation.

This study contributes original insights by addressing these critical gaps in the literature, exploring new mechanisms, materials, and design configurations that can improve efficiency and adaptability. To address these gaps and limitations, there is an opportunity for further research that explores alternative mechanism combinations and materials. Such research aims to enhance the simplicity, durability, lifespan, and adaptability of mechanical footstep electricity generation systems. Furthermore, this endeavor seeks to achieve higher output power by considering a multitude of factors, including the weights of individuals, the number of steps taken, and the properties of the springs used.

In the context of this paper, we introduce a novel and simplified design for a mechanical footstep electricity generator. This design utilizes a rack and pinion configuration, spur gears, flywheels, and direct current (DC) generators (dynamos) to efficiently convert the kinetic energy generated by human locomotion into valuable electricity. The specific objectives of this study encompass:

(i) Establishing the intricate relationships between the variables relevant to mechanical footstep power generation and the resultant power output.
(ii) Determining the expected power output of this innovative mechanical footstep power generator, considering the integration of various parameters, including step count, spring characteristics, and human weight. (iii) Demonstrating how the study's findings can be applied to real-world scenarios, such as powering urban infrastructure like streetlights and pedestrian signals, thereby contributing to sustainable energy solutions.

In essence, this research endeavors to push the boundaries of knowledge in the field, offering a simplified and adaptable solution that optimizes the potential of mechanical footstep electricity generation while addressing critical research gaps in the domain. The implementation of this system will assist countries in reducing their reliance on fossil fuels, mitigating global warming, creating resilience to volatile prices, and lowering energy costs. This is especially important as rising fossil fuel prices, driven by a combination of geopolitical tensions, supply chain disruptions, and increased global demand, are placing additional strain on poor energy-importing countries.

This paper is organized as follows: Section 1 contains the introduction, and Section 2 contains the materials and methods. Section 3 also presents the design concept. Section 4 discusses the theoretical results and analysis of the mechanical footstep electricity generator, as well as the study's limitations. Finally, Section 5 presents the conclusions reached as well as future research directions.

2 Materials and Methods

2.1 Site Selection

Identifying an appropriate site for a renewable electricity project is an important consideration when deciding to develop one. The following site conditions must be considered for the mechanical footstep electricity generator to be a success:

2.1.1 Landscape

The characteristics of the slope of the selected region will determine whether or not excavation is possible.

2.1.2 Accessibility of Roads or Passageways

The selected region should have existing roads or passageways to ensure that humans or pedestrians can walk on the system.

2.1.3 Population Size

The system is hugely dependent on human footsteps; thus, the number of people walking on the system affects the power produced by the system. The more people who walk on the system, the more power is generated. As a result, the selected region necessitates a higher population density or a high level of foot traffic.

2.2 Data Collection

It is crucial to collect data prior to designing to ensure that the work will practically solve the issues encountered by the parties involved. Furthermore, data collection helps in establishing the project's boundaries so that it can achieve its goal. The data for this project was gathered from various sources, including:

(i) On-site observations;

(ii) Available literature in relation to footstep power generation.

The data collected includes the following:

2.2.1 The Nature of the Springs

The properties of the spring used in the design are very essential. The length and tension of the spring influence the number of revolutions of the flywheel, which in turn influences the amount of power generated.

2.2.2 The Weights of the People

To determine the feasibility of the design, different human weights are used to calculate the output power generated. It is crucial to understand the relationship between human weight and electrical power output. This relationship is discovered after conducting a theoretical analysis with different weighted humans and calculating the amount of power generated.

2.2.3 The Number of People and the Number of Steps per Person

On-site observations were conducted at a local shopping mall in Kumasi, Ghana, where there is significant foot traffic. This site was chosen due to its high density of people and consistent movement, making it ideal for the footstep power generation system. Using this data set, the most suitable site is chosen based on the observation method, to produce a higher amount of electricity. The number of people, together with the number of steps, helps determine the amount of power generated by the system. The amount of electricity generated by the system increases as the number of people and steps increases.

2.3 Components of the Design

This section presents the proposed conceptual design framework for the energy harvesting system, highlighting its key components and their interrelations. The system comprises three main components: a spring mechanism, a rack and pinion configuration, and a flywheel. The integration of these elements facilitates the conversion of mechanical energy generated from human footsteps into usable electrical energy. A block diagram illustrating the main components of the proposed design is shown in Fig. 1, with each component discussed in detail below.

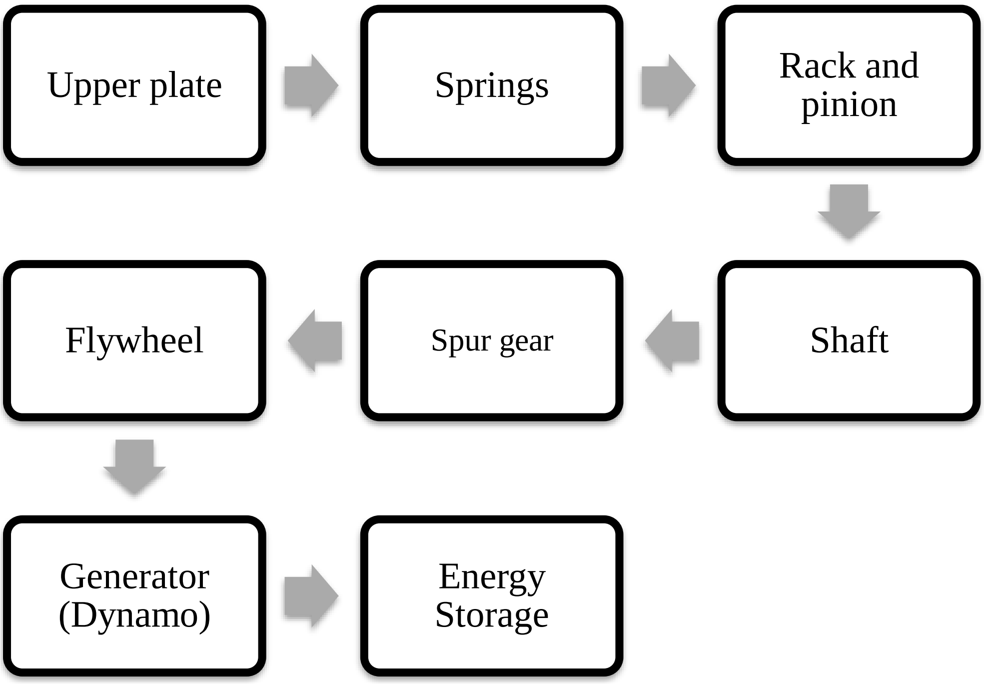


Fig. 1 Conceptual Design Framework

2.3.1 Spring

Spring is defined as an elastic body that twists when stacked and returns to its original shape when no load is applied to it. There are various types of springs; however, helical compression springs are used in this work. Helical springs are made of wire coiled in the shape of a helix and are mostly used for compressive or tensile loads. Shear stresses generated by twisting are the primary stresses in helical springs. The load applied to the spring acts along the axis of the coil, causing the spring to either compress or extend. Some advantages of helical springs include (i) ease of fabrication; (ii) reliability; (iii) possession of a constant spring rate; (iv) accurate performance prediction, etc. (Jeffus, 2020). In selecting the spring material, it is crucial to ensure it possesses a high endurance limit, greater adaptability, and resilience to withstand repeated loading and environmental factors. The helical springs used in this design are composed of oil-tempered carbon steel wires, which contain 0.60 to 0.70% carbon and 0.60 to 1.0% manganese (Jeffus, 2020). This material selection is essential for achieving the desired mechanical properties, ensuring the springs can endure prolonged use without significant fatigue or deformation. Fig. 2 shows a 3D design of a helical spring made of carbon steel.

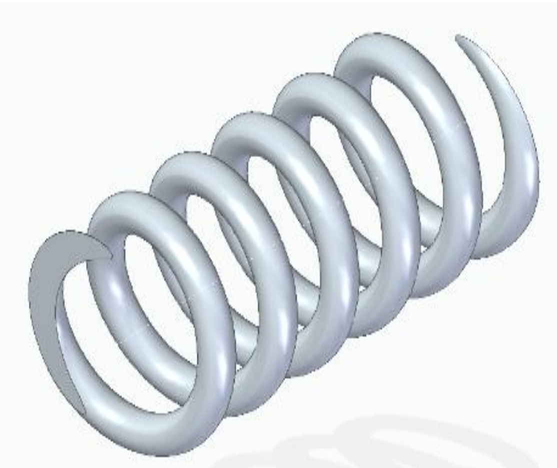


Fig. 2 Spring

(i) Spring calculations

Some of the values used in this study are standard values obtained from manufacturers' data sheets (Anon., n.d.-a; Anon., n.d.-b; Anon., n.d.-c), while others are based on assumptions.

The ultimate tensile strength S_{ut} is given as 841 MPa = 841 N/mm^2 (Anon. n.d.a).
The modulus of rigidity G is is given as 79 GPa = 79000 N/mm^2 (Grarcia, 2011).
The parameters used in sizing the spring were calculated using equations (1) – (14) (Jeffus, 2020).

The deflection of the spring σ is assumed to be 45 mm and is given by:

$$\sigma = \frac{8FD^3N_{act}}{Gd^4} \quad (1)$$

where F is the force acting on the spring, D is the inside diameter and d is the wire diameter, and N_{act} is the number of active coils.

Assuming the permissible shear stress τ is 50% of the ultimate tensile strength:

$$\tau = 0.5 \times S_{ut} \quad (2)$$

This assumption is based on empirical studies in material science, which demonstrate that a shear stress of up to 50% of the ultimate tensile strength is commonly used in design to ensure safety and reliability under fluctuating loads (Hertzberg *et al*., 2020).

$$\tau = 0.5 \times 841 = 420 \text{ N/mm}^2$$

The spring with a spring index ranging from 6 to 12 has been reported as the best fabrication range and less expensive (Spring, n.d). Hence, it is assumed that the spring index C is 6, which is given by:

$$c = \frac{D}{d} \quad (3)$$

Also, Wahl Factor is calculated as follows:

$$K = \frac{(4C-1)}{(4C-4)} + \frac{0.615}{c} \quad (4)$$

$$K = \frac{4\times6-1}{4\times6-4} + \frac{0.615}{6}$$

$$K = 1.25$$

The permissible shear stress is given as:

$$\tau = \frac{K8FC}{\pi d^2} \quad (5)$$

This equation accounts for the geometric and loading conditions of the spring, providing a more refined approach to calculating permissible shear stress based on the actual operating conditions, including factors such as the number of active coils and the spring index.

The use of both equations (2) and (5) allows for a comprehensive understanding of the shear stress in the context of spring design. Equation (2) provides a conservative estimate based on material properties, while equation (5) incorporates the specific geometrical and load-related factors unique to the helical spring in this application.

Assuming a human weight of 60 kg, the force F will be 60 kg × 9.81 m/s^2 = 588.6 N. Therefore, the wire diameter d in equation (5) is calculated as follows:

$$d = \sqrt{\frac{K8FC}{\pi\tau}} = \sqrt{\frac{1.25\times8\times588.6\times6}{420\pi}} \quad (6)$$

$$d = 5.17 \text{ mm} = 5 \text{ mm}$$

From equation (3):

$$D = C \times d \quad (7)$$

$$D = 6 \times 5 = 30 \text{ mm}$$

From equation (1), the number of active coils N_{act} is calculated as follows:

$$N_{act} = \frac{79000 \times 45 \times (5)^4}{8 \times 588.6 \times (30)^3}$$

$N_{\text{act}} = 18.07 = 18$

The spring possesses both spur and gear ends, and the number of inactive coils is assumed as 2. Therefore, the total number of coils N_T is calculated as:

$$N_T = N_{\text{act}} + N_{\text{inact}} \tag{8}$$

$$N_T = 18+2 = 20$$

Furthermore, Solid Length L_{solid} is calculated as follows:

$$L_{\text{solid}} = N_T \times d \tag{9}$$

$$L_{\text{solid}} = 15\times5 = 75 \text{ mm}$$

From equation (1), the true or required deflection of the spring is calculated as:

$$\sigma = \frac{8 \times 588.6 \times 30^3 \times 18}{79000 \times 5^4}$$

$$\sigma = 46.34 \text{ mm}$$

Assuming that the gap between the successive coils when a maximum force acts on the spring is 1 mm. Using the total number of coils, the total axial gap between the coils is calculated as

$$\text{Axial gap} = (N_T\text{-}1) \times 1 = (20\text{-}1)\times1 = 19 \text{ mm} \tag{10}$$

Free length is then calculated as:

$$L_{\text{free}} = L_{\text{solid}} + \text{Total Axial Gap} + \sigma \tag{11}$$

$$L_{\text{free}} = 75+19+46.34 = 140.34 \text{ mm}$$

The pitch of the coil is also calculated using equation (12):

$$L_{\text{pitch}} = \frac{L_{Free}}{(N_T - 1)} \tag{12}$$

$$L_{\text{pitch}} = 7.38 \text{ mm}$$

Also, the compression length $L_{\text{comp.}}$:

$$L_{\text{comp.}} = L_{\text{solid}} + \text{Total Axial Gap} \tag{13}$$

$$L_{\text{comp.}} = 94 \text{ mm}$$

Stiffness can then be calculated as:

$$k = \frac{F}{\sigma} \tag{14}$$

$$k = \frac{588.6 \text{ N}}{46.34 \text{ mm}}$$

$$k = 12.7 \text{ N/mm}$$

2.3.2 Rack and Pinion Configuration

A rack and pinion gearing configuration converts the to-and-fro motion of a human footstep into rotational motion (see Fig. 3). The pinion (circular gear) meshes with the rack (linear gear), allowing the transfer of motion between them in both external and internal engagement. This type of gear is known as a rack and pinion gear. As shown in Fig. 3, the rack is a linear gear, whereas the pinion is a circular gear that captures the rack's teeth; rotational motion applied to the pinion facilitates rack movement. This mechanism is indeed applied in the proposed design, where the motion generated by human footsteps is effectively transformed into rotational motion, enabling the generation of electricity.

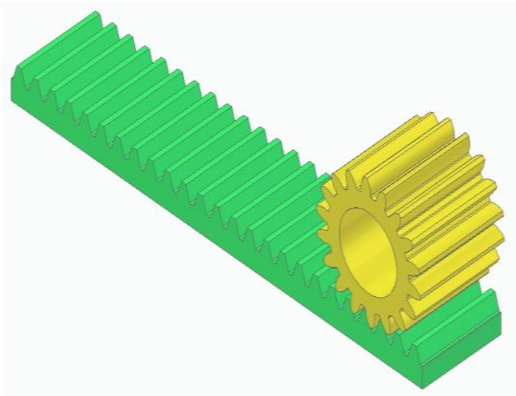


Fig. 3 Rack and Pinion

The rack and pinion are made of steel. The specifications of the rack and pinion used in this study are presented in Table 1. The specifications for the rack and pinion were determined based on industry standards and manufacturer data sheets. The following parameters were used in the design calculations to ensure optimal performance in the proposed energy generation system.

Table 1 Specifications of Rack and Rinion

Parameter	**Value**	
	Rack	**Pinion**
Number of teeth	28	16
Tooth thickness	3.71 mm	3.71 mm
Pressure angle	20 °	20 °
Diameter		25 mm
Whole depth	4.5 mm	4.5 mm
Face width	31 mm	31 mm
Circular pitch	6.28 mm	6.28 mm
Clearance	10.5 mm	
Pitch circle diameter	72 mm	
Module	1.56 mm	1.56 mm
Length	157 mm	
Addendum		2.77 mm
Dedendum		1.73 mm

2.3.3 Shaft

A shaft is a rotating device with a circular cross-section (solid or hollow) that transmits power from one point to another. A tangential force supplies power to the shaft and the torque established in the shaft allows the power to be transported to several devices connected to the shaft. In the proposed design, the solid steel shaft is connected to the upper plate, which receives the linear motion generated by the footstep. As the footstep applies force to the upper plate, the motion is converted into rotational motion at the shaft.

The shaft then transmits this rotational motion to the spur gear, which is connected to the rack and pinion mechanism. The pinion, which is affixed to the shaft, engages with the rack to convert the rotational motion back into linear motion, facilitating the overall power transmission from the upper plate through the shaft to the spur gear and ultimately to the rack and pinion system.

The specifications of the shaft, as shown in Fig. 4 and presented in Table 2, were derived from standard engineering tables and material property data.

Fig. 4 Shaft

Table 2 Specifications of the Shaft

Parameter	Value (mm)
Length	200 mm
Outer diameter	10 mm
Inner diameter	5 mm
Modulus rigidity of steel (G)	80 GPa
Deflection	0.119 mm
Torque	146.4 N-mm
Shear stress	0.0539 N/mm

2.3.4 Spur Gear

A gear is a spinning component made of carbon steel that has cut teeth or cogs that mesh with another tooth component to transmit torque. Spur gears are the most basic type of gear. They are made of a cylinder with spirally protruding teeth. Though the teeth are not straight-sided, they are mostly of a unique shape to achieve a constant drive ratio; they are mostly composite but less circular; and the tooth edge is linear and parallel to the spinning axis. These gears will only connect properly if they are attached to parallel shafts. Table 3 presents the specifications of a spur gear shown in Fig. 5.

Fig. 5 Spur Gear

Table 3 Specifications of Spur Gear

Parameter	Small Gear	Big Gear
Number of teeth	16	32
Tooth thickness	3.71 mm	3.71 mm
Pressure angle	20 °	20 °
Whole depth	4.5 mm	4.5 mm
Face width	31 mm	31 mm
Circular pitch	6.28 mm	18.84 mm
Addendum	2.77	2.77 mm
Dedendum	1.73	1.73 mm

2.3.5 Flywheel

An electromechanical system that stores energy in a rotating mass is known as a flywheel energy storage system. The flywheel is constructed of mild steel. Flywheels are classified into two types: solid and ring. The solid-type flywheel with the specifications presented in Table 4 was used in this work (see Fig. 6). In order to maintain constant torque throughout the cycle, the flywheel is usually attached to the end of the shaft (rotation of the shaft).

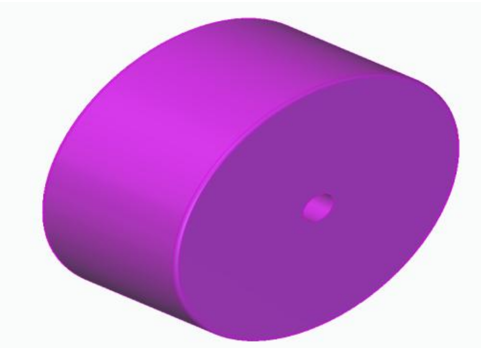


Fig. 6 Flywheel

Table 4: Specifications of the Flywheel

Parameter	Value
Weight	1 kg
Circular Diameter	250 mm
Thickness	15 mm

2.3.6 DC Generator (Dynamo)

A dynamo is an electrical generator that uses a commutator to generate direct current. A 12V DC generator, as shown in Fig. 7, is placed within the seat and secured with bolts and nuts in the proposed design. The dynamo is used in this application to convert the rotational force from the rack and pinion system into electrical output

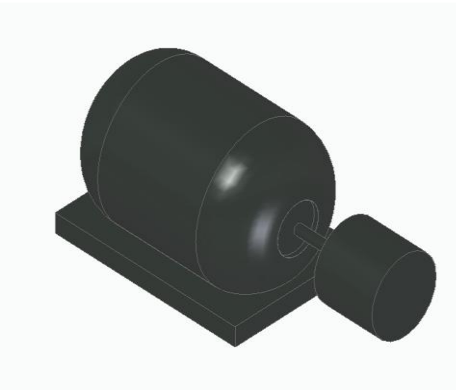
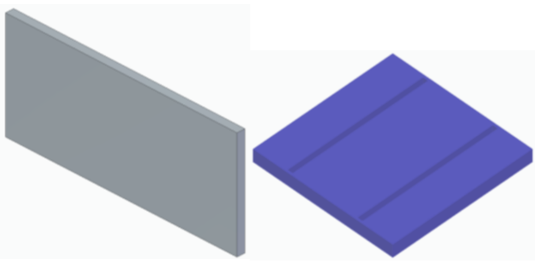


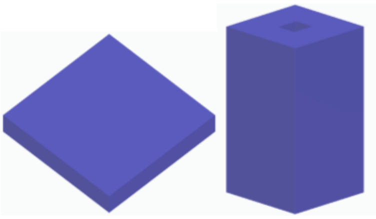
Fig. 7 DC Generator (Dynamo)

2.3.7 Other Components

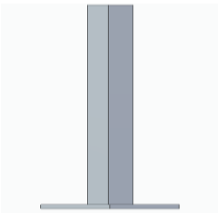
The design includes additional components such as the upper plate, base plate, inner support plate, and spring support. The upper plate is positioned at the top of the foot mechanism and is engaged during walking. Its primary function is to support the human weight. The system's bottom is formed by the base plate. Both the upper and base plates are made of mild steel. Fig. 8 shows the remaining components of the design. Table 5 also presents the specifications for the upper and base plates



(a) (b)



(c) (d)



(e)

Fig. 8 Additional Components. (a) Inner Support Plate. (b) Base Plate (300 mm x 300 mm). (c) Upper Plate (300 mm x 300 mm) (d) Upper Plate Support Pillar. (e) Spring Support

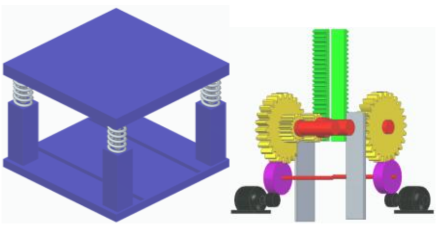
Table 5 Specifications of the Upper and Base Plates

Parameter	Value (mm)
Length	300
Width	300
Height	5

3. Design Concept

As mentioned previously, the mechanical footstep power generation system with dimensions 300 mm

× 300 mm × 280 mm, is designed using the rack and pinion configuration coupled with springs, spur gears, flywheels, and generators (dynamos). The 3D design of the system was made possible using solid-edge software. The overall system design comes with an upper plate, a base plate, two (2) spur gears, two (2) rack and pinion arrangements, four (4) springs, four (4) spring supports, four (4) upper plate supports, two (2) flywheels, and two (2) dynamos. Fig. 9 shows 3D designs of the various component combinations



(a) (b)

Fig. 9 Major Mechanical Component Combinations. (a) Spring-Loaded Upper and Baseplates, and (b) Two (2) Racks with Pinions and two (2) flywheels Attached to the Ends of the two (2) Shafts Coupled with two (2) Dynamos

The factors considered for surface area calculation include the following:

(i) Dimensions of Components: The overall system dimensions significantly influence the available surface area.

(ii) Component Arrangement: An optimal layout is essential for efficient utilization of surface area for power transmission.

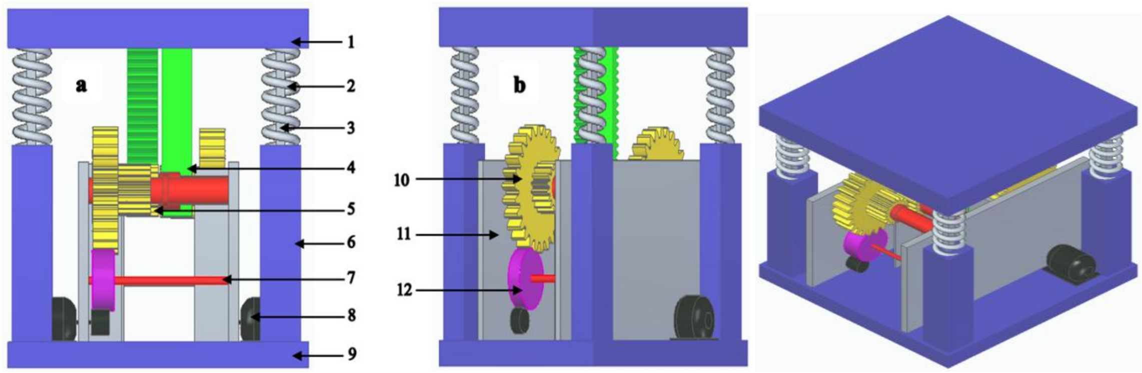
(iii) Material Properties: The choice of materials impacts the strength and surface treatment requirements.

(iv) Weight Distribution: Proper weight distribution ensures stability and minimizes deformation.

(v) Spring and Gear Placement: The location of these components affects the effective surface area available for energy conversion.

These considerations are critical for optimizing the design's functionality and efficiency.

Moreover, Figs. 10a to 10c also show the front views and top view of the 3D assembly of the mechanical footstep power generation system, with the various components listed in Table 6



(c)

Fig. 10 A 3D Assembly of the Proposed Design. (a) Front View of the Proposed Design with Upper Plate. (b) Front-Right View of The Design with Upper Plate, (c) Top View of the Design

Table 6 Parts of the System in Fig. 10

Number	Part
1	Upper plate
2	Spring
3	Spring support
4	Rack
5	Pinion
6	Upper plate support pillar
7	Shaft
8	Generator (dynamo)
9	Base plate
10	Spur gear
11	Inner support plate
12	Flywheel

The design presented in this study shares similarities with that of Magdum *et al*. (2017), with a few notable discrepancies. While the upper and base plates of our system (as depicted in Fig. 10) are constructed from steel, Magdum *et al*. opted for plywood, which compromises the system's durability and strength. Steel plates offer a significantly higher strength-to-weight ratio compared to plywood. Concerns regarding the ergonomics of walking on steel plates have been taken into account. To address these concerns, the design includes a textured surface and cushioning elements to enhance grip and reduce impact during footfalls, thereby improving user comfort while maintaining the structural integrity and durability of the system.

Moreover, similar designs by Ang *et al*. (2019) and Saeed *et al*. (2019) incorporate bearings that could produce additional noise during operation and may be susceptible to failure due to shock. The assembly diagram of the system, along with the rack and pinion configuration, is shown in Fig. 11.

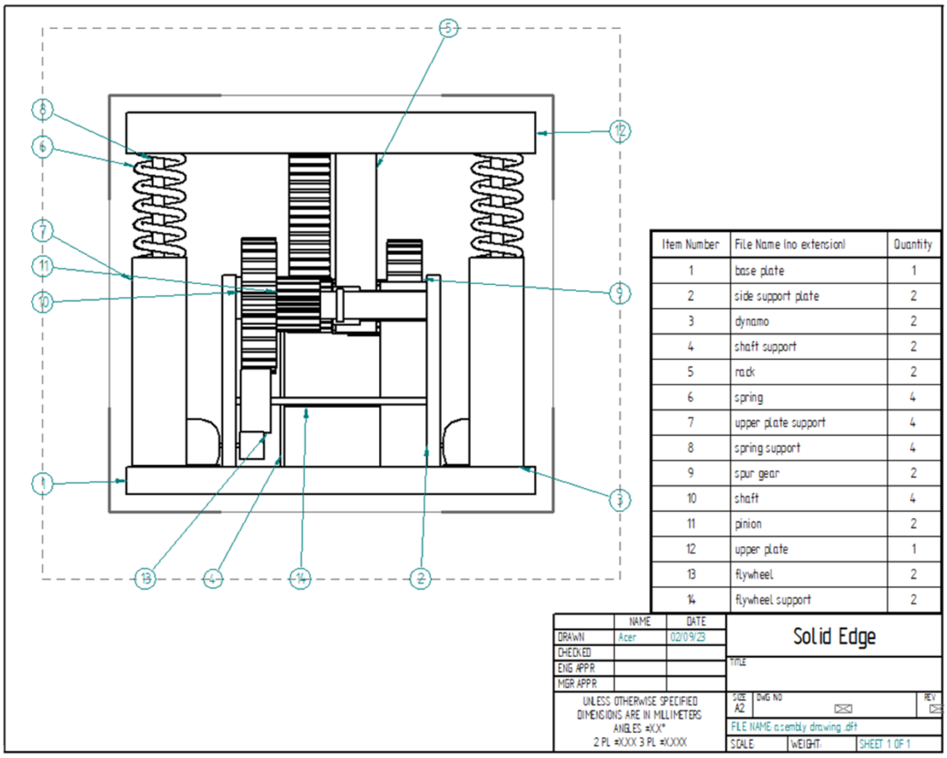


Fig. 11 Detailed Drawing of the Proposed Design, together with the Rack and Pinion Configuration

3.1 Operational Concept

As previously stated, a person's energy is dissipated while walking; this energy can be converted into useful electricity using special mechanisms. This unique mechanism is an electro-mechanical system that generates and stores power using both electrical and mechanical means. The proposed design, as shown in Figs. 10 and 11, consists primarily of racks and pinions with spur gears, springs, flywheels, dynamos, an upper plate, and a base plate. The base plate is mounted on a strong, rigid platform, and four springs are positioned between the base plate and the upper plate, providing cushioning and support, while the upper plate is rigidly supported by the four springs.

When a person steps on the upper plate, the plate will dip down by some amount due to the person's weight; the springs attached at each corner of the upper plate are then compressed. The plate's subsequent movement pushes the rack down, which is directly attached to the underside of the upper plate. The pinion's rotational motion is transferred to the spur gears, which increases the pinion's rotational speed. The increased rotational speed is then transferred to the flywheels, which are mounted on the shafts, through the spur gears, ensuring smoother operation and energy storage. The flywheel's function is to control the variation in energy, thereby conserving it. The shaft rotates at a certain rate of revolutions per minute. The mechanical energy is then converted into electrical energy by releasing energy to the dynamo. The conversion is comparable to the upper plate's applied load. The springs will then return to their original length, causing the upper plate to return to its original position. This causes the rack, which is attached to the upper plate, to move upward, resulting in the rotation of the gears. As a result, the racks' downward and upward linear movements are used to generate electrical energy. Using various electrical devices, the overall energy generated when a load is applied to the system can be amplified or stored.

4 Results and Discussion

4.1 Output Power

4.1.1 Power Generated Based on Adult Human Weight

According to a report by Walpole *et al.* (2009), the typical adult weight varies by continent and is roughly 57.7 kg in Asia, 60 kg in Africa, 70.8 kg in Europe, and 80 kg in North America. Men are often heavier than women. Thus, using the actual deflection of the spring σ after one step, which is measured as 46.34 mm (0.04634 m), and assuming that an adult African human weighs 60 kg, the work done W_d on the plate by the impact is calculated as follows:

$$W_d = \text{Weight of the Body x Height of the Spring per Step} \quad (15)$$

$$W_d = (60 \text{ kg} \times 9.81 \text{ ms}^{-2}) \times 0.04634 \text{ m}$$

W_d = 27.28 joules per step

The power output per step is therefore calculated as: Power per step,

$$P = \frac{W_d \text{ (joules per step)}}{\text{Time (sec)}} \quad (16)$$

$$P = \frac{27.28 \text{ J/step}}{60 \text{ sec}}$$

$$P = 0.4545 \text{ watts per step}$$

This implies that for every pushing force exerted by a 60 kg human, an output power of 0.455 W is generated. This result agrees quite well with the 0.85-watt power output obtained by Nandan and Trivedi (2019). In another study, Munaswamy *et al*. (2018), reported a lower power value of 0.1635 W when a weight of 20 kg is applied to a spring with a displacement of 0.05 m. This discrepancy is primarily due to the significantly lighter weight applied in their study, confirming that power generation is directly related to human weight and spring deflection. Furthermore, based on the statistical data gathered above in terms of human weight (Walpole *et al*., 2009), installing this system in North America will produce more energy than installing it in Asia or Africa.

4..1.2 Power Generated Based on the Weight of Children from 1 to 10 Years

Furthermore, using the Leffler formula in equation (17) (So, 2012), the weight of children aged 1 to 10 years is calculated as follows:

$$m = \frac{1}{2} a_y + 4 \quad (17)$$

where, a_y is the number of years old a child is.

For a child of 10 years:

$$m = \frac{1}{2} \times 10 \text{ years} + 4$$

$$m = 9 \text{ kg}$$

Based on this calculation, if the compressed height of the spring after one step by an adult weighing 60 kg is 0.04634 m, then the compressed height of a child weighing 9 kg is 0.00695 m. As a result, the work done on the plate is calculated as follows:

W_d= (9 kg ×9.81 ms^{-2})× 0.006951 m
W_d= 0.6137 joules per step

Therefore, power output per step:

$$P = \frac{0.6137 \text{ J/step}}{60 \text{ s}}$$

$$P = 0.0102 \text{ watts per step}$$

Since power production varies linearly with the weight of the human body, this suggests that children produce significantly less power than adults because they are lighter. This linear relationship between weight and power output is evident when comparing data across various age groups and weights. Table 7 presents the power generated per step by persons of different body weights (4.5 kg, 9 kg, 60 kg, 70 kg, and 80 kg).

Table 7 Power Generated Per Step by Different Persons of Different Weights and Corresponding Compression Length

Age Range (Years)	Weight (kg)	Actual Deflection (m)	Power Generated (W) per Step
5	4.5	0.00347	0.0026
10	9	0.00695	0.0102
25-30	60	0.0463	0.455
30-40	70	0.0541	0.619
40-60	80	0.0618	0.808

The age ranges and corresponding weights presented in Table 7 are derived from existing literature on pediatric growth patterns and averages. Specifically, the weights for children were obtained from the Leffler formula (So, 2012), while the adult weights are referenced from Walpole *et al*. (2009), which provides an overview of average weights by continent. These averages are critical for understanding the relationship between weight and power generation across different age groups.

Teenagers and adults over the age of 18 years typically have body weights between 55 and 80 kg. Due to the fact that these participants are typically stronger, it can be shown from Table 8 that the actual power generated by those who weigh between 60 and 80 kg is significantly higher and has a higher deflection than those who weigh less. Fig. 12, which shows the power generated in watts per step by people of various ages and associated weights, further exemplifies these findings

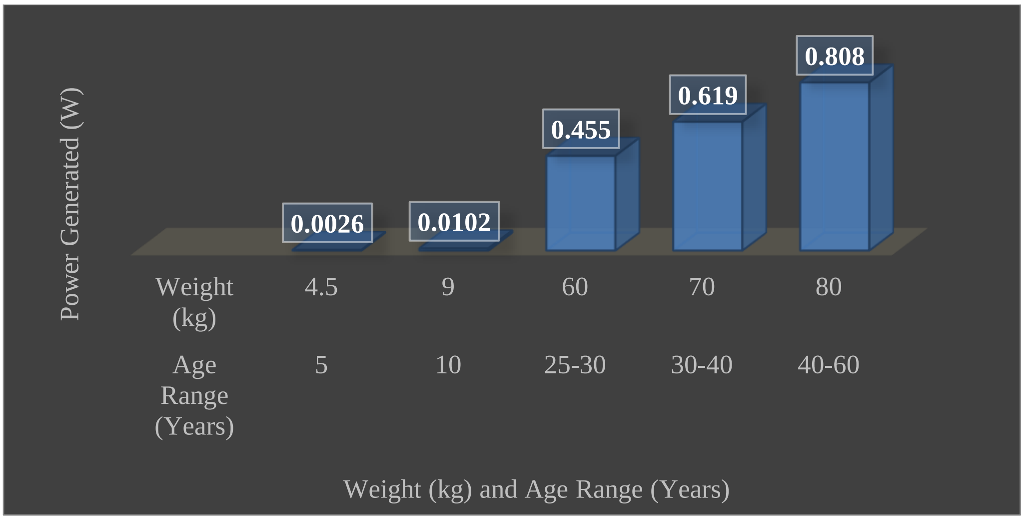


Fig. 12 Power Generation Characteristics by Age Range and Weight

As stated earlier, it could be deduced from Fig. 12 that the power generated varies proportionally with age and the weight of a person. Comparing the calculated results of this study (see Table 8 and Fig. 12) with existing experimental and theoretical results reported by Ang *et al.* (2019), it could be deduced that the power produced increases proportionately with the mass or weight of persons. The team also stated that persons with body masses ranging from 55 to 59 kg fall under the adult category, and since they are usually stronger, they exhibit very high-power generation capability compared to persons with body masses of 15 kg and below. These analyses agree reasonably well with the theoretical results obtained in Table 8 and Fig. 12.

It is also established that several steps will be required to generate a significant amount of power. Table 8 presents the weights of the participants, the number of steps taken (500 and 200 steps), and the corresponding power generated.

Table 8 Ages and Mass Of Persons, Number of Steps Taken, and Corresponding Power Generated

Age (Years)	Weight (kg)	Number of Steps	Power Generated (W)
5	4.5	500	2.6
5	4.5	200	1.04
10	9	500	10.5
10	9	200	4.5
25 - 30	60	500	220.5
25 - 30	60	200	88.2
30 - 40	70	500	628.0
30 - 40	70	200	251.0
40 - 60	80	500	819.5
40 - 60	80	200	327.8

The choice of step counts (500 and 200) in Table 8 reflects typical human activity patterns. Specifically:

(i) 500 Steps: Represents a scenario of moderate to prolonged walking, common in environments such as shopping malls or during outdoor activities.
(ii) 200 Steps: Simulates a shorter duration of activity, akin to quick errands or brief walks.

These step counts were strategically selected to showcase the energy harvesting system's effectiveness under varying levels of pedestrian activity. The resulting power outputs highlighted in Table 8 emphasize the system's potential for energy generation from human movement.

According to Table 8, one major factor that contributes to higher power generation is the number of steps. For instance, persons weighing 60 kg who walk 500 steps generate 628 W of power, which is higher than the 327.8 W generated by humans weighing 80 kg who take 200 steps. Fig. 13 presents these outcomes in more detail

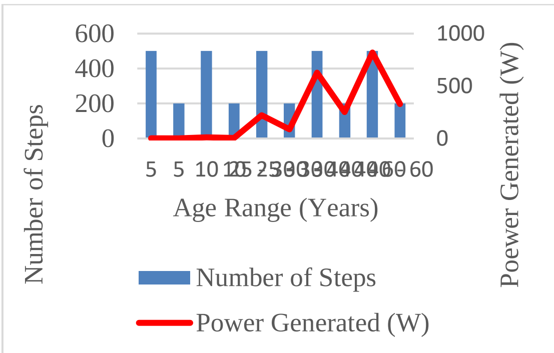


Fig. 13 Power Generated by Age and Number of Steps

The results in Table 8 and Fig. 13 imply that installing several of these systems in crowded places will ensure a very high power generation since many people will be treading on the devices. Moreover, repeated movements made by people carrying a lot of weight will gradually produce more power. The trends observed in this study, power increasing with weight and the number of steps taken, are consistent with the findings of Nandan and Trivedi (2019). For example, participants weighing 60 kg generated significantly higher power (220.5 W with 500 steps) compared to lighter individuals (Table 8).

4.2 Economics of the Proposed System

Table 9 presents the cost estimation of the major components of the proposed mechanical footstep electricity generation system. The cost data were sourced from Foundations of Materials Science and Engineering by Smith and Hashemi (2023).

Table 9 Cost Estimation of the Major Components of the System

S/N	Component	Details	Cost US$
1	The base plate and Upper Plate	Mild steel	40
2	Springs	Carbon steel (US$20 × 4)	80
3	Rack and pinion	Steel (US$ 40 × 2)	80
4	Shaft	Stee (US$ 10 ×4)	40
5	DC Generator (Dynamo)	12 V (US$ 30 ×2)	85
6	Flywheel	Mild Steel (US 40 ×2)	80
Total Cost			405

From Table 9, the estimated total cost of the system is US$ 405. In the future, if fabrication and assembly of the system are taken into consideration, the cost could increase to about US$ 460.

4.3 Limitations of the Study

(i). Variability in Human Activity:

The power output is based on average weights and step dynamics, which may vary widely in real-world scenarios, impacting actual energy generation.

(ii). Environmental Factors:

External conditions, such as surface materials and weather, can affect the efficiency of energy harvesting systems, leading to inconsistent results.

(iii). Sample Size and Diversity:
The study's findings rely on a limited sample of individuals, which may not fully represent broader demographic variations in weight, age, and activity levels.

(iv). Mechanical Limitations:

The durability and maintenance of energy-harvesting systems could be challenges in high-use environments, necessitating ongoing assessments.

4.4 Research Implications

(i). Sustainable Energy Solutions:
This study demonstrates that human-powered energy harvesting systems can significantly contribute to sustainable energy in urban areas, such as subway stations and malls. Optimizing for different human weights enables tailored energy solutions in high-traffic areas.

(ii). Wearable Technology:

The results suggest the potential for integrating energy harvesting in wearables (e.g., fitness trackers, and medical devices), enabling self-sustaining power from everyday activities.

(iii). Applications in Developing Regions:

Energy-harvesting floors in schools, hospitals, or community centers in regions with limited power access (e.g., Africa, and Asia) could provide off-grid renewable energy, improving energy resilience.

(iv). Smart Cities:

Embedding energy-harvesting systems into urban infrastructure supports smart city initiatives, offering scalable power solutions from crowd movement.

(v). System Design Optimization:

Insights from this research guide improvements in spring-based energy systems, enhancing efficiency and durability for diverse environments, including industrial settings.

4 Conclusion and Future Research Directives

This research presents the design and analysis of a Mechanical Footstep Electricity Generation System, with dimensions of 300 mm × 300 mm × 280 mm. The system employs a combination of rack and pinion, springs, spur gears, flywheels, and dynamos to efficiently convert mechanical energy generated by human footsteps into electricity.

Key design features include the use of steel plates for the upper and base components, enhancing durability and strength in comparison to plywood alternatives. The estimated total cost of the system is approximately US$ 405, with potential fabrication and assembly costs increasing to about US$ 460.

The system's applications are well-suited to densely populated areas, such as transportation hubs, educational institutions, parks, and other high-traffic locations. It offers a cost-effective and environmentally friendly means of energy generation, with output power varying based on the weight and number of steps taken by individuals. For example, a 60 kg person generates approximately 0.455 watts per step, and the number of steps significantly influences total power generation.

However, the system has limitations, including its relatively small energy output, which restricts its use to powering lighting and smaller appliances. Additionally, it relies on consistent human movement, making it less suitable for areas with sporadic mobility.

In summary, the Mechanical Footstep Electricity Generation System represents a promising sustainable, and cost-effective energy solution. Further research and development in materials and design improvements may enhance its practicality and expand its potential applications in various settings.

The following are a few of the recommended methods:

(i) The incorporation of a ratchet: A ratchet is a mechanical device that allows constant linear or rotary movement in just one direction while preventing movement in the other direction. This mechanism will enable continuous energy generation during movement while ensuring that energy can still be harvested even if intermittent or minor movements occur. However, it does not imply that electricity can be generated without any movement.

(ii) Modification of the system to be applicable in a staircase: In some places, aside from the bulk movement of people on pavements and entrances, staircases can also be of help to optimize the amount of electricity. The design can therefore be modified for use in structures where there are staircases.

(iii) Future research should focus on the fabrication of a prototype to validate the economic viability and operational efficiency of the proposed mechanical footstep electricity generation system.

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