Design simulation of a novel fluid based footstep energy harvesting system


School of Engineering and Physics, the University of the South Pacific, Suva, Fiji
Department of Biomedical Physics and Technology, University of Dhaka, Bangladesh
School of Science and Engineering, University of the Sunshine Coast, Queensland, Australia

ARTICLE INFO

Keywords:
Renewable energy
Hydro generator
Footstep
Fluid
Electrical energy production

ABSTRACT

With the ever-increasing demand for energy and a growing concern for the non-renewability of the energy sources as well as the environmental pollution, renewable energy harvesting systems have emerged as one of the energy technologies globally. In this context, this research work addresses a novel, clean and environmentally friendly renewable energy generation technology that harvests energy from human locomotion, like walking and running. The developed system is based on two square sized tiles structure paver in which two fluid bags are connected through flow control mechanisms including unidirectional valves and mini hydro generators that convert the human kinetic energy into electricity via fluid movements. All the design related simulations were performed in ANSYS software to find out the optimal parameters like fluid velocity, power output and fluid bag shape etc. Sequentially, it was experimentally observed that the energy harvesting paver can produce an average output power of 1.4 W per step during typical human walking and can power up a DC load of 390 Ω LED. The system is easily reproducible and can be installed with relative ease to power up street lamps, billboards and emergency lighting systems etc. Furthermore, the system is eco-friendly and cost-effective in comparison to other available energy harvesting paver systems. Hence, this novel fluid based footstep energy harvesting paver has considerable prospects as an effective renewable energy system.

Introduction

The increasing energy demand all over the world poses a significant concern on policy makers [1,2], yet the energy consumption is expected to increase by 34% by the year 2030 [3]. However, governments and policy makers are concerned with the consumption of energy from non-renewable resources that cause environmental and climate change issues. Consequently, a large number of researches are focused on the use of renewable energy to mediate such issues [4]. These renewable energies are primarily converted from energies like wind, solar, hydro and tidal energy [5–9]. In addition, small, mid and large-scale energy harvesting from a piezoelectric based system [10–13] or electromagnetic dynamic model [14–18] are in practice.

Interestingly one of the most growing harvesting technologies is connected with human beings as human body contains vibration, sound, pressure (weight), potential (height) and kinetic energies [19,20], but most of the energy is wasted as heat and movement while walking, jogging, running or even dancing [21,22]. Energy through these activities resides into sweats, body heat and most of it into kinetic and potential energy [7,8,23]. Hence, energy from the foot step is lost to the ground every time a step is taken [24]. If there were a sustainable way to extract the energy being lost to ground, this might bring a milestone achievement in the renewable energy sector. Just from the pedestrians moving on a footstep mechanism, a renewable, safe and eco-friendly energy can be produced. Furthermore, extracting this energy at a low cost would be suitable for setting up more foot energy harvesting platforms in heavy pedestrian traffic areas. Thus, the produced energy can be stored and later be used to power up street lights, low energy devices and be a supplement to existing renewable sources of energy.

Some earlier ways of energy harvesting through human locomotion are reported in the literature shown in Table 1.. An energy harvesting system has been designed using an electromagnetic generator to harvest kinetic energy from human walking [25], obtaining a maximum output power of 7.4 W. Similarly, an average power of 5 W system was designed with an electromagnetic energy harvester based on the motions of knees and legs [26]. Besides, pedestrian shore system was developed using footstep-induced airflow and harvested 6 mW power [27] and a...
new design developed electromagnetic wearable 3-DoF resonance human motion energy harvester that produced 2.3 mW [28]. Furthermore, it was demonstrated that energy harvesting by paver can produce an average power output of 3.6 W over 0.5 s of step time, with a peak power of 12 W; it was also shown that 75% of the potential energy that is theoretically available can be mechanically harvested [29]. Another approach of harvesting footstep energy is using piezoelectric energy harvester by placing a piezoelectric tile below the floor surface [30]. An average output power of 2–3 mW through passing automobiles over the piezoelectric surface can be produced [31]. In summary, the overall achievement of existing research on energy harvesting has great potential. Table 2 lists some of the existing ways of harvesting footstep energy, some are still being developed and some have been commercialized.

In this context, an innovative method of harvesting energy from footstep using hydro power was introduced in [55]. The system was conceptualized on a two tile structure made up of two fluid bags connected through flow control mechanisms including unidirectional valves and mini hydro generators. Hence, the aim of this article is to present the design and development of a human footsteps energy harvesting system using mini hydro generator. After discussing the design and modeling of the system, simulation and practical experiments are
The working principle of the proposed system is designed considering a simple structure of two tiles and aims to utilize this force by converting the kinetic energy into electricity. The system is designed for places where frequent human movements are available to provide optimum performance. A single unit of this system consists of two fluid bags connected through flow control mechanisms including unidirectional valves and mini hydro generators. Once a bag is pressed, fluid travels through the generator producing electrical energy since the unidirectional valve prevents the fluids to flow backwards. The fluid from bag 1 flows to bag 2 and when this is pressed, the fluid flows through the other generator back to bag 1 and the process is repeated [55], an exploded view of the system design is shown in Fig. 1. The outputs of these two generators are connected to a rechargeable lead acid battery through a charge control circuit which can be used to supply low power DC devices. This design enables the mini generator to provide continuous output power if footstep is maintained in a continuous manner. When the step is released, the generator is disengaged by unidirectional valves and the springs in the four corners reset the top panel to its original position. The working principle of the proposed energy harvesting system is shown in Fig. 2.

The power generated from the footstep based hydro generators is instantly stored in the super-capacitors and dissipated to the charge controller for battery charging. The super-capacitor bank is used to capture the sudden power output produced by the generator before it is delivered to the battery through the charge controller. Afterwards, the charge controller regulates the charging of the rechargeable battery of 6 V at 4.5 Ah. Furthermore, a microcontroller is used to count the number of footsteps per tiles, read charge status from the battery and deliver the super-capacitor output to the battery through the charge controller. The super-capacitor bank is used to capture the sudden power output produced by the generator before it is delivered to the battery through the charge controller. Afterwards, the charge controller regulates the charging of the rechargeable battery of 6 V at 4.5 Ah. Furthermore, a microcontroller is used to count the number of footsteps per tiles, read charge status from the battery and deliver the super-capacitor output to the battery through the charge controller. The super-capacitor bank is used to capture the sudden power output produced by the generator before it is delivered to the battery through the charge controller. Afterwards, the charge controller regulates the charging of the rechargeable battery of 6 V at 4.5 Ah. Furthermore, a microcontroller is used to count the number of footsteps per tiles, read charge status from the battery and deliver the super-capacitor output to the battery through the charge controller.
terminal of the battery is connected to one of the inputs of the microcontroller to display the battery voltage and state of charge. Additionally, the output of the generator is connected to another input port of the microcontroller which in turn display the output voltage of the generator. For real time data extraction, the microcontroller is connected to a personal computer (PC). Parallax data acquisition (DAQ) tool is used to display and analyse the real time data. Schematics of the overall system can be visualised in Fig. 3.

To obtain the maximum energy from the generator, the design of the mini hydro generator is a key factor. The mini hydro generator is comprised of:

a. a stator with winding of wires that provides DC electrical energy,
b. a permanent magnet rotor where structure is structure like a pelton wheel. The rotor is moved by the torque produced by the fast flowing fluid.

---

**Fig. 2.** Control design of the fluid based system.

**Fig. 3.** A schematic design of the harvesting system for graphical representation.
Table 3 shows the data sheet of the mini-hydro generator and Fig. 4 shows the mini hydro DC generator.

### Mathematical modeling

The fluid flow of the system can be divided into two categories - laminar and turbulent flow according to Reynolds number for dimensionless quantity. In the case of power generation using footsteps, the flow is a laminar flow in a pipe. A custom designed bag was fabricated and tested. The bag was designed in a such way that it has a laminar flow with a velocity of 0.2 m/s (This value has been considered for the simulation from an empirical test conducted from the prototype of the bag measuring the water flow from bag to bag using a orifice meter). The velocity was verified and obtained by testing water flow (flow rate) by connecting with a mini hydro generator. The Reynolds number is computed by:

\[ Re = \frac{\nu D}{\mu} \]  

(1)

where \( \nu \) is the velocity of the fluid (m/s), \( \rho \) is the density of the fluid (kg/m³), \( D \) is the diameter of the pipes (m) and \( \mu \) is the dynamic viscosity of the fluid [Pa.s]. The major losses for internal pipe flows are the frictional head loss and the pressure drop. The frictional head \( h_l \) (m) loss can be obtained by using Darcy’s equation:

\[ h_l = \frac{fL
u^2}{2g} \]  

(2)

where \( f \) is the Darcy’s friction factor. For a laminar flow, this can be found by \( f = 64/Re \), where \( Re \) is the Reynolds number, \( L \) is the distance between \( P_1 \) and \( P_2 \) (m), \( \nu \) is the average velocity of the fluid (m/s), \( g \) is the acceleration of gravity (m/s²). The pressure always decreases in a constant diameter pipe in the direction of the fluid flow. The pressure drop inside a pipe for a laminar flow is shown in Fig. 5 and can be calculated as:

\[ \Delta P = \frac{32\nu L}{D^2} \]  

(3)

It is essential to analyze the fluid flow in the piping systems since it represents the source of energy for the hydropower system. In particular, a typical piping network, presents various elements that disrupt the fluid flow as shown in Fig. 6. In a typical system with long pipes, these losses are minor compared to the frictional head loss, but in some cases where losses may be the main ones.

The maximum power \( P \) supplied to the hydropower system is given by:

\[ P = T\omega \]  

(4)

where \( P \) is power (W), \( T \) is the torque (Nm) and \( \omega \) is the rotational rotor speed (rad/s).

Since the inlet and outlet diameter of the hydro generator are fixed (20 mm), the minimum starting pressure is met by the increasing fluid impact force. By recalling the rate of change of linear momentum of a particle is equal to the net force acting on the particle as:

\[ \sum F = \frac{d(m\nu)^2}{dt} = \frac{dP}{dt} \]  

(5)

where \( m \) is the mass (kg) and \( P \) is the momentum (kg m/s).

The power which is supplied to the mini hydro generator once the step is taken can be calculated by:

\[ P = \rho gQH\gamma \]  

(6)

where \( \rho \) is the density of fluid (kg/m³), \( Q \) flow rate (m³/s), \( H \) height (m) and \( \gamma \) is the global efficiency ratio.

The system was modeled as a second order spring mass damper system. The frame represents the harvester which consists of the mass \( m \) (paver) suspended on a spring with the stiffness \( k_s \) as shown in Fig. 7.

The system also consists of the electrical component. The use of a steady state movement of stepping, assumed by sinusoidal is the minimum amplitude of the hydropower system. The output of the generator is the displacement \( y(t) \):

\[ y(t) = \dot{y}\sin(\omega t) \]  

(7)

where \( \dot{y} \) is the displacement of the paver, \( \xi \) is the mass motion, \( \omega \) is the angular vibration and \( \phi \) is the phase different between \( \dot{y} \) and \( \dot{\xi} \).

The relative displacement of the mass \( m \) with respect to the frame is:

\[ z(t) = \dot{\xi}\sin(\omega t + \phi) \]  

(8)

To derive the equation of the general kinetic energy harvester, it is assumed that the mass of the excitation source is much larger than \( m \), so the excitation source is not damped by the energy harvester and thus it is assumed to provide infinite power. The force balance is given as:

\[ ma = m\ddot{z} + dz + k_s z + F_2 \]  

(9)

The acceleration acting on the harvester frame can be expressed as:

\[ a(t) = \ddot{y}(t) = -\omega^2\dot{y}\sin(\omega t) = a\sin(\omega t) \]  

(10)

If the restoring force is considered as a damping force \( F = d_1 z \), can be rewritten as shown in Eq. (14). So, \( ma \) is the external force exerted on the paver. Transfer function is obtained by Laplace transform using Eq. (9) and shown as:

\[ ma^2\dot{y} = ma^2\dot{z} + (d + d_s)z + ksZ \]  

(11)

Using mechanical and electrical damping dimensional conditions,

\[ \zeta_d = \frac{d}{2ma_\xi_1} \text{and} \zeta_e = \frac{d}{2ma_\xi_2} \]  

(12)

where \( d \) is the damper, \( d_s \) is the electrical damper and \( \omega_m = \frac{\nu}{\sqrt{m}} \) is the natural frequency of the mechanical system, that can be rearranged to provide the transfer function as:

\[ Z(s) = \frac{s^2 + 2\omega_m(\zeta_d + \zeta_e)s + \omega_m^2}{s^2 + 2\omega_m\zeta_d s + \omega_m^2} \]  

(13)

Human stepping results in a Vertical Ground Reaction Force (VGRF) on the ground that is displayed in Fig. 8 for different physical activities. The potential energy from the human walking is given by:

\[ W = \int F dy \]  

(14)

where \( W \) is the energy; \( F \) is the VGRF and \( y(t) \) is the displacement of the tile’s top surface.

### Charge control circuit

The charge control circuit as shown in Fig. 9 is responsible for delivering the produced energy to the battery. The output voltage of the charge controller can be adjusted through the potentiometer according to the battery that has to be charged. The Schottky diode D1 prevents backflow of current to the generator. The circuit can also be directly

Table 3

<table>
<thead>
<tr>
<th>DC generator parameters</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>The output voltage</td>
<td>12 V</td>
</tr>
<tr>
<td>Wire resistance</td>
<td>10.5 ± 0.5 Ω</td>
</tr>
<tr>
<td>Insulation resistance</td>
<td>10MΩ</td>
</tr>
<tr>
<td>The maximum pressure</td>
<td>0.6 MPa outlet closed</td>
</tr>
<tr>
<td>The outlet opening maximum pressure</td>
<td>1.2 MPa</td>
</tr>
<tr>
<td>Start pressure</td>
<td>0.05 MPa</td>
</tr>
<tr>
<td>Axial clearance</td>
<td>0.3-1.0 mm</td>
</tr>
<tr>
<td>Mechanical noise</td>
<td>≤55 dB</td>
</tr>
<tr>
<td>The weight of the Generator</td>
<td>90 g approx</td>
</tr>
<tr>
<td>Generator life</td>
<td>≥3000 h</td>
</tr>
</tbody>
</table>
connected to a load (charging phones). A drawback of this type of charge controller is that there is a voltage drop across the two diodes and the voltage regulator [63].

Simulation results

ANSYS Fluent software simulation was carried out to see how the output velocity of the fluid inside the bags was influenced with a constant pressure applied on the top surface of each container. This was done by applying a constant pressure on the top surface of each container as it represented the weight force due to the stepping action. Two different sets of simulation were carried out to see how the output velocity is influenced with a constant pressure applied on the top surface of each container. Foot to container and container to container design was finalized considering the average human stride length of 72 cm [7]. The pressure simulation carried out in this research was using the mesh information for CFX analysis, the data for both foot to paver and paver to paver with Domain 1 and more parameters are available in Appendix B.

- Nodes: ranges from 4162 to 3887
- Elements: ranges from 14,986 to 1383

Initially, simulation was carried out to find out whether the nature of the shape of the paver influences fluid circulation between containers or not. This was done by assuming an inlet velocity of 0.2 m/s for all the shapes and monitoring the output velocity to see which shape gave the maximum output [64]. The flat tile of 350 mm × 350 mm comes fully in contact with the red surfaces for each of the possible solution. The
assumed time for the duration of the footstep was about 2 s. At around 1.5 s, the tile was expected to fully make contact with the red surface (on which the pressure is applied) while the shape undergoes maximum compression during this time. Table 4 lists different types of fluid bag with their governing equations for pressure.

The parameters used in Table 4 denotes as, $m$ is the applied mass (footstep), $g$ is the gravity ($9.81 \text{ m/s}^2$), $l$ and $w$ are the side lengths of the bag, $r$ is the radius for circler bag, $a$, $b$ and $c$ are the semi-major, semi-minor and semi vertical axes respectively and $x$ is the distance between the center to straight edge.

Table 5 shows the pressure for the different type of bag design. The force applied was kept at a constant value that falls within the normal human body force of 500–1000 N. The force applied to the bag is 833.85 N.
Each container experiences a force due to the stepping action. Similarly, the output velocity was influenced by a constant pressure applied on the top surface of each container. This was done by applying a constant pressure on the top surface of the bag. Results of software simulation for velocity contour in case of container to container and foot to container are displayed in Figs. 10–15. The “Container to Container” simulation results represent fluid flow (velocity at the outlet nozzle) between bags with an assumed inlet velocity of 0.2 m/s. All the simulation result outputs are shown in Table 5.
Simulation for foot to container

Results of software simulation for velocity contour in case of foot to container are displayed in Figs. 16–21. The “Foot to Container” simulation results are a representation of fluid dispersion from the container’s outlet nozzle due to the stepping action of the user on the bag. All the simulation result outputs are shown in Table 5.

After analysing the simulation results in the above mentioned figures and tables, the highest output for velocity contour is found to be $5.406 \times 10^{-1}$ m/s (*marked) for the rectangular container in case of foot to container. On the contrary, the semicircular container had the best results for best flow between container to container with a contour velocity of $2.295 \times 10^{-2}$ m/s (**marked). Summary of all pressure
contours, velocity streamlines and velocity vectors for both foot to paver and paver to paver is appended under Appendix A.

On the other hand, the square container in Table 6 had the second highest output velocity contour in both cases indicating a fairly high electrical output. Hence, the choice for the final prototype was a square container that had a higher performance compared to most of the other container designs. Furthermore, in terms of manufacturing flexibility and cost, it is easier and cheaper to make a container. Besides, straight walled mould with less curvature also results in a less production time. Finally, the square container (excluding nozzle and inlet attachment) is geometrically symmetric, i.e., the shape can be placed equidistantly from the walls of the structure. In addition, tile attachment will have a greater stability because of the nature of the shape.

**Experimental results**

**Load calculation**

In order to find out the optimal load for maximizing the power output per step, the relationship between the harvested power and load resistance was mapped i.e loads of increasing resistance was connected to the generator output as the harvester experienced the stepping force.

<table>
<thead>
<tr>
<th>Table 6</th>
<th>Simulation results of the contour velocities for the two case scenarios.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape</td>
<td>Foot to Container</td>
</tr>
<tr>
<td></td>
<td>Velocity Contour (m/s)</td>
</tr>
<tr>
<td>Square Container</td>
<td>54.06</td>
</tr>
<tr>
<td>Rectangular Container*</td>
<td>54.11</td>
</tr>
<tr>
<td>Half Ellipse Container</td>
<td>53.9</td>
</tr>
<tr>
<td>Quarter Ellipse Container</td>
<td>37.87</td>
</tr>
<tr>
<td>Semi Circular Container**</td>
<td>53.95</td>
</tr>
<tr>
<td>Vertically Cut Cylinder Container</td>
<td>53.89</td>
</tr>
</tbody>
</table>

**Table 7**

<table>
<thead>
<tr>
<th>Load (Ohms)</th>
<th>Voltage (V)</th>
<th>Current (I)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>2.3</td>
<td>0.32</td>
<td>0.748</td>
</tr>
<tr>
<td>50</td>
<td>2.9</td>
<td>0.28</td>
<td>0.838</td>
</tr>
<tr>
<td>80</td>
<td>4.2</td>
<td>0.24</td>
<td>0.993</td>
</tr>
<tr>
<td>120</td>
<td>5.4</td>
<td>0.2</td>
<td>1.098</td>
</tr>
<tr>
<td>200</td>
<td>8</td>
<td>0.17</td>
<td>1.334</td>
</tr>
<tr>
<td>270</td>
<td>9.2</td>
<td>0.15</td>
<td>1.382</td>
</tr>
<tr>
<td>390</td>
<td>11.1</td>
<td>0.13</td>
<td>1.443</td>
</tr>
<tr>
<td>500</td>
<td>12</td>
<td>0.1</td>
<td>1.221</td>
</tr>
<tr>
<td>750</td>
<td>13</td>
<td>0.07</td>
<td>0.952</td>
</tr>
</tbody>
</table>

**Fig. 22.** VGRF exerted by stepping on tile.

**Fig. 23.** Voltage output by device as stepped.

**Fig. 24.** Walking trails results with different weight.
of a 70 kg person and the results were tabulated. The harvested power due to stepping by an average built person of 70 kg could light up a torch light (390 Ω LED) at its specified conditions and was found to be the optimal load condition. Table 7 depicts how voltage and current behaved according to different load due to the stepping by an average build person of 70 kg.

**VGRF and average output power**

VGRF and voltage output of the system after stepping were simulated and measured experimentally. Fig. 22 represents the VGRF exerted on the ground by a single person (solid line) while walking, whereas the average VGRF (dashed line) is the average force exerted on the ground by a group of people with different weights. It can be observed that the values peak around 0.3–0.4 s of the stepping time. For this paper, to have a better visualization and understanding, a numerical simulation was carried out by fitting the parameters are determined by Eq. (14). Added to this, Fig. 23 demonstrates the simulated (solid line) and experimentally measured (dashed line) voltage output for stepping. In this case, voltage had peak values around 0.4 s of stepping time.

Volunteers for experimentations were weighed and categorized into different weight groups. Five volunteers for each weight category was chosen whereby the volunteers were asked to step through the harvester 4 times each making it 20 trials per weight category. They were then trialed to obtain average output power for varying weight. Power outputs were measured for activities like walking and running for a load of 390 Ω light emitting diode (LED). A DM7560 digital multimeter (high-accuracy, high-speed data logging (up to 30 k S/s) with deep 100 k reading memory and built-in statistical analysis) was used for measuring the current and voltage. Fig. 24 shows the result of walking while Fig. 25 displays the result of running. The average of the results is displayed in Table 8 for different weight categories. It can be observed that output power is directly proportional to the mass. Besides, the average output power due to walking tends to be generally higher in comparison to output power on account of running. It is worth mentioning that running, speed walking and walking on hard and plain surface has slightly different VGRF as shown in Fig. 7, compared to the VGRF obtained in this research as the system is fluid based.

**Prototype implementation**

**Tile and frame design**

The design of the tile and its placement is one of the essential parts in the design. The modular energy harvesting system was designed of 40 × 40 × 15 cm as shown in Fig. 26. To get an optimum output, the design is integrated with locally purchased spring (spring constant

---

**Table 8**

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time (s)</th>
<th>50–55 kg</th>
<th>55–60 kg</th>
<th>60–65 kg</th>
<th>65–70 kg</th>
<th>70–75 kg</th>
<th>75–80 kg</th>
<th>80–85 kg</th>
<th>85+ kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking</td>
<td>0.5</td>
<td>0.89 W</td>
<td>1.19 W</td>
<td>1.36 W</td>
<td>1.41 W</td>
<td>1.54 W</td>
<td>1.63 W</td>
<td>1.76 W</td>
<td>1.89 W</td>
</tr>
<tr>
<td>Running</td>
<td>0.2</td>
<td>0.91 W</td>
<td>1.09 W</td>
<td>1.19 W</td>
<td>1.28 W</td>
<td>1.37 W</td>
<td>1.42 W</td>
<td>1.55 W</td>
<td>1.70 W</td>
</tr>
</tbody>
</table>
750 N/m), which keeps a uniform profile of the walking area. The bag is made of polyvinyl chloride (PVC) and the size is $30 \times 30 \times 10$ cm. In addition, the frame is made up of timber which is found to be relatively cheaper. The spring and fluid bag arrangement is fixed below the foot step which had been mounted on the base. Spring system is used for the return mechanism of upper plate after the release of step.

When the foot is stepped on the paver, the kinetic energy is transferred into the system. Consequently, the energy from the flow of water rotates the turbine of the hydro-generator which produces electrical energy. From here, the water passes through a one way valve which prevents back flow of water. Finally the water reaches the second water bag under the second tile and upon compression, the power harvesting cycle starts again. The components of the system include unidirectional valves, mini-hydro water turbine generator, pipes, water bags, super capacitor, micro controller and battery.

**Final prototype**

The prototype of footstep energy harvester which was showcased and tested is presented in Fig. 27, where the top panel displacement was of 4 cm and capable of producing an average power of 1.4 W per step with an average built person of 70 kg.

**Viability aspects of footstep energy harvester**

From the literature, there has been no cost information available for the making of energy harvesting paver. However, an UK based company that commercialized their footstep energy generation units, provided a cost of 6580 USD for a complete unit [33]. On the other hand, our novel footstep energy harvesting paver system costs about 125 USD which is relatively on the cheaper side. The cost information is listed in Table 9. Besides, all the material used in the fabrication process is available in common localities. Furthermore, the system uses water as the circulating fluid which ensures a clean energy source. The system is easy to use and can be installed in large scale in road crossings pavements, cross section pavements, school, shopping mall, rural areas and playing parks for power up DC devices directly. The stored energy can be utilized for broad applications ranging from powering lights, illuminating billboards and energizing Wi-Fi networks etc. with necessary modifications. A graphical abstract is shown in Fig. 28. Overall, the manufacturing flexibility is on the simpler side and the costing of this device is cheaper. Once the manufacturing quantity of the system increases, the cost of the system will come down eventually.

**Conclusion**

This research work attempted to present a non-conventional, eco-friendly and renewable energy harvesting system based on human locomotion and hydro power. A complete model of the system was developed based on two square sized tiles structure in which mini hydro generators convert the human kinetic energy into electrical energy. Experimental results demonstrate that this system can produce an average of 1.4 W output power per step with a walking of 70 kg person over the tile structure. The developed system is economically viable, easy in manufacturing, and relatively simple in assembling and installation. The system has the potential to be effectively installed with necessary modifications in places where high level of pedestrian movement is available, e.g., footpaths near road crossing, shopping mall etc. to power up street lights, billboards, security lights and emergency lighting systems etc. Nevertheless, the power delivered by the prototype is relatively lower than some other footstep energy harvesting systems as reported in the literature. Hence, the fluid based energy harvesting paver has both promising potentials as well as scopes of improvement to be regarded as an efficient and robust renewable energy system.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>USD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of materials</td>
<td>60</td>
</tr>
<tr>
<td>Labor cost</td>
<td>25</td>
</tr>
<tr>
<td>Cost of assembly</td>
<td>40</td>
</tr>
<tr>
<td>Total Capital investment</td>
<td>125</td>
</tr>
<tr>
<td>Expected output</td>
<td>1.4 W per step</td>
</tr>
</tbody>
</table>

**Fig. 28.** Graphical abstract.
Conflict of interest

There is no conflict of interest.

Author’s Contribution

Aneesh A. Chand: Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection.

A. S. M. Shamsul Arefin: Application of formal techniques to analyze or synthesize study data and editing article.

F. R. Islam: Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection and writing- Original draft preparation.

K. A. Mamun: Ideas; formulation or evolution of overarching research goals and Writing- Original draft preparation.

Kushal A. Prasad: Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection. Utilized software to validate the data.

Shivneel Singh: Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection.

Maurizio Cirrincione: Management activities to annotate, scrub data and maintain research data.

Acknowledgement

This research project is funded by The University of the South Pacific (USP) under the research office Strategic Research Theme (SRT grant-2017); Project Title namely “Future of Renewable Energy in Fiji: Harvest Energy from Footsteps at USP (HEF)”. Authors also acknowledge the support from the School of Engineering and Physics at USP.

Appendix A

Appendix A.1 Pressure contour of foot to container

See Figs. 29–34.

Fig. 29. Square bag with maximum pressure contour.

Fig. 30. Rectangular bag with maximum pressure contour.
Fig. 31. Half ellipse bag with maximum pressure contour.

Fig. 32. Quarter ellipsoid bag with maximum pressure contour.

Fig. 33. Semi-circular bag with maximum pressure contour.
Appendix A.2 Pressure contour of container to container

See Figs. 35–40.

Fig. 34. Vertically cut cylinder bag with maximum pressure contour.

Fig. 35. Square bag with maximum pressure contour.

Fig. 36. Rectangular bag with maximum pressure contour.
Fig. 37. Half Ellipse bay with maximum pressure contour.

Fig. 38. Quarter ellipsoid bay with maximum pressure contour.

Fig. 39. Semi-circular bay with maximum pressure contour.
Appendix A.3 Velocity Streamline contour of foot to container

See Figs. 41–46.

Fig. 40. Vertically cut cylinder bay with maximum pressure contour.

Fig. 41. Square bag with maximum velocity streamline.

Fig. 42. Rectangular bag with maximum velocity streamline.
Fig. 43. Half Ellipse bag with maximum velocity streamline.

Fig. 44. Quarter ellipsoid bag with maximum velocity streamline.

Fig. 45. Semi-circular bag with maximum velocity streamline.
Appendix A.4 Velocity Streamline contour of container to container

See Figs. 47–52.

Fig. 46. Vertically Cut Cylinder bag with maximum velocity streamline.

Fig. 47. Square bag with maximum velocity streamline.

Fig. 48. Rectangular bag with maximum velocity streamline.
Fig. 49. Half Ellipse bag with maximum velocity streamline.

Fig. 50. Quarter Ellipsoid bag with maximum velocity streamline.

Fig. 51. Semi-Circular bag with maximum velocity streamline.
Appendix B. Mesh information for ANSYS CFX Analysis

Electronically available on Google Drive. [url: https://drive.google.com/file/d/1g6i8vE2iwXT3uKNG_kCsok47hbHSERB/view?usp=sharing].

Appendix G. Supplementary data

Supplementary data to this article can be found online at http://doi.org/10.1016/j.seta.2020.100708.

References


