Design and development of gait-powered active thermoregulatory insole using thermoelectric module (TEC) powered by lead zirconate titanate (PZT) piezoelectric discs

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Abstract

Existing footwear design lacks crucial potential foot thermoregulation feature. By utilizing piezoelectric and thermoelectric energy manipulation, the study successfully developed a battery-replenishing thermoregulating insole which is solid-state and portable with zero carbon-emission capable of harvesting 500 mW of power with an efficiency of 0.3, heating the foot up to 40°C with a COP of 1.89, and cooling the foot down to 23°C with a COP of 0.89.

Keywords: *renewable energy source, foot thermoregulation, piezoelectricity, thermoelectricity*

Introduction. The feet extremities are considered to be an efficient heat exchanger [1] by containing arteriovenous anastomoses, connections of arteries and veins, where dramatic elevations in skin blood flow occur when shunts of these vessels open and a surface area to mass ratio of 2.5 and 3 times larger relative to the entire body of a male and female, respectively leading to a theoretical peak heat transfer from the core to both feet of 16 W [2].

However, due to the feet's little local metabolic heat production caused by small muscle mass, a lot of heat radiation may cause significant drops in temperature posing various health risks on the feet. This heat delivery and dissipation are advantageous as it facilitates central cooling, but can be dangerous in the cold [2]. The responses of the body's attempt for self thermoregulation may cause shivering, diminishing muscle power and performance, loss in sensitivity, pinching pain, numbness causing distractions and behavioral changes leading to accidents [1].

Conversely, heat buildup creates discomfort and exacerbates friction that causes blisters [3] and promotes bacterial growth through sweat [2]. Exercise in the heat may also cause heat stress which can be detrimental to performance [4]. Workers have been reported to resort in removing their footwear in order to cool their feet down consequently exposing their feet to hazards. Amidst the cruciality of foot thermoregulation, studies regarding footwear have largely been ignored in clothing research [4] where thermal comfort is often overlooked [5]. For instance, alterations in footwear have the ability to influence the forces acting through the body, posture, and movement [3].

Some attempts have been made to to regulate foot temperature such as doping fabrics with microcapsules containing phase change materials (PCMs) and carbon nanofibers (CNFs) to improve the thermal comfort [6] and developing functional knitted fabrics for moisture management and thermoregulation [7]. However, these passive ways are deemed insufficient which requires an active way to pump heat. A study proposed an active heater footwear system containing a heating pad using polyester filament and micro metal conductive fiber folded into a protective polyimide film powered by Li-ion battery [8]. Another heating system was developed for feetillness using a thermoelectric module and a rechargeable battery power source [9]. In this system, electronic circuit was placed in the middle base of the shoe where pressure is minimum.

Thermoelectricity is the ability to pump heat electronically producing a temperature difference with current flow used in various cooling and heating applications bearing reliable temperature control and no chlorofluorocarbon (CFC) emission [10]. Considered as an efficient thermoelectric material, Bismuth telluride (Bi_2Te_3) [11] has been used as water chillers, cold plates, portable insulin coolers, and computer heat dissipation systems [12].

Due to batteries' limitations, constant charging may be a major hindrance of such system. The system may utilize a larger battery to keep it running throughout the day, but would not be feasible considering the consequent increase in portability, weight, and size [13]. When a person walks or runs, there is a sufficient amount of inherent kinetic energy generated that can be harvested for renewable power of an estimated 67-watt power present on an average 68 kg person walking at two steps per second with the foot moving 5 cm vertically [14]. This amount of energy may be harvested through piezoelectricity, a material's tendency to produce voltage in response to physical deformation. In particular, piezoelectric ceramics such as lead zirconate titanate (PZT) are an optimal element for this application due to their low cost, flexibility, and easy integration into elements such as shoes.

Gupta and Sharma (2015) developed an experimental shoe harvester design using PZT discs. with a calculated 80% system efficiency. Zhao and You (2014) explored the idea of optimizing piezoelectric harvesting on shoes by utilizing LTC3588-1 chip containing buck converter, rectifier, and shunt regulator confined within a single chip. By utilizing these energy transformations, piezoelectricity and thermoelectricity, development of a solid-state, portable, and zero carbon-emitting energy harvester and heat pumping system could reduce our reliance on fossil fuels and air-conditioning systems, mitigating greenhouse effect, global warming, and ultimately, climate change.

Methods. A thermoregulating insole with battery-replenishing capability was designed and developed through a series of steps shown in Figure 1. A theoretical energy flow model was conceptualized aiming to harvest mechanical energy to be utilized in pumping heat in the interior of the shoe. Using the model, the system circuitry was designed accordingly. The insole system prototype, composing of a harvester and a heat pump, was derived using the designed circuit. Final system design was constructed, developed, and analyzed in terms of its dimensions, performance, limitations, and potential implications. Finally, problems that may arise are troubleshooted accordingly.

Prototype Design. An insole system prototype capable of both energy harvesting and heat pumping was designed.

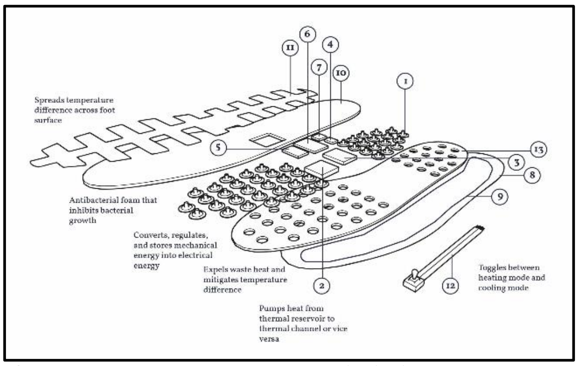

Figure 1. System Prototype Exploded View

The above figure shows an exploded view of the system design. Pusher-incorporated piezoelectric PZT discs (1), placed on an acrylic base (13) along with the system circuitry - battery (3), step-up converter (4), and energy-harvester module (5), convert, regulate, and store mechanical energy into electrical energy. The stored energy in the battery powers up the thermoelectric module (2) via a detachable switch (12) that could be inserted in a switch jack (7). The incorporated micro-USB charging port (6) is located on the side of the insole system. Waste heat generated from the thermoelectric module is deposited on the thermal reservoir (8) with a coolant water interior (9). An antibacterial foam (10) cushion layer is placed above the piezoelectric array for comfort and hygiene. The heat pumping is carried and spread across the foot surface via the thermal channel (11).

Electrical flow. Piezoelectric discs arrays from both heel and forefoot area are responsible for harvesting the mechanical energy and converting it into DC voltage through the LTC3588 energy harvesting module. The voltage will be stepped up into 5.0 VDC through a mini DC-DC step-up boost converter for power storage into a 3.7 V battery. An external DPDT switch will be connected with the

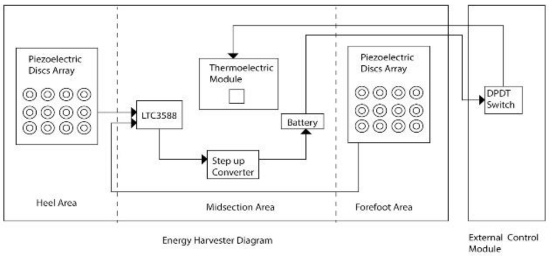

Figure 2. System Circuit Schematic Diagram

battery facilitating the toggle of heating and cooling pump of the thermoelectric module.

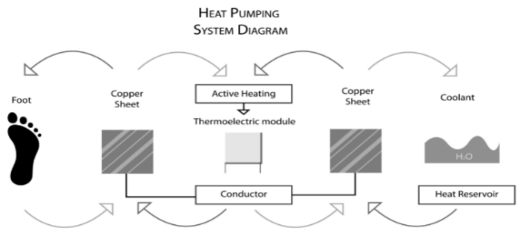

Figure 3. Heat Flow Diagram

Heat flow. In cooling mode as shown by the blue arrows in figure 3, the thermal channel will conduct heat from the foot of the user. This heat will be actively pumped into the thermal reservoir using a thermoelectric module. In heating mode as shown by the red arrow in figure 3, the internal heat of the thermal reservoir will be pumped into the thermal channel with direct conduct on the user's feet by actively pumping out heat using a thermoelectric module.

Piezoelectric Array Development. A poly (methyl methacrylate) acrylic sheet with 2 mm thickness was cut to the shape and size of an average insole which is 9.5 inches. Placeholders the PZT discs with a diameter of 12 mm were marked and outlined along the the acrylic sheet on the toe and heel area, leaving space for the circuitry on the midsection area. Each of the outlined area was bored with an 8 mm-diameter hole serving as deformation cavities of the discs. The discs were adhered to the marked outlines using epoxy adhesives. A parallel connection was made among the array of the piezoelectric elements. Wooden pushers were adhered above each disc.

Power Optimization Circuit Development. As shown in Figure 3, the midsection area of the harvester is left unused as a chamber for circuitry. The harvester circuit composed of the LTC3588-1 chip, a DC-DC step up boost converter, and a battery, was placed and connected in the midsection part of the acrylic platform. The piezoelectric discs array was connected into the input pins of the LTC3588-1 where the output is connected and fed into the boost converter. The output of the boost converter is connected into a 3.7 V LiPo battery for power storage. TP4056 micro-USB charging module was incorporated to safely charge the battery alternatively when there is an apparent conventional energy source such as power banks and power outlets.

Heat Pump and Detachable Control Switch Development. The thermoelectric module was placed in the circuitry chamber. An antibacterial polyurethane foam of 1.5 mm thickness was cut into the similar dimensions of the acrylic platform. Location of the thermoelectric module within the acrylic layer was traced and cut out replacing it with the said module. Both the thermoelectric module and the battery were connected into a 4-pin female connectors which will serve as *jack* of the detachable control module. The external switch module consists of a DPDT switch connected to a 4-pin male connector which will serve as the *plug* of the detachable control module.

Thermal Reservoir Development. The thermal reservoir was constructed using two layers of copper sheet to form a relatively thin container filled with water coolant. The thermal reservoir was thermally connected to the bottom part of the thermoelectric module beneath the acrylic sheet using thermal grease to serve as both heat sink and heat mitigator by spreading heat into a larger surface area and mitigating temperature difference due to high specific heat and additional mass of water coolant.

Thermal Channel Development. Copper sheet was designed to evenly spread out heating or cooling across the foot maximizing temperature differential and increase heat distributing efficiency of thermoelectric module heat pumping. The thermal channel is mounted above an antibacterial polyurethane foam for cushion.

Performance Evaluation. *Harvester Conversion Efficiency.* In order to compute for the efficiency of the piezoelectric harvester, time-averaged power ratio of mechanical input and electrical output is taken into account. Thus, efficiency, according to Shu (2006), is given by the following equations:

$$eff = \frac{W^e}{W^{in}} \quad (1)$$

The electrical output power W^e can expressed as:

$$W^e = V_C \times I \quad (2)$$

where V_c is the rectified voltage from the harvester and I is the output current. Conversely, input power W^{in} can be expressed as:

$$W^{in} = \frac{\pi \times F \times u}{t} \quad (3)$$

where F is the force applied (weight) of the user, u is the displacement of the piezoelectric material compression, and t is the period of the footstep. Eq. (3) is used to calculate for the mechanical input power. The force F applied is the weight of the user at 539 N (55 kg person), u is equal to 1 mm, and the period t for each step is 1 s.

Charging Time. The system battery can be charged within a definite amount of time. Total system charging time can be calculated using the equation:

$$t_{charging} = \frac{C_{Ah} \times V_{nom}}{V_{charge} \times I} \quad (4)$$

where $t_{charging}$ is the total charging time in hours, C_{Ah} is the capacity of the battery in Ah and V_{nom} is the nominal voltage of the battery, V_{charge} is the charging voltage in volts and I is the charging current in amperes. Two modes of charging time, mechanical (piezoelectric harvesting) and conventional (power outlets/power banks) charging mode, are calculated.

Coefficient of Performance. The coefficient of performance directly describes the efficiency of heat pumping of the system. Five variable parameters applicable to a thermoelectric module that affect its operation are the input current (I), the input voltage to the module expressed in volts (V_{IN}), the hot side temperature of the module expressed (T_h), the cold side temperature of the module (T_c), and the heat input to (or heat pumped by) the module expressed in watts (Q_c). Temperature-dependent parameters, Seebeck coefficient (S_M), module resistance (R_M), and module thermal conductance (K_M) are computed by deriving from an industry-standard 71-couple, 6-ampere module. The study utilized TEC1-3104 module (31-couples, 4 A maximum current); therefore, correction factors are applied accordingly.

The temperature measurements were gathered from the uppermost copper surface measured at the peak of heat pumping where maximum temperature differential is achieved and stabilized. The temperature difference (DT) across the module in °K or °C is:

$$DT = T_h - T_c \quad (5)$$

where Th is the temperature at hot side; Tc is the temperature at cold side. The coefficient of performance of the system as a cooler is calculated using the equation below:

$$COP = \frac{[(SM \times Tc \times I) - (0.5 \times I^2 \times RM) - (KM \times (Th - Tc))]}{[(Vin) \times I]} \quad (6)$$

In heating mode, the coefficient of performance may realize in excess of 100% efficiency under certain conditions. Using Carnot's theorem, coefficient of performance in heating mode is given by the expression:

$$COPH = COP + 1 \quad (7)$$

The heat pumped (Q_c) by the system (in watts) is:

$$Q_c = (SM \times T_c \times I) - (0.5 \times I^2 \times RM) - (KM \times DT) \quad (8)$$

The input voltage (Vin) to the module in volts is 3.7 V The electrical input power (P_{in}) to the module in watts is:

$$P_{in} = V_{in} \times I \quad (9)$$

The heat rejected by the module (Q_h) in watts is:

$$Q_h = P_{in} + Q_c \quad (10)$$

Safety Procedure. Lead Zirconate Titanate (PZT) piezoelectric discs contain an amount of Lead (Pb) element which is a neurotoxin that may cause cancer and can pose other significant health hazards if the material is not safely handled. Gloves were worn when handling lead weights or lead-contaminated items. Hands, arms, and face were thoroughly washed after handling lead. Eating, drinking, or smoking in or around areas where lead is handled or stored were avoided. The system also involves electric circuit system. Electricity poses health hazards when mishandled. Power storage was regulated properly. No battery was disassembled as the materials inside may be toxic and may damage skin and clothes. No battery was also short-circuited. Doing so can damage the product and generate heat that can cause burns. Disposing of a battery in fire can cause the battery to rupture. Placing batteries in water was also avoided as this may cause the battery to fail. Nothing was soldered directly into the battery. This can destroy the safety features of the battery by damaging the safety vent inside the cap. Permanent connections to an energy cell may be made by spot welding solder tags to the terminals. A soldered connection can subsequently be made to the tag. Battery was not inserted with the positive and negative poles reversed as this can cause permanent damage to the battery which may swell or rupture. A capacitor was not charged with higher current or higher voltage than specified. Like a battery, soldering directly and reversing the polarity of a capacitor was avoided. Finally, forced discharging of a capacitor was also avoided. To guarantee safety, an electrical expert was consulted before testing.

Results and Discussion. *Prototype Specification.* The integrated system is 27.5 cm long, 6.5 cm wide, and 0.6 cm thick while the switch module is 14.6 cm long, 1.2 cm wide, and 3.0 cm high.

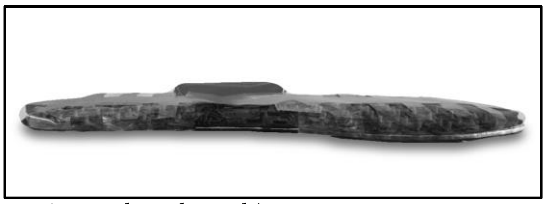

Figure 4. Developed Working Prototype

The above figure shows the developed prototype. The system can be controlled using a detachable activation and heating-cooling toggle switch which could be connected into the switch jack on the side of the insole.

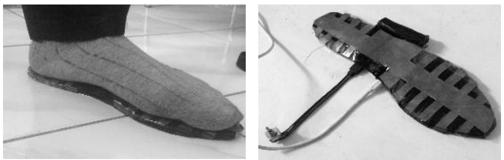

Figure 5. Prototype Charging Through Walking (Left) and Conventional Power Source (Right)

The insole prototype can be charged in two ways as shown in Figure 5. In mechanical charging, applying force on the insole through walking, running, jumping, or any form of locomotion deforms the piezoelectric arrays and produces voltage charging up the system battery. In conventional charging mode, a micro-USB charger, commonly used with smartphones, can be used to charge the system battery from power outlets, power banks, computers (such as laptops and desktops), and other power sources. LED indicators are used to determine battery charging status (red in charging state; blue in fully-charged state) as shown in the figure. The heat pump can be activated by plugging in the switch module.

Systems Performance. Through piezoelectricity, 500 mW is extracted from human locomotion. Using the developed harvester, the concept of connecting multitude arrays of PZT discs may surpass the usage of loud and bulky dynamo in terms of utility. The harvester converts mechanical energy into electrical energy with a conversion efficiency of 0.30. Although relatively inefficient compared to fossil fuels, it converts energy from an otherwise wasted energy source. The developed prototype has an efficiency of 0.01 more than the theoretical limits of photovoltaic at 0.29 (Blakers et al, 2013). Theoretical calculations on the system mechanical charging time is 6 hours and 17 minutes while conventional charging time is 38 minutes.

Performance of the heat pump data were gathered and computed in terms of power consumption, effective heat pumped in cooling mode, cooling time, minimum cooling temperature, coefficient of performance as a cooler, effective heat pumped in heating mode, heating time, maximum heating temperature, coefficient of performance as a heater, and system total discharging time

In cooling mode, starting at an ambient temperature of 32°C, it drops and stabilizes at 24°C (296.15°K) minimum temperature after 14 seconds by effectively pumping 9.79 W of heat away from the thermal channel.

The minimum temperature reached by the cold side is considered safe for this mode being significantly higher than the threshold of pain at 15°C (ISO 13732-3, 2005) for skin to cold surface contact. Any lower than 15°C may cause numbness (7°C) or frostbite (0°C).

In heating mode, the system pumps effectively pumps 20.8 W of heat into the thermal channel; starting at 32°C, temperature rises up until 40°C (313.15°K) maximum after 15 seconds and exhibits minor fluctuation of ±1°C thereafter.

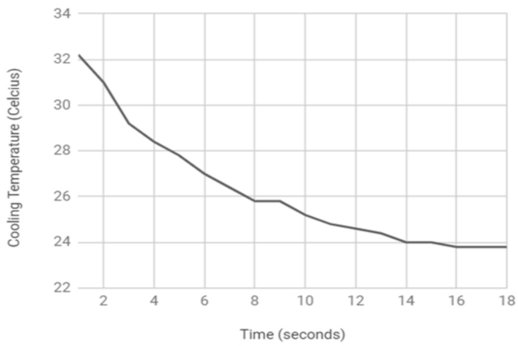

Figure 6. Prototype Cooling Graph

The maximum temperature achieved is significantly below the burning threshold of the skin which is 44°C (ISO 13732-1) thereby, again, achieving a safe heating mechanism. The portable heat pump can decrease large-scaled HVAC (Heating, Ventilation, and Air Conditioning) systems by focusing the heat pumping mechanism directly into the human body thereby efficiently converting energy sources into thermal comfort.

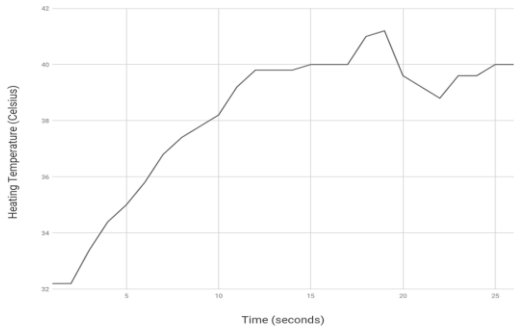

Figure 7. Prototype Heating Graph

The integrated prototype is solid-state, produces no noise, is lightweight and portable, requires no maintenance, and has no moving parts. It may be used drastically reduce reliance on non-renewable energy sources such as coal, oil, and natural gas, which are not only currently in the state of depletion, but also has negative environmental impacts. The system has various implications from eliminating thermal discomfort, aiding in the treatment process of medical conditions that require foot temperature regulation such as diabetes and plantar fasciitis, improving the health of workers working on extreme temperatures for a sustained period of time or athletes prone to heat stress, up to the capability of influencing and regulating overall body temperature which may reduce large-scaled air conditioning usage.

Error Analysis. Temperature measurements conducted did not take atmospheric room temperature into account. This may have significant impacts on the COP calculations of both heater and cooler systems. Furthermore, the power output of the harvester was measured directly on the output pins of LTC3588 microchip. Transformation waste energy of piezoelectric mechanical energy conversion into electrical was not taken into account in the calculation of the harvester.

Conclusion. Using piezoelectricity to convert mechanical energy and thermoelectricity to pump heat accordingly within the footwear, the study successfully developed a battery-replenishing thermoregulating insole which has both the capability of foot thermoregulation and energy harvesting. The developed prototype has various implications on, body comfort, thermal hazards safety, and greenhouse gas reduction.

Recommendations. The system may be improved in various aspects. System ergonomics may be improved by reducing thickness, improving flexibility by incorporating living hinges, improving overall cushioning comfort, and optimizing the surface to conform with the foot contour. Precise temperature control, automatic temperature regulation, and wireless control may be developed on a mobile phone using RF transmitter or Bluetooth™ module using microcontrollers. Piezoelectric array efficiency may be improved by incorporating piezoelectric elements possessing higher mechanical coupling factor, thus, may significantly improve charging-discharging time.

The computed charging-discharging ratio of r=22.2 proves that the developed energy harvester may have rooms for improvement to suffice with the energy demand of the thermoelectric module. Since the thickness of individual PZT discs are insignificant, the system could utilize more layered piezoelectric arrays mounted on top of each other. Strategically incorporating additional layers of piezoelectric arrays could multiply the harvested current to a desired amount.

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