Research Article

Experimentation of a Wearable Self-Powered Jacket Harvesting Body Heat for Wearable Device Applications

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The development of special wearable/portable electronic devices for health monitoring is rapidly growing to cope with different health parameters. The emergence of wearable devices and its growing demand has widened the scope of self-powered wearable devices with the possibility to eliminate batteries. For instance, the wearable thermoelectric energy harvester (TEEH) is an alternate to batteries, which has been used in this study to develop four different self-powered wearable jacket prototypes and experimentally validated. It is observed that the thermal resistance of the cold side without a heat sink of prototype 4 is much greater than the rest of the proposed prototypes. Besides that, the thermal resistance of prototype 4 heat sinks is even lower among all proposed prototypes. Therefore, prototype 4 would have a relatively higher heat transfer coefficient which results in improved power generation. Moreover, an increase in heat transfer coefficient is observed with an increase in the temperature difference of the cold and hot sides of a TEEH. Thus, on the cold side, a heat flow increases which benefits heat dissipation and in turn reduces the thermal resistance of the heat sink. Besides that, the developed prototypes on people show that power generation is also affected by factors like ambient temperature, person's activity, and wind breeze and does not depend on the metabolism. A different mechanism has been explored to maximize the power output within a 16.0 cm^2 area, in order to justify the wearability of the energy harvester. Furthermore, it is observed that during the sunlight, any material covering the TEEH would improve the performance of prototypes. Prototypes are integrated into jacket and studied extensively. The TEEH system was designed to produce a maximum delivering power and power density of $699.71\text{ }\mu\text{W}$ and $43.73\text{ }\mu\text{W}/\text{cm}^2$, respectively. Moreover, the maximum voltage produced is 62.6 mV at an optimal load of $5.6\text{ }\Omega$. Furthermore, the TEEH (prototype 4) is connected to a power management circuit of ECT310 and LTC3108 and has been able to power 18 LEDs.

1. Introduction

Thermoelectric energy harvesters (TEEHs) can convert heat energy into electricity based on the Seebeck effect. In this case, the motion of charge carriers (electrons and holes) leads to a temperature difference across the device [1]. The thermoelectric energy harvester (TEEH) demand is increasing over recent decades, especially in personal gadgets and implantable [2] wearable biomedical devices [3, 4]. Immense reduction in portable device power consumption has improved battery's drainage duration in personal electronic gadgets. However, electronic devices, which operate continuously, require repeated recharging and replacement of bat-

teries, which may cause reliability issues during operation and monitoring. Consequently, such limitations have motivated researchers to look for environment-friendly and self-sufficient energy sources [5]. Several techniques have been adopted for energy harvesting but all have their own drawbacks; for instance, solar energy may not be available at night or not that effective during cloudy conditions. Similarly, a motion-based energy harvester requires continuous mechanical motion, which may not be suitable for patients. Radio frequency (RF), unlike other energy sources, provides continuous power but its dependency on distance from the transmitter becomes a major issue. Keeping in view all above, to overcome the operational issues on account of

TABLE 1: Power requirements of wearable biomedical devices.

Type of wearable device	Measurement activity	Power consumption (mW)	Operating voltage (V)	Battery's life	Ref.
Electrocardiogram (ECG)	Cardiac activity	500	3.3	10 hours	[7]
Electroencephalography (EEG)	Brain activity	2.5	3	1 week	[8]
Pulse oximeter	O ₂ /CO ₂ concentrations/saturations	0.062	3	1 week	[9]
Blood pressure sensor	Blood pressure	0.385			[10]
Pedometer	Step count	25.2			[11]
Hearing aid	Sound pressure level	1.4	1	7-10 days	[12]
Glucose sensor	Sugar	0.003		1 week	[13]
Pacemaker	Correct an abnormal heart rhythm	0.008	2.8		[14]

TABLE 2: Material thermoelectric properties.

Materials	Type	Operating temperature (°C)	Maximum figure of merit (ZT)	Thermal conductivity (W/mK)	Seebeck coefficient (μV/K)	Electrical resistivity (μΩm)	Ref.
PbTe	p, n	500-700	0.75-0.85				[21]
Bi _{0.5} Sb _{1.5} Te ₃	P	150	1.4		410		[22]
Bi ₂ Se _{0.3} Te _{2.7}	N	420-515	1.0	1.10	157	9.43	[23]
Bi ₂ Te ₃	p, n	150	0.8	0.75	150	12.2	[24]
Zn ₄ Sb ₃	P	150-500	1.3	8			[25]
CeFe ₄ Sb ₁₂	P	400-700	0.8	28			[26]
CoSb ₃	N	550-600	0.8-0.9				[26]
SiGe	p, n	700-900	0.6-1.0	n-31.5, p-31.2	n-57, p-103		[27]

continuous power supply, a self-powered energy harvesting system, integrated into the biomedical wearable gadgets, will do the needful. Numerous research studies have focused on reducing the power consumption of the micro-electro-mechanical system (MEMS) and microelectronics for wearable biomedical sensors. Table 1 shows the operating features of wearable biomedical monitoring devices, such as (1) electrocardiogram (ECG) which is used for cardiac activity, (2) electroencephalography (EEG) which measures brain activity, (3) pulse oximeter which monitors oxygen saturation, (4) blood pressure sensor which is utilized to take blood pressure readings, (5) glucometer which is needed for sugar measurement, (6) hearing aid which is necessary for deaf people, and (7) pacemaker which is implanted in heart patients [6] to control an abnormal heart rhythm. Typically, the power requirements for wearable biomedical devices range from 0.003 to 500 mW, which can easily be produced by energy harvesting technology.

Thermoelectric energy harvesters (TEEHs) are developed and produced based on operating temperatures, ceramics [15], alloys [16], bulk material [17], complex crystals, oxide materials [18, 19], and nanocomposites. Table 2 provides the main features of the materials used in the production of TEEHs. Within the range of normal daily temperature, a suitable TEEH material is Bi₂Te₃. Development of high-temperature TEEH materials is expensive, but Bi₂Te₃ is rather economical and operates at room or sunny day temperature. The Seebeck coefficient helps to maximize the energy conversion for Bi_{0.5}Sb_{1.5}Te₃ and as in

the acceptable range for Bi₂Te₃ material. Furthermore, lowering the thermal conductivity of the material, the better are results to maintain heat at junctions to maintain large temperature difference across the TEEH and so to minimize losses through the thermoelectric material [20].

Harvesting the body's heat opens up a new era of self-powered wearable devices. It is considered a more reliable energy source for life-long operation of electronic gadgets and devices, increasing compliance and safety [28]. Wearable energy harvesters are an alternative to battery-based wearable devices [29]. For TEEHs, the human body is a great source of thermal energy and generates heat from metabolic functions [30]. Usually, a human body produces 100 to 525 W of thermal energy which can be converted into electrical power [31]. Wearable TEEH is an appropriate energy harvesting technology for power generation from the human body to operate wearable electronic devices.

Considerably, TEGs have been widely used throughout commercial and industrial levels. Starting from watches, automobiles, and ending in spacecraft [32]. Wang et al. [33] reported a TEEH for human body applications based on a surface micromachined poly-SiGe thermopile. The wearable TEEH produced an open-circuit output voltage of 0.15 V. Wabiah et al. [34] developed a TEEH of 9 cm² size for powering biomedical devices using body's heat. The developed device on wrist produced a power of 20 μW at 22°C room temperature. Leonov et al. [35] developed a TEEH for applications of biosensors. The power density obtained by mentioned TEEH is 20 μWcm⁻³. Similarly,

Mitcheson [36] reported the TEEH that produced sufficient power to operate a hearing aid device. Lay-Ekuakille et al. [37] fabricated a Velcro strap for application of wearable gadgets for different locomotion activities which are performed, such as walking and jogging. The output power achieved is 0.5 mW for a temperature difference of 8.5°C. For power improvement efficiency, a heat sink is placed on the cold side of the TEEH [38].

Nowadays, TEEH-based wearable devices are commercialized and are available for personnel usage. The most recently powered TEEHs in the market are smart watches. The first one is ThermaTron [39], which is developed by Bulova; however, it could not capture the market because of the high price of \$2000; further advancement in the field brought another smart watch into market with features like step tracking, calorie counting, and sleep monitoring which have been developed by Menlo Park startup [40] with a retail price of \$160. Matrix PowerWatch is a continuation of prior smart watches, available in the market for \$199 [41], with functions of sleep and steps tracking and calorie counting. Moreover, the first ever medical wearable device powered by TEEH is a pulse oximeter (SpO₂ sensor) [42] developed and fully powered by a watch-style TEEH using commercial BiTe thermopiles. The device is used to measure an oxygen content in arterial blood. The developed TEEH can produce a power of more than 100 μ W. Torfs et al. used a module TES1-12704 [43] for wearable TEEH. The power production for the TEEH is from 5 to 50 μ W. The first ever μ -TEEH-based wrist watch [44] was fabricated by a Japanese company which is composed of 104 thermocouples with an overall size of 2 mm $\times$ 2 mm $\times$ 1.3 mm. The maximum output electrical power generation is 22.5 μ W.

Further work on wearable TEEHs to power portable devices is extended by Proto et al. in [45]. The use of copper foam as the heat sink to increase the power capability of the TEEH is also reported. As a thermoelectric leg, inner temperature gradient is relatively small when a TEEH is worn; a copper foam is inserted to overcome the low power generation. TEEHs without a heat sink, with a copper foam and plate fin heat sink comparison, show that foam as a heat sink could reduce the thermal resistance at the cold side, which increased the temperature difference and output voltage generation. Furthermore, the TEEHs with the copper foam heat sink have the highest power-to-weight ratio, with a value of 30.73 μ Wg⁻¹ at $\Delta T = 45$ K, making it more comfortable to wear and produces almost similar power to the TEEH with a plate fin heat sink. Likewise, Shi et al. developed [46] a polymer-based flexible heat sink (PHS) comprised of a superabsorbent polymer (SAP) and a fiber which promotes liquid evaporation. The TEEH produces a power of 70 μ W and is integrated to drive the ECG module.

In the 1820s, Thomas J. Seebeck tested those two dissimilar metals, joined together by two legs at their ends, with temperature differences, and developed a magnetic field. The phenomenon is known as a Seebeck effect. The magnetic field occurs due to opposite currents in the two metal strip legs. The thermal difference between the materials causes an electric potential across the junction, producing current. If the temperature difference is maintained and even

FIGURE 1: Thermal model of a skin-based TEEH and an impact of resistance.

FIGURE 2: Electrical analog of the thermal equivalent circuit employed by the model.

if one junction is open, the current will not flow in the legs; however, a voltage can still be measured across the open circuit. This generated voltage (V) is Seebeck voltage. In TEEH, the generated voltage [47]

$$V = \alpha \Delta T \quad (1)$$

is directly proportional to the temperature difference ΔT and the Seebeck coefficient α of the thermoelectric (TE) material. The TEEH has p-type and n-type semiconductors, where the p-type has surplus holes and the n-type has surplus electrons to carry the electrical current. When heat flows from the hot surface to the cold surface, the free charges, electrons, and holes of the semiconductor start moving, and thus, the thermal energy is converted into electrical energy.

The efficiency of the device is affected because of three thermal resistances as shown in Figure 1; human skin leads to thermal resistance between the body core and TEEH. Secondly, due to the rough skin morphology, a thermal contact resistance exists at the skin-TEEH interface. Moreover, the ambient interface with TEEH attributes to the third thermal resistance. Finally, a thermal resistance is discussed in the three cases, which is between TEEH-ambient interface largely determined by convection. To increase the convection efficiency, a heat sink surface area is increased. However, wearing on a human body, this could be an issue due to discomfort. Therefore, a heat sink with small form factor is not acceptable while achieving an acceptable heat sink thermal resistance. For efficient harvesting of body heat, the three parasitic resistances must be reduced and the TEEH parameters need to be chosen accordingly.

TABLE 3: Properties of thermoelectric energy generator module (TEC1-12706).

Description	Feature	Value	Ref.
Dimension	$l \times w \times t$	$40 \times 40 \times 3.8$ mm	[49]
Weight		27 g	[49]
Ceramic substrate material	Al_2O_3 (aluminum oxide)		[49]
P-N junction	127 couples		[49]
Temperature difference	$\Delta T_{\max}$ ($^{\circ}\text{C}$)	66–75	[50]
Maximum electric charge	$Q_{\max}$ (W)	50–57	[50]
Maximum current	$I_{\max}$ (A)	6.4	[50]
Maximum voltage	$V_{\max}$ (V)	14.4–16.4	[50]
Seebeck coefficient	Volts per Kelvin (V/K)	40 mV/ $^{\circ}\text{K}$	[51]
Thermal resistance	Kelvin per watt (K/W)	1.9 $^{\circ}\text{K/W}$	[51]

In view of the above discussion, it is therefore favorable not to use a heat sink or to use a heat sink with a small form factor, while achieving an acceptable heat sink thermal resistance R_{hs} at this interface. Across these three thermal resistances, a sizable portion of temperature difference drops. Consequently, for efficient harvesting of body heat, it becomes critical to minimize these parasitic resistances and choose the TEEH parameters accordingly.

The drawback of wearable thermoelectric energy harvester (TEEH) is that the human thermal resistance depends on a heat flow of a TEEH in contact with the human skin. In case a human skin has high thermal resistance, it essentially would decrease the power generation so to avoid this issue improved prototypes are developed. The proposed heat sink mechanism on cold side improved the heat transfer coefficient which results in better output power.

Different mechanism has been explored to maximize the power output within a 16.0 cm^2 area, in order to justify the wearability of the energy harvester. Furthermore, it is observed that during the sunlight, any material covering of the TEEH would improve the performance of prototypes.

2. Modeling of TEEHs

Modelling a basic equivalent electrical circuit model for a TEEH is shown in Figure 2. In Figure 1, the analysis yields the following equation [48].

$$\begin{aligned} \frac{T_{\text{hot}} - T_{\text{cold}}}{R_{\text{TR}}} &= \frac{T_{\text{cvt}} - T_{\text{hot}}}{R_{\text{hot}}} + \frac{C_j}{2} - C_p, \\ \frac{T_{\text{hot}} - T_{\text{cold}}}{R_{\text{TR}}} &= \frac{T_{\text{cold}} - T_{\text{at}}}{R_{\text{cold}}} - \frac{C_j}{2} + C_p' \end{aligned} \quad (2)$$

where T_{cold} and T_{hot} are the temperatures of cold and hot sides of TEEH legs, respectively, R_{TR} is the thermal resistance of the legs of TEEH, the hot side resistance (R_{hot}) includes skin-TEEH contact resistance and vertical resistance through the substrate to the leg; ambient and core body/cloth temperatures are represented by the ideal voltage sources, T_{at} and T_{cvt} , respectively. C_p is a two-voltage-dependent current source representing cooling and heating resulting from the electrical current flowing through the

FIGURE 3: Photograph of prototype 1 TEEH integrated with the shoulder.

TEEH, where the voltage can be computed by $C_p = I\Pi$, where I is the current flowing through a junction and Π is the Peltier coefficient of the semiconductor.

Furthermore, Peltier coefficient is determined by Seebeck coefficient, α , and the junction temperatures, T_{cold} or T_{hot} , as $\Pi = \alpha T$. Moreover, $C_j/2$ are two current sources showing joule heating from an electrical current I , flowing through the legs once the generator is connected to an external load. The net heat generated due to the current is $C_j = I^2 R$, where R is TEEH leg resistance.

FIGURE 4: Photograph of prototype 2: (a) TEEH module, (b) heat sink, (c) heat sink integrated to TEEH module, and (d) TEEH and heat sink stitched into a jacket through a cotton fabric (developed prototype 2).

While R_{cold} is the cold side resistance, which is determined by the thermal heat sink resistance R_{hs} , vertical resistance through the substrate, and metallic cooling block resistance R_{mcb} , the ambient and core body/cloth temperatures are represented by the ideal voltage sources, T_{at} and T_{cbt} , respectively, and an extrinsic temperature differential is presented by $\Delta T_e = T_{\text{cbt}} - T_{\text{at}}$.

The open-circuit voltage of TEEH is given by the following equation:

$$V_{\text{oc}} = N(\alpha n + \alpha p)\Delta T_i, \quad (3)$$

where pairs of p-n legs N , αn , and αp are the Seebeck coefficients of the n-type and p-type legs, the electrical resistivity, ρ , of each TEEH leg of the material, and an intrinsic temperature differential $\Delta T_i = T_{\text{hot}} - T_{\text{cold}}$.

The model calculates ΔT_i for a given ΔT_e and uses this differential to calculate the power generated by the TEEH.

The source resistance, R_s of the TEEH is given by the following:

$$R_s = \frac{N}{2} \left(\rho_p + \rho_n \right) \frac{h}{W^2} + R_{\text{ext}}. \quad (4)$$

Each leg of TEEH is denoted by height (h) and width (w), where ρ_p and ρ_n are the electrical resistivities of P-

and N-type legs, and R_{ext} includes the contact resistance of the metal and the resistance of metal lines connecting the TEEH legs in series.

The power across the load can then be calculated as follows:

$$P_m = \frac{V_{\text{oc}}^2}{R_s((1 + R_L/R_s))^2}. \quad (5)$$

This paper investigates an energy harvesting technique from the human body using TEEH to achieve higher output voltage and power during different daily activities, under different environmental conditions and varying load situation. Four wearable prototypes have a novel architecture (attached to the shoulder). Moreover, a novel developed mechanism of prototype 4 is implemented for the first time. In prototype 4, the cold side of TEEH is integrated to Peltier cooling block, which is further integrated to a heat sink half filled with PF (water injected into PF) to improve the performance under both outdoor and indoor conditions. For the maximum energy extraction, Peltier cooling block and a heat sink are integrated into the same size TEEH that results in a very high-power density and reduced size of the developed harvester. Furthermore, ECT310 and LTC3108 performances were

FIGURE 5: Photograph of prototype 3: (a) PF cut through a surgical cutter, (b) heat sink half filled with PF, (c) TEEH attached to a heat sink with PF, (d) tap water injected into PF through a syringe, and (e) complete developed prototype 3.

FIGURE 6: Continued.

FIGURE 6: Photograph of prototype 4: (a) Peltier cooling block, (b) rubber tube for connectivity of Peltier cooling block and transfusion set, (c) rubber tubes connected to Peltier cooling block, (d) transfusion set, (e) two PVC bags are connected to Peltier cooling block through transfusion set, (f) inner side of jacket where PVC bags are to be hung with buttons, (g) inner side of prototype 4, and (h) front view of a complete developed prototype 4.

evaluated and integrated to the wearable TEEH to turn “on” 18 LEDs.

3. Development of a Self-Powered Jacket

Four TEEH prototypes have been developed and experimentally tested. A Peltier module TEC1-12706 is chosen for energy generation. An advantage of TEC1-12706 module is a large number of n-type and p-type elements that are integrated into a very small area for better operation and efficiency. Table 3 shows the main features of TEC1-12706 module.

3.1. Development of Prototype 1. Prototype 1 is TEEH (TEC1-12706) individually stitched into a wearable jacket on the shoulder as shown in Figure 3. A surgical cutter is used to cut the jacket equal to the size of TEEH. Then, a TEEH is placed and stitched in such a way that the hot side of the TEEH is facing the clothing (human body), whereas the cold side of the TEEH is exposed to environment.

3.2. Development of Prototype 2. In prototype 2, a TEEH (TEC1-12706) is integrated with a heat sink (aluminum) for better operation. As shown in Figure 4, a prototype 2 is comprised of TEEH module (Figure 4(a)), a heat sink (dimension of 4×4 cm) (Figure 4(b)), and the integrated prototype 2 (Figure 4(c)). The TEEH module is located inside the jacket and is not visible from the outside; only the heat sink can be seen protruding outside of the jacket’s fabric. Initially, the heat sink fins’ thickness and width are measured, and accordingly, the fabric is cut with a surgical knife and through these slots, the fins are passed out to face the environment. Then, the cotton fabric is stitched in between the two fabric layers of the jacket to hold the heat sink. The TEEH module is then integrated with a heat sink as shown in Figure 4(d). The heat sink on the surface of the jacket gives a stylish look, yet comfort is not compromised. This way, the heat sink will keep the cold side of the TEEH cold, whereas the hot side is kept warm because of the inner clothing on the human body.

3.3. Development of Prototype 3. In prototype 3, a slight addition is done, as shown in Figure 5(a). PF is cut into

FIGURE 7: Photograph of a TEEH integrated in a wearable jacket: (a) sitting, (b) walking, and (c) jogging on a treadmill.

0.5 × 4 cm size with a surgical cutter. Then, the heat sink is half filled with PF as shown in Figures 5(b) and 5(c). Afterward, the TEEH module is attached to a heat sink (with added PF) and is stitched into the jacket, and then, 12 ml of tap water is injected through a syringe (5 cc) (Figure 5(d)). In this prototype, half of the heat sink is left exposed to air, to keep the heat sink cool, in case of drying of PF during sunlight. Prototype 3 attached to the jacket is shown in Figure 5(e).

3.4. Development of Prototype 4. Prototype 4 is an extension of prototype 3. The prototype 4 TEEH module integration is shown in Figure 6, where initially rubber tube (Figure 6(b)) was inserted inside the inlet and outlet of Peltier cooling block (Figure 6(c)). Then, a transfusion set (Figure 6(d)) connects the two PVC bags with a Peltier cooling block (Figure 6(e)).

PVC bags are filled with 100 ml of ethylene glycol liquid injected through a syringe (5 cc). Furthermore, on top, the cold side of the TEEH has a Peltier cooling block which is further attached to a heat sink half filled with PF, while the hot side on the inner side of the jacket is facing the human body. Thus, the integrated module includes TEEH, Peltier cooling block, and a heat sink. Moreover, two PVC bags are connected to an inlet and outlet of Peltier cooling block through a transfusion set. The arrangements allow the ethylene glycol liquid to flow from one PVC bag to another through a Peltier cooling block. The features of the developed prototype are to control the liquid flow of ethylene glycol with a roller clamp. Another feature is to detach and interchange the PVC bags to change the liquid flow direction. After integration all the parts, a complete prototype is shown in Figure 6(g).

4. Experimental Characterization

For performance evaluation, all four prototypes are individually tested on subject body part: the shoulder of a wearable jacket. The experimentation is performed outdoor in sunlight, night, and indoor. Each experiment was performed for 20 min during sitting, walking, and jogging to evaluate the performance of TEEH in all scenarios. Experiments while walking and jogging were performed at 5 km/h and 7 km/h, respectively, on a treadmill. In prototype 1, a temperature sensor is used to measure the temperature difference of the cold and hot sides of TEEH, whereas, in the rest of the prototypes, the temperature difference of the hot side and a heat sink is monitored. The voltage is measured at a specific time interval (i.e., after 1, 3, 6, 9, 12, 16, and 20 min). A photograph of sitting (Figure 7(a)), walking (Figure 7(b)), and jogging (Figure 7(c)) experimentation is shown in Figure 7.

4.1. Experimentation of Developed Prototypes. The experimentation of a wearable TEEH-based jacket at shoulder position was performed during sitting, walking, and jogging activities of the subject. The experimentation is conducted during winter (month of November) inside and outside the lab on a treadmill for 20 min, in which load voltage and

FIGURE 8: Power of prototypes plotted against load resistance.

power levels are measured after 1, 3, 6, 9, 12, 16, and 20 min. The prototypes are characterized at variable load resistance as shown in Figure 8 where maximum power levels are obtained at an optimal load resistance of 5.6 Ω.

Moreover, the output of the four prototypes is also compared. For all four prototypes, the load voltage measurement as a function of time for indoor sitting, walking, and jogging activities is depicted in Figure 9. The readings are obtained from the TEEH at the shoulder. All experimentation is performed during the winter season in November to evaluate prototypes in cold weather, whereas hot weather experimentation is justified by sunny day performance evaluation.

During sitting TEEH, Figure 9(a) shows the maximum voltage generation from the shoulder as for prototype 1, prototype 2, and prototype 4 voltage increases from 6.6 mV to 7.7 mV, 10.1 mV to 12.6 mV, and 48.4 mV to 48.6 mV, respectively, whereas, for prototype 3, the voltage decreases from 40.3 mV to 19.7 mV. The decrease in voltage over 20 min time is due to the dryness of PF. The voltages at the shoulder while sitting can be seen in Figure 9(a), respectively.

The load voltage measurements (indoors) while walking at a speed of 5 km/h on a treadmill are depicted in Figure 8(b). Almost similar pattern is seen, the voltage increases for all prototypes from 1 min to 20 min except for prototype 3. For prototype 1, at the shoulder, voltage increases from 7.6 mV to 8.7 mV, as shown in Figure 9(b). Similarly, prototype 2 voltage increases from 12.5 mV to 13.5 mV. The same experimentation is performed for prototype 3, and the voltages appeared at the shoulder are recorded as 46.6 mV to 37.5 mV which can be seen in Figure 9(b). A slight decrease in voltage with time is due to the dryness of water in PF which results a decrease in heat transfer coefficient and heat dissipation. In the case of prototype 4, for the TEEH at the shoulder, the voltage decreased from 49.2 mV to 43.4 mV due to the movement of the displacement in TEEH causing a decrease in heat transfer

FIGURE 9: Load voltage output of all four prototypes during indoor experimentation: (a) resting, (b) walking, and (c) jogging.

coefficient. The issue can be resolved by a proper placement of a TEEH or controlled movement of a subject.

In jogging, again, similar experimentations are performed as shown in Figure 9(c). In prototype 1, the load voltage at the shoulder increases from 8.6 mV to 10.6 mV. For prototype 2, the voltage increases for the shoulder from 16 mV to 20.2 mV. Unlike the previous voltage results for prototype 3, the voltage increased in the case of jogging at the shoulder possibly due to warmth on the hot side causing an increase in temperature of TEEH but decreased during walk and sitting due to decrease in temperature. The decrease in temperature is recorded due to drying of PF in a heat sink. For prototype 4, the voltage increased for the shoulder from 44.2 mV to 48.7 mV.

TEEH when integrated with the shoulder produced a power level as shown in Figure 10 while sitting on the chair; during rest and jogging. It can be seen in Figure 10 that four prototypes are differentiated by four colors and comparatively evaluated at 1, 3, 6, 9, 12, 16, and 20 min.

The results show that PF dryness depreciates the performance improvement, and sustainability is only possible in case of continuous injection of water. As can be seen in Figure 10, the temperature difference is different for each prototype because of different environmental temperatures and differences in prototype design.

During experimentation, performance for the shoulder (Figure 10(a)) resulted in an increase in the power of prototype 1 from 7.7 μ W to 10.58 μ W. In prototype 2, the power

FIGURE 10: Power evaluation of all four prototypes during indoor experimentation: (a) resting, (b) walking, and (c) jogging.

level for the shoulder increased from $18.21 \mu\text{W}$ to $69.3 \mu\text{W}$ during 20 min rest. Contrary to the previous cases, in prototype 3, the power decreased in Figure 10(a) from $290 \mu\text{W}$ to $69.3 \mu\text{W}$, mainly because of the drying of PF. On the other hand, prototype 4 produced a power of $360 \mu\text{W}$ on the shoulder at 20 min.

Experimentation is performed during walking on a treadmill at a speed of 5 km/h which is depicted in Figure 10(b). Results, as can be seen in Figure 10(b), for prototype 1 on the shoulder show an increase in power levels from $10.31 \mu\text{W}$ to $13.51 \mu\text{W}$. Furthermore, Figure 10(b) shows that in prototype 2, the power production increases

FIGURE 11: Load voltage evaluation of all four prototypes during outdoor (night) experimentation: (a) resting, (b) walking, and (c) jogging.

from $27.9 \mu\text{W}$ to $32.54 \mu\text{W}$, respectively. For prototype 3, interestingly, Figure 10(b) shows power generation at the shoulder which decreases from $387.77 \mu\text{W}$ to $252.11 \mu\text{W}$. Like previously, prototype 4 on the shoulder produced a power of $488.44 \mu\text{W}$ at 12 min (Figure 10(b)). It is observed that the output power is decreased to $336.35 \mu\text{W}$ at 20 min because of sweating that results in the reduction of the body temperature due to cooling effect causing a decrease in heat transfer coefficient.

Furthermore, experimentation for jogging on a treadmill is performed at 7 km/h speed. For prototype 1 as shown in Figure 10(c) at the shoulder, power levels increase from

$13.20 \mu\text{W}$ to $20.44 \mu\text{W}$, whereas, for prototype 2, at the shoulder, power generation increases from $45.7 \mu\text{W}$ to $72.86 \mu\text{W}$. Furthermore, regarding prototype 3, the power output level increases from $324 \mu\text{W}$ to $298.71 \mu\text{W}$ for the shoulder (Figure 10(c)). If the experimentations were prolonged for a longer period, there would have been a definite more decrease in power, since the water in PF would dry with time, but the experimentation is confined to 20 min. Lastly, prototype 4, as shown in Figure 10(c), the shoulder gives power of $423.5 \mu\text{W}$ at 20 min.

Experimentation for load voltage is repeated outdoor at night (11:00 pm) and is depicted in Figure 11 during sitting,

FIGURE 12: Power evaluation of all four prototypes during outdoor (night) experimentation: (a) resting, (b) walking, and (c) jogging.

walking, and jogging activities. While sitting, an increase in voltage for TEEH at the shoulder is achieved for all prototypes except prototype 3, as shown in Figure 11(a) which is recorded to decrease from 42.6 mV to 22.7 mV. Moreover, in the case of walking, the voltage output of all prototypes increased on the shoulders; however, during jogging on the treadmill, again, the TEEH on a shoulder shows that the voltage generation for the four prototypes has increased. Comparatively, during jogging, outdoor at night, a maximum voltage is generated for prototype 4. The voltage for all three scenarios (sitting, walking, and jogging) is evaluated

in which prototype 4 outstands all other prototypes. The maximum voltage of 62.5 mV is produced by TEEH (prototype 4) at the shoulder. The result shows that prototype 4 performs better than any other prototypes with a capability to power any wearable device.

Outdoor experiments, during the night, on specified body part, i.e., shoulder while sitting, walking, and jogging, are carried out. Respective results have been computed in Figure 12.

While sitting, for prototype 1, an increase in power is observed, i.e., power at the shoulder from $24.44 \mu\text{W}$ to

FIGURE 13: Load voltage evaluation of all four prototypes during outdoor (sunlight) experimentation: (a) resting, (b) walking, and (c) jogging.

34.5 μW (Figure 12(a)). Likewise, for prototype 2, the power levels increased at the shoulder from 38.06 μW to 86.42 μW (Figure 12(a)), respectively. In prototype 3, a decrease in power from 324 μW to 92 μW at the shoulder (Figure 12(a)) has been recorded. Similarly, in prototype 4, power at the shoulder followed a similar trend as observed in previous cases, wherein power increased at the shoulder from 350.44 μW to 430.5 μW , as shown in Figure 12(a).

Experimentation for walking was performed on a treadmill; the results computed for prototype 1 showed an increase in power level for the shoulder which increases

from 34 μW to 59.15 μW (Figure 12(b)). Results were compiled for prototype 2 while walking, which follows exactly the same pattern that of prototype 1, where the increase in power for the shoulder is 90.4 μW to 143 μW (Figure 12(b)). In prototype 3, a slight decrease, i.e., 590 μW to 423 μW (Figure 12(b)), in power level at the shoulder is encountered. In the experimentation as discussed earlier, the decrease in power occurs due to decrease in heat transfer coefficient.

Similarly, during jogging, in prototype 1, the power produced by TEEH at the shoulder (Figure 12(c)) increases from 54.68 μW to 75.77 μW , while in the increase in

FIGURE 14: Power evaluation of all four prototypes during outdoor (sunlight) experimentation: (a) resting, (b) walking, and (c) jogging.

prototype 2, the power increase for the shoulder (Figure 12(c)) was observed from $171.6\mu\text{W}$ to $222.51\mu\text{W}$, whereas the increase of power in prototype 3 and prototype 4 for the shoulder is $307.54\mu\text{W}$ to $509.20\mu\text{W}$ and $600.71\mu\text{W}$ to $699.71\mu\text{W}$, respectively. The prototype 3 and prototype 4 powers for the shoulder can be seen in Figure 12(c).

While sitting outdoor on a sunny day, in the voltage of prototype 1, an increase is recorded for the shoulder (Figure 13(a)) from 7 mV to 7.1 mV . Similarly, during sit-

ting experimentation for prototype 2, an increase in voltage is observed for the shoulder (Figure 13(a)) which is measured to be 7.8 mV to 8.2 mV . In the case of prototype 3, as can be depicted in Figure 13(a), the voltage decreased for the shoulder due to the dryness of water in PF. Furthermore, an injection of water can improve the performance of TEEH; otherwise, the dryness of PF will degrade the performance of TEEH with time. Like previously, in prototype 4, the voltage result obtained for prototype 4 remains almost the same which could be due to the

early fresh breeze stopped blowing causing a decrease in temperature difference.

Similarly, during walking for the 20 min experimentation of prototypes 1 and 2, an increase in voltage is observed for the TEEH attached to the shoulder (Figure 13(b)), whereas, in prototype 2, an increase in voltage is noted for TEEH attached to the shoulder (Figure 13(b)). The results show the increase in voltage for TEEH attached to the shoulder which is measured to be 13.1 mV to 21 mV.

Furthermore, during jogging, prototype 1 voltage for the shoulder (Figure 13(c)) increased from 12.9 mV to 13 mV. Similarly, in the shoulder Figure 13(c), 20 min experimentation is performed which results in an increase in voltage level for prototype 2 from 13.8 mV to 13.9 mV, while the voltage produced by TEEH at the shoulder (Figure 13(c)) is 25.3 mV to 24.7 mV. The decrease in voltage for prototype 3 has occurred due to dryness of PF. Lastly, in prototype 4, the shoulder (Figure 13(c)) voltage increased from 34.2 mV to 38.3 mV.

In the next phase, the experimentation of TEEH is performed in an open environment at 7 km/h on a bright sunny day. Results compiled for prototype 1, in the case of the shoulder (Figure 14(a)), showed a similar trend; i.e., the power of the shoulder increased from 8.75 to 9 μ W.

In the case of prototype 2, a TEEH at the shoulder (Figure 14(a)) power varies between 10.86 μ W and 12 μ W due to the fresh breeze. In prototype 3, in a TEEH at the shoulder, as can be seen in Figure 14(a), the power decreased from 61.77 μ W to 9.77 μ W. The result shows that a heat sink filled half with PF degrades the performance of TEEH after the injected water dries in sun. If a PF inserted in a heat sink is continuously filled with water, this will help sustain power, but with dry PF, the power would decrease even more than recorded, as no air flow will be possible through the heat sink fins. For prototype 4, the power decreases for the shoulder (Figure 14(a)) from 235.3 μ W to 150.17 μ W. Shoulder reading is taken after spending some time in the sun which has an impact on the temperature difference due to which power decreased.

During the walk, for prototype 1, experimentation of TEEH was performed at the shoulder; the power increases from 28.35 μ W to 30.17 μ W. The increase in power is recorded due to a mild fresh breeze. Moreover, experimentation for prototype 2 was performed for TEEH at the shoulder (Figure 14(b)) power which increases from 30.64 μ W to 78.75 μ W, whereas, for prototype 3, a TEEH on shoulder power decreased from 92.01 μ W to 70 μ W due to the drying of PF in the sun. To the similar experimentation for prototype 4, as seen in Figure 14(b), when the TEEH is attached to the shoulder the power decreased from 287.14 μ W to 199.2 μ W.

Similar experimentation for jogging on a treadmill was performed at 7 km/h speed. For prototype 1, as shown in Figure 14(c), the power on shoulder almost remained 29 μ W for the entire 20 min experimentation, whereas, for prototype 2, shoulder (Figure 14(c)) power generation increases from 34 μ W to 34.5 μ W. Similarly, in prototype 3, as can be depicted in Figure 14(c), the shoulder power decreases from 114.3 μ W to 108.9 μ W. Moreover, in proto-

FIGURE 15: LTC3108 and ECT310 output open-circuit voltage comparison based on varying of input voltage.

type 4, a TEEH integrated on the shoulder (Figure 14(c)) is recorded to increase from 208.8 μ W to 261.94 μ W.

5. DC Power Control from the Developed TEEHs

DC-DC converter increases or decreases the voltage level as per the desired requirement. For this purpose, two DC-DC converters (EnOcean ECT310 and LTC3108 converters) are evaluated based on performance and used in the developed wearable TEEH jacket. The ECT310 module operates at as low as 20 mV for the 2 K temperature difference and has an input impedance less than 12 Ω . Similarly, LTC3108 step-up converter circuit has a storage capacitor and variable output voltage selectivity pins. A 1 : 100 transformer is used with LTC3108 to increase the voltage level to operate at 20 mV. After integration of 1 : 100 transformer, it has typically an input impedance less than 15 Ω .

ECT310 and LTC3108 are evaluated based on open-circuit voltage, load voltage, and power performance. Initially, both DC/DC converters are compared based on an open-circuit voltage while varying an input voltage as shown in Figure 15. The output is almost the same for both DC/DC converters, but the difference occurs when the load voltage and power are evaluated. As can be depicted from Figures 16(a) and 16(b), the voltage and power of ECT310 are better than those of LTC3108. The maximum power produced by ECT310 DC-DC converter integrated with a jacket is 189 μ W at an optimal load of 100 k Ω , whereas in LTC3108, the maximum power production is 81.22 μ W at 100 k Ω .

Furthermore, at an ambient temperature of 14°C, experimentation was performed to charge a 1.2 V AA size 2400 mAh battery. As shown in Figure 17, during 100 min experimentation, ECT310 charged the battery fast and slightly more than LTC3108 DC/DC converter. In 100 min experimentation, an ECT310 DC/DC converter charged the battery approximately 900 mV, while TEEH connected

FIGURE 16: LTC3108 and ECT310 comparison based on (a) load voltage and (b) power.

to LTC3108 could charge the battery only 750 mV. As the battery is 2400 mAh, and the current drawn by the rechargeable battery is only $30 \mu\text{A}$ to charge the battery, so the experimentation of charging battery is limited to a specific period of time to represent the charging potential of a proposed TEEH.

Then, 18 light emitting diodes (LEDs) are turned “on” using TEEH connected to LTC3108 and ECT310 DC/DC converters. LEDs are connected to a wearable TEEH at the shoulder (Figure 18(a)) through LTC3108. Similarly, ECT310 is also attached to wearable TEEH at the shoulder (Figure 18(b)). As can be depicted in Figure 18, 18 LEDs are turned “on” with ECT310 DC-DC converters, but in the case of LTC3108, the LEDs blink due to low power production. Thus, it shows that prototype 4 works efficiently and harvests the maximum power to operate 18 LEDs with ECT310.

6. Environmental Effect

Experimentation result shows a drastic improvement in power outside during the night especially during jogging, and the maximum power of $699.71 \mu\text{W}$ is achieved. Even indoors, the power level of $423.5 \mu\text{W}$ is obtained during jogging. In both cases, a maximum power is generated for TEEH stitched on the shoulder. However, in sunlight, the power is not effectively harvested as in the prior cases. The power during sunlight produced is $261.94 \mu\text{W}$. This issue could be resolved in case of protection of the device from direct sunlight exposure by covering the device with shaded clothing pieces.

7. Comparative Analysis

A comprehensive comparison of TEEHs reported in the literature is shown in Table 4. The harvesters are assessed based on important parameters, such as material, flexible/

FIGURE 17: Charging time of AA size 2400 mAh 1.2 V battery.

rigid type, TEEH dimensions, generated voltage, TEEH power, and power density. The thickness and large size of TEEH material increase the power of the harvester which can be observed from [52, 53]. Less power is produced from relatively small or flexible size TEEHs in [54–58]. However, the reported harvester in [57] can generate more power by increasing the size of TEEH. The TEEH shows the size may largely contribute to the power of TEEH. Furthermore, the developed prototypes are compared with [52–58] based on size of the reported TEEHs, as shown in Table 4. The size of reported TEEHs in [51, 56, 57] is smaller than the developed TEEH, but there, the power production is not even 10% of the prototype 4 developed in this work. Moreover, the developed prototype 3 and prototype 4 power densities are much better than any reported device till date to the best of our knowledge.

FIGURE 18: 18 LEDs are turned on after integration of TEEH with (a) LTC3108 and (b) ECT310.

TABLE 4: Comparison of wearable TEEHs.

TEEH module material	Material	Type	Size (cm ²)	Voltage (mV)	Power (μW)	Max temp diff. (K)	Power density (μW/cm ²)	Ref.
TES1-12704 (aluminum oxide)	Bi ₂ Te ₃	Rigid	9		50		5.55*	[52]
	Bi ₂ Te ₃ and Sb ₂ Te ₃	Flexible	32*	10	0.015	35	0.00046*	[54]
	Bi _{0.5} Sb _{1.5} Te ₃ and Bi ₂ Se _{0.5} Te _{2.5}	Flexible		182.3	3900	50		[55]
	Bi ₂ Te ₃	Flexible	12*	48	8.3	11	0.691*	[56]
		Flexible	54.11*	80	450		8.31*	[57]
Ceramic plate TES1-12706 (aluminum oxide)	Bi _{0.5} Sb _{1.5} Te ₃ and Bi ₂ Se _{0.3} Te _{2.7}	Flexible	1.5*	14.1	0.224	15	0.149*	[58]
	Bi ₂ Te ₃	Rigid	10	108	285	2.16	28.5	[53]
	Bi ₂ Te ₃	Rigid	16	20.6	75.77	277.15	4.735*	Prototype 1
	Bi ₂ Te ₃	Rigid	16	35.3	226.31	280.15	14.14*	Prototype 2
	Bi ₂ Te ₃	Rigid	16	53.4	590	281.15	36.875*	Prototype 3
TES1-12706 (aluminum oxide)	Bi ₂ Te ₃	Rigid	16	62.6	699.71	281.15	43.73*	Prototype 4

*Calculated.

In the literature review, the voltage produced by the reported TEEHs ranges from 10 to 182.3 mV, whereas prototype 1, prototype 2, prototype 3, and prototype 4 voltages are 20.6 mV, 35.35 mV, 53.4 mV, and 64.3 mV, respectively.

The voltage generated in [55] is more than the proposed prototypes, as it is an open-circuit voltage, unlike the proposed prototypes which are measured at an optimal load resistance of 5.6 Ω. Furthermore, the circuitry required for

boosting voltage would maintain 3.3 V, which is normally required to operate the wearable devices. The power as reported in the literature of TEEHs ranges between $0.015\ \mu\text{W}$ and $3900\ \mu\text{W}$, where the power produced in [55] is high, since the reported TEEH has comparatively low internal resistance. In the developed prototype, the internal impedance is higher, which consequently reduces the power generation. The developed prototype 4 in this work produced a power of $699.71\ \mu\text{W}$, which is better than the reported TEEHs except for reference [55]. A TEEH reported in [52] is rigid and produces only $50\ \mu\text{W}$. It is quite clear in the reported literature that our device performs much better than all others except [57], which has a bigger size than the developed prototypes.

8. Conclusion

The results are promising, and the combination of the three thermoelectric energy harvesters (TEEHs) can easily power the wearable devices. Even a single TEEH can power a wearable device for most times of the day. Harvesting human body heat is a promising alternative to power electronics and sensors. In this study, four different self-powered wearable jacket prototypes are developed and experimentally validated. All prototypes are placed at the jacket shoulder. During experimentation, the maximum power and power density obtained are $699.71\ \mu\text{W}$ and $43.73\ \mu\text{W}/\text{cm}^2$, respectively, at an optimal load of $5.6\ \Omega$. The developed TEEH can fulfill the power requirement of pulse oximeter, blood pressure sensor, glucose sensor, and pacemaker especially during winter (indoor or outside at night), whereas, on a sunny day, hybridization of the prototype is important to power the sensors. ECT310 and LTC3108 are compared and evaluated based on performance. Moreover, prototype 4 is integrated with ECT310 and LTC3108 power management circuits to power 18 LEDs.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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