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Wearable thermoelectric generators for human body heat harvesting

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HIGHLIGHTS

- An optimized thermoelectric generator was designed for body heat harvesting.
- Optimized heat spreaders were implemented on both sides of the TEG.
- The generator has small form factor appropriate for wearable applications.
- The power generated on different parts of the human skin were reported and compared.
- The upper arm was identified as the proper location for powering EKG sensors.

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ABSTRACT

A thermoelectric generator (TEG) can be used to harvest electrical energy from human body heat for the purpose of powering wearable electronics. At the NSF Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST), TEGs are one of the enabling technologies being explored to advance the center's mission of creating wearable, self-powered, health and environmental monitoring systems. As part of this effort, an exploration of the relevant parameters for maximizing the wearable TEG power output from the body heat and maintaining the body comfort is particularly important. For this purpose, the heat from the body must be directed into TEG with minimal loss, the generator must be designed for maintaining a high temperature differential across the thermoelectric material, and the generator must have a small form factor to maintain the body comfort. In order to address these requirements, an optimum TEG design was developed and experiments were conducted both on a temperature-controlled hot plate and on different body locations including the wrist, upper arm, and chest. The TEG was further fabricated into a T-shirt and the power was recorded for different human activities. Comparison of the experiments on various body locations and on the T-shirt yielded the highest to lowest power generated on the upper arm, wrist, chest and T-shirt, respectively. The prospect of powering a wearable electrocardiogram sensor by a TEG on the upper arm is discussed.

1. Introduction

Recently, thermoelectric generator (TEG) devices have emerged as a viable alternative for certain power generating applications [1–3]. Interest has grown in the TEG energy due to its ability to produce power from low grade or waste heat leading to advancements in the growing field of Green Technologies. This new field of technology involves producing less waste by using renewable resources for power generation while creating and producing sustainable energy resources. TEGs can reduce or eliminate use of batteries in applications where a heat source exists. Since batteries have a limited lifetime before having to be replaced or recharged, TEG devices give the ability to produce uninterrupted power by charging or replacing batteries. A notable progress in the development of TEG devices is their recent use in the automotive industry [4]. TEGs are also being developed for effective recovery of a vehicle's waste heat to enhance fuel efficiency and reduce greenhouse gas emissions [5–7]. Despite the recent progresses on various applications of thermoelectric devices, there has been much less attention given to the development of body heat harvesting via TEG devices. Only recently, interests in TEGs have grown due to their wearability and functionality in different applications [8,9]. In particular, body heat harvesting has taken attention for powering wearable sensors and electronics [10,11]. By eliminating the use of a battery, wearable devices will be more reliable due to their ability to harness consistent and uninterrupted energy from body heat. Furthermore, since fewer batteries will be used, there will

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be a reduction in hazardous chemicals being released into the environment from the battery construction. Within the ASSIST Center, TEGs are one of the enabling technologies being explored to advance the center's mission of creating wearable, self-powered, health and environmental monitoring systems [12,13].

One major progress for body heat harvesting has been the development of flexible TEGs for wearable applications [14–16]. By using a flexible TEG, better contact between the TEG and skin resulting in less thermal interface resistance is possible, which would consequently enhance the temperature differential across the TEG. Several studies have demonstrated wearable TEG devices for human body heat harvesting. Weber et al. proposed a coin-size coiled up wearable TEG device [17]. The device could generate only 0.8 $\mu W/cm^2$ power at a temperature difference of 5 K. Considering the typical temperature difference between the skin and ambient temperature is ~1 K, we expect that the power will be even smaller on the body. Jo et al. demonstrated a flexible TEG device with PDMS and PMMA mold [15]. The fabricated TEG could generate 2.1 μW power on the human body with a 50 mm × 50 mm device area, which makes the output power only 0.084 $\mu W/cm^2$. Lu et al. reported a silk-fabric based flexible TEG device [16]. The maximum power output on the human body was again very small in the range of 15 nW with a 4 cm × 8 cm device area, which makes the output power 0.47 nW/cm^2. While the form factor of the flexible devices were suitable for wearable applications, the overall power densities were too low to be utilized for viable sensor technologies. This major problem that is faced when integrating a TEG into clothing or wearable technology is that the efficiency of the device is related to various factors such as: device structure, body heat content, air speed in respect to the person, basic human anatomy for a man and woman, and placement on the human body [18].

In order to increase the output power of the device, we propose and demonstrate wearable TEG devices with optimized heat spreaders. Advantages to the heat spreader use include better dissipation of heat and cooling throughout the TEG device, increasing its overall performance for on body applications as well as durability to be worn on various parts of the body, including the upper arm and T-shirt. By integrating the device into clothing on the body and using the sandwich design, the device was subjected to optimal airflow, which increased the overall temperature gradient, resulting in higher power output. The TEG devices were finally tested on different parts of the body to determine which part is more efficient overall considering both the skin temperature and the ambient air cooling to power the device. By using a TEG integrated with optimized heat spreaders, the maximum output power reached 6 $\mu W/cm^2$ at no motion and 20 $\mu W/cm^2$ at normal walking speed. The output power is adequate to run small environmental and health monitoring devices such as accelerometer, ozone sensor and electrocardiogram (EKG) sensor. The power consumption of those devices are approximately 10, 150 and 50 μW, [19] respectively, which can be provided with our optimized TEG device with areas of 0.5, 7.5 and 2.5 cm^2, respectively.

2. Device design, fabrication and optimization

2.1. Device design and fabrication

The basic structure of a TEG device is schematically shown in Fig. 1. The thermoelectric (TE) elements are alloys based on n and p type bismuth telluride each measuring approximately 0.7 mm × 0.7 mm × 1.2 mm. These TE legs are sandwiched by two Aluminum Oxide ceramic headers. The TE elements are arranged in a 5 × 10 array, for a total of 50 elements. The overall device measures 13.2 mm × 6.6 mm. A heat spreader layer is glued to the bottom of the device with solder paste. The device is surrounded by PDMS (Polydimethylsiloxane) to help insulate and reduce the amount of heat lost when transferred from the heat spreader to the TEG. PDMS has a small thermal conductivity (~0.15 W/m K) and is very flexible, which makes it appropriate for wearable applications.

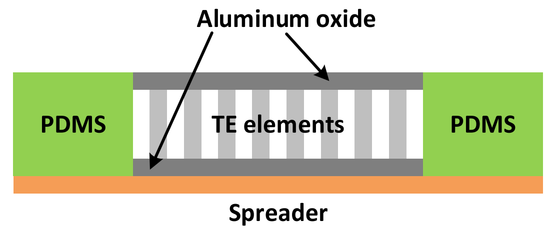

Fig. 1. Schematic of a TEG device.

2.2. Device optimization

In order to optimize the device performance, various devices with different spreader materials, spreader sizes, PDMS insulation layer and structures were fabricated and characterized. The characterization setup is shown in Fig. 2. The device was placed on a hot plate with the first layer of PDMS about 1 mm thick underneath the spreader to imitate the human body skin layer. The hot plate was set to a temperature of roughly 37 °C, also imitating the underskin temperature. The temperatures of the PDMS (under the spreader) and on top of the spreader close to the TEG, were measured with a thermocouple. A second PDMS of ~1 mm thick was placed on the spreader to reduce the heat loss to ambient. The temperature on top of the TEG was also measured with a thermocouple. Meanwhile, the output voltage and current of the TEG device were characterized by making electrical contacts to a multimeter.

2.2.1. Heat spreader material

Two heat spreader materials were selected based on their thermal conductivity properties for testing. The first one was a carbon film with thermal conductivity of 1000 W/mK, and the second one

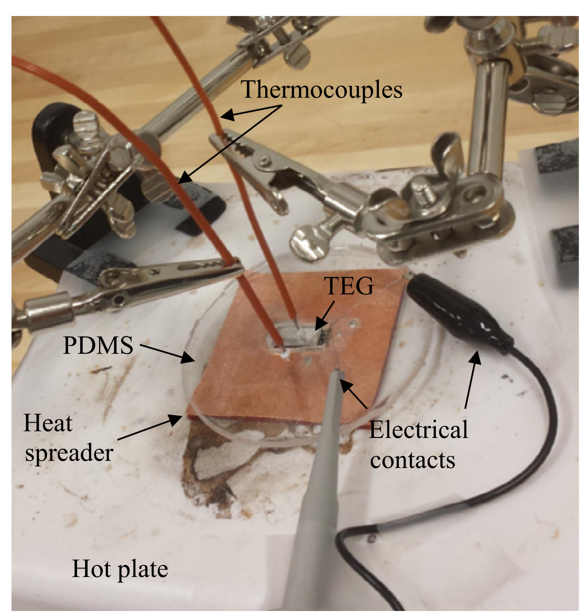

Fig. 2. Characterization setup of the TEG device consisting of the heat spreader and PDMS on the hot plate.

was copper with nominal thermal conductivity of 385 W/mK. The characterization results are shown in Table 1.

The results from this test showed that there was not a significant difference between the carbon and the copper heat spreaders. This result may not seem compliant with the fact that carbon has higher thermal conductivity and must be superior to copper as a spreader. The reason for this lies in the thickness of each of the spreaders. The in-plane thermal resistance R_{TH} can be estimated by $R_{TH} = l/\kappa A$, in which l is the lateral length, κ is the thermal conductivity, and A is the spreader cross-section area, i.e. thickness times width of the spreader. Therefore, the higher thickness of the copper compensates its smaller thermal conductivity resulting in similar TEG power. The decision was to continue with the copper spreader due to its durability for the experiments. The carbon film had a tendency to rip easily when the TEG was moved or attached to it. Any holes or rips in the film would decrease the heat transfer ability of the spreader. The copper sheet was malleable and more durable for the experiments.

2.2.2. PDMS heat isolation layer

The purpose of this experiment was to determine the effectiveness of the second PDMS layer (on top of the spreader). Two TEG devices were fabricated using a 50 mm × 50 mm copper spreader with and without a PDMS layer. The devices were tested under similar conditions. The results indicated that, contrary to the initial idea that PDMS would block the heat dissipation from the spreader to ambient and should improve the power; the PDMS layer does not have a significant impact on the behavior of the TEG. It even slightly reduced the power. This can be understood as the PDMS would also block the air flow around the TEG leading to smaller temperature differential across the TEG as indicated in Table 2. This result led to the elimination of PDMS from the design, thereby lowering the cost and assembly time of the device.

2.2.3. Heat spreader size

Once the PDMS was eliminated, the optimal size of the copper heat spreader had to be determined. Several devices with different sizes of spreaders were fabricated and characterized. All the devices were characterized under two air flow conditions: 0 and 2.2 m/s. The air flow was created by using a fan located approximately 0.3 m away from the hot plate, resulting in 2.2 m/s airflow over the TEG. The airflow was measured with an airflow meter at the TEG location. Characterization results can be seen in Fig. 3.

The testing of the spreader was conducted with perfect squares of copper that adhered to the TEG with solder paste. The copper heat spreader was used in various sizes, ranging between zero to 50 mm × 50 mm. The experimental results showed that to maximize the power output, the optimal heat spreader size is close to 40 mm × 40 mm with and without airflow conditions. These results indicated that the spreader provides useful heat capture and transfer to the TEG.

Table 1
Comparison of two TEGs employing copper or carbon films as heat spreader.

	Copper spreader	Carbon film spreader
Spreader thickness	0.13 mm	0.07 mm
Room temperature	17.5 °C	16.6 °C
Top of 1st PDMS temperature	32.1 °C	30.7 °C
Top of 2nd PDMS temperature	30.1 °C	27.8 °C
Top of TEG temperature	32.1 °C	30.3 °C
Open circuit voltage, ΔV	7.0 mV	7.1 mV
Short circuit current, I	0.03 mA	0.04 mA

Table 2
Comparison of the TEG devices with and without PDMS.

	With PDMS	Without PDMS
Top TEG temperature	34.6 °C	34.3 °C
Copper temperature	35.7 °C	35.5 °C
Power ($\mu W/cm^2$)	3.8	4.26

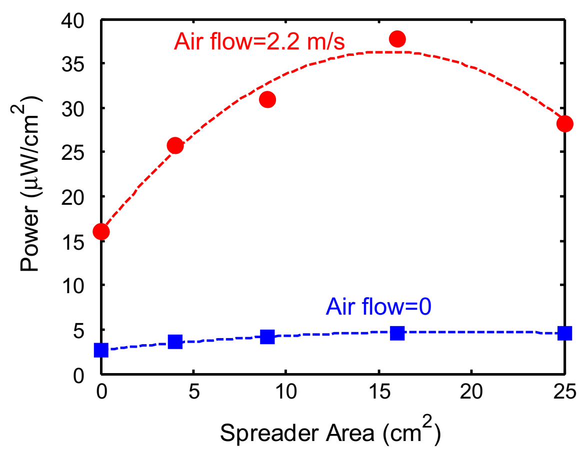

Fig. 3. TEG power versus the heat spreader size under two conditions of with (red circles) and without (blue squares) air flow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2.4. Sandwich device structure

To further increase the device performance, the TEG was sandwiched between two copper heat spreaders as shown in Fig. 4. The electrical wires from the TEG that were touching the copper were insulated to avoid short circuiting of the device. Measurements were conducted on a hot plate at 37 °C with a room temperature of 18.3 °C, and under two air flow conditions.

The results of the experiment can be seen in Table 3.

By having a copper spreader on both the top and bottom of the TEG, there was a higher power output and temperature difference across the device. The difference in average power generated by these two devices is 1.5 $\mu W/cm^2$. While the bottom spreader acts as capturing and conducting more heat into the TEG, the top header acts as heatsink and enhances the heat dissipation on the cold side. The advantage of the heat spreader compared to conventional finned heatsinks is its flatness and flexibility, making it suitable for wearable applications. In the subsequent experiments performed on the body, the TEG design with two spreaders was used.

3. Body heat energy harvesting

After the optimal TEG devices were obtained, they were placed on different body locations including the wrist, upper arm, chest, and T-shirt to measure the amount of energy that can be harvested from the body temperature. However, we reduced the spreader

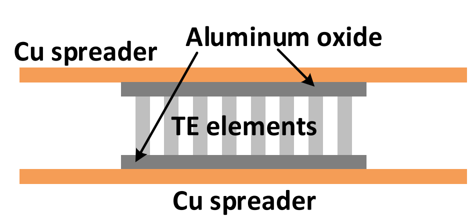

Fig. 4. Schematic of a TEG device mounted between two copper spreaders.

Table 3
Comparison of the TEGs with and without the top copper heat spreader.

Device structure	Open circuit voltage (mV)	Short circuit current (mA)	Power Average ($\mu W/cm^2$)
Without top spreader	12	1.4	4.6
With top spreader	14.8	1.5	6.1

size to 20 mm × 25 mm to improve the body comfort for wearing the TEGs.

3.1. Energy harvesting on wrist

Two 20 mm × 25 mm copper heat spreaders were tested with a middle layer of PDMS between them as shown in Fig. 5(a). PDMS was used to make the device easily attached to the wrist. Tests were conducted at a room temperature of 17.2 °C. The TEG device was connected to a load resistor, rather than open circuit, allowing for power calculation. The arm was swung to a metronome which was a smart phone application. The metronome was set at various beat per minutes, simulating the condition of the device at different walking speeds. The device was connected to the oscilloscope, which would record the change in voltage during the swing periods. The average voltage collected from the oscilloscope was used for the power calculation. Power was calculated from the readings according to Power = V^2/R_L, where V and R_L are the voltage reading and the load resistance, respectively. The optimum load resistance of 1.8 Ω was chosen according to $R_L = (1 + ZT)^{0.5}R_{TE}$ [20], in which ZT is the dimensionless figure of merit and R_{TE} is the total electrical resistance of the TE device. The device ZT was measured using transient Harman method to be approximately 0.8.

The experimental setup is shown in Fig. 5(b). In order to represent different desired air flow values (m/s), beats per minute (BPM) were calculated using the equation:

$$\text{Velocity} = \text{Arm length} \times \text{Angle in radian} \times \text{BPM}/60$$

Here, the angle is between the arm and the vertical line at maximum swing. The measurements from test subject one represented an arm length of 0.507 m and angle of 0.41 rad.

The measurements were taken in ten second increments for a total of one hundred and ten seconds. The first thirty seconds of each trial were without motion in order to achieve a steady state reading. Arm swing began at thirty seconds. The results showed that power generation increases to a specific point, then saturates at a maximum power level for that particular swing speed.

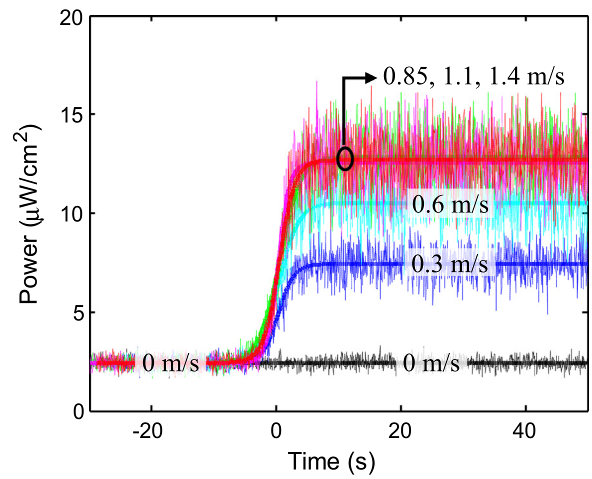

Fig. 6. Power generated from the TEG on the wrist at different walking speeds.

The power calculations, shown in Fig. 6, indicate that the maximum power directly correlates with faster arm speed; however, the power was saturated at the speed of ~0.85 m/s. For comparison, the average human walking speed is roughly 1.2 m/s. By collecting this data, it was safe to estimate that the average power output for this walking speed would be approximately 13 $\mu W/cm^2$ for the wrist area of the body with this specific design. The next three measurements were performed on the upper arm, chest and a T-shirt to compare the results to the wrist.

3.2. Energy harvesting on upper arm

Another body heat harvesting measurement involved the inside of the upper arm. This part of the body was chosen for multiple reasons. The upper arm is very close to the heart and is appropriate for measuring electrocardiogram (EKG or ECG) signals. A TEG on the arm can be used to power a wearable EKG recorder, enabling continual heart monitoring. The upper arm has a smoother and larger area compared to the wrist, which allows better thermal contact of the TEG to the skin. It also allows for efficient air flow due to natural arm swing when walking. The device that was tested on the upper arm was the same device that was used on the wrist. The TEG device was again connected to a 1.8 Ω load resistor, allowing for power generation. The device was attached to the upper arm using tapes, which also served as insulation for the wires running between the spreaders, preventing them from shorting out the device. The arm was swung to a metronome that was set at

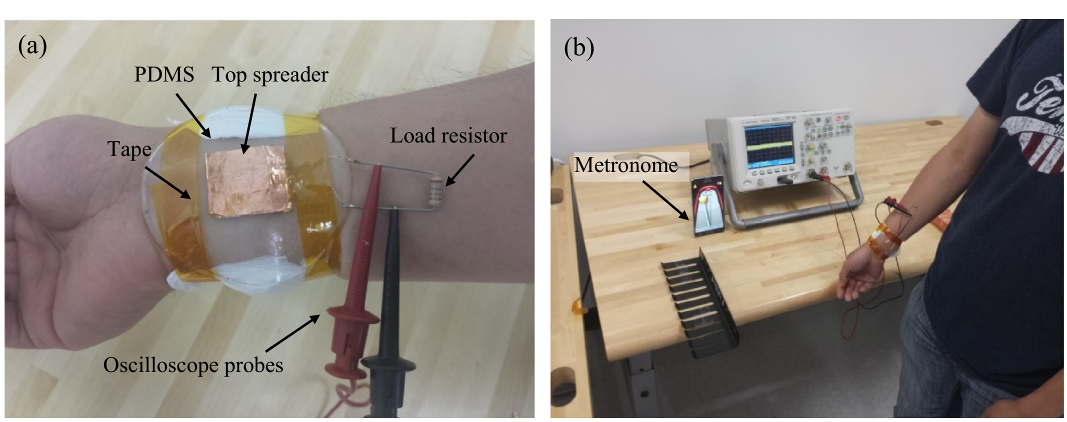

Fig. 5. (a) Picture of TEG device on the wrist used in the arm swing test, and (b) experimental setup of the arm swing synchronized to the metronome beats.

various speeds, to simulate the operation condition of the device at different walking speeds. The same beat per minute (BPM) and air speeds were used as in the wrist experiment. The device was connected to the oscilloscope, just as it was seen in the wrist experiment.

The results are shown in Fig. 7. At a walking speed of about 1.1 m/s, 20 μW/cm^2 of power was generated, which was higher than the power generated on the wrist (13.6 μW/cm^2) at similar walking speed. This result proved that the upper arm was a better area for power generation.

3.3. Energy harvesting on T-shirt

The body heat energy harvesting measurement was conducted by integrating the TEG device into a T-shirt. The same device without PDMS that was used for the wrist was integrated into the T-shirt by cutting through the fabric. A small rectangle was cut allowing the device to be inserted with the top copper layer exposed to air and the bottom copper layer resting inside the T-shirt next to the chest area for the male or bra for the female person. The fabric would then act as a layer between the top and bottom copper spreaders (Fig. 8).

Our earlier experiments proved that the PDMS layer should not have a significant impact in these types of applications; therefore, it was disregarded for this experiment. In fact, the fabric between the two copper spreaders would play a similar role as the PDMS layer. The measurement conducted for the T-shirt test was walking (or running) in a straight line while the person was holding an air flow reader vertically. A multimeter was used to measure the voltage across the load resistor connected to the TEG during the walk. The reading from both the air flow meter and the multimeter were recorded and the results can be seen in Fig. 9.

The data points near 1.2 m/s speed were obtained with walking trials. The average walking speed was around 1.2 m/s. The other data points were obtained with running trials. The data collected from these trials showed that the power increases significantly with the walking or running speed, which was expected. The faster the running speed, the greater the power output. The maximum generated power collected was approximately 18 μW/cm^2. The data trend showed that with both the increase in the heat produced from the body and the airflow at the faster running speed, more power could be produced. Interestingly, there was no significant difference between the power generated from the T-shirts worn by male and female persons in this experiment.

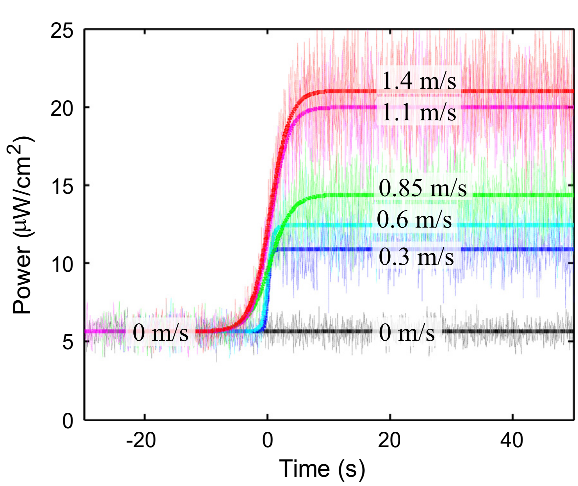

Fig. 7. Power generated from the TEG on the upper arm at different walking speeds.

3.4. Energy harvesting on chest and comparison with other experiments

The final body heat harvesting experiment involved taping the TEG device directly to the chest over the heart (Fig. 10). The device that was tested on the chest was the same device that was used in the T-shirt. The TEG device was connected to a 1.8 Ω load resistor, allowing for power generation. The tests were completed with varying air flow from a fan. The experiment was conducted at a room temperature of 18.3 °C.

The results are shown in Fig. 11. The power results from the previous experiments are also plotted on the same figure for comparison. At a walking speed of about 1.1 m/s, 10.2 μW/cm^2 of power was measured. This result was lower than the upper arm experiment, but higher than the T-shirt experiment. It is interesting to note that the power generated from the wrist is almost similar to the power generated from the chest covered under the cloth. While the TEG on the wrist has the advantage of the airflow, it is not generating more power than the TEG on the chest. This may be associated with the rough skin surface on the wrist that deteriorates the thermal contact of the TEG with the skin. In addition, the skin temperature on the chest is usually a few degrees higher than on the wrist [21], which can compensate for the lack of airflow on top of the TEG.

Based on Fig. 11, it is clear that the highest amount of power produced, about 20 μW/cm^2, was with the upper arm model when air speed was fastest at about 1.4 m/s. Overall, the upper arm testing has a strong linear increase when relating air velocity to power, resulting in the best performance of all the tests. The least efficient test was proved to be the T-shirt model, which consistently produced the lowest power, but still showed a reasonable power in the range of 2–8 μW/cm^2 in similar air velocities. Although the most convenient device to wear would be the T-shirt, it is demonstrated that the best power production comes from the upper arm due to the variability of the air flow as well as good contact to the skin.

4. Conclusion

The recent significant progress in the development of thermoelectric devices for power generation has led to the emergence of wearable body heat harvesting thermoelectric generators (TEGs). Such wearable devices will be more reliable, sustainable and allow for continuous battery-less operation. In this research, we designed and fabricated TEG devices with different structures, and characterized the devices both on a temperature controlled hot plate and on different body locations including: the wrist, upper arm, chest, and suspended on a T-shirt under various conditions. After characterizations, a three-layered device structure consisting of two flat heat spreaders, one on the top and one on the bottom of a thermoelectric device, was chosen as the final design due to its high efficiency and low form factor. Carbon and copper sheets were tested as heat spreaders. Copper was chosen as the final design due to its durability. A thin layer of polydimethylsiloxane (PDMS) was used on the bottom heat spreader to block the heat loss to ambient temperature. It was found that an optimum size exists for the heat spreader. In addition, airflow can significantly increase the generated power. The optimum size of the spreader was found to be a weak function of the airflow, which would allow one to adapt an optimal size for all practical conditions. After various tests, it was found that the power generation is highest on the upper arm, with the wrist and the chest producing less power. The smallest power was produced from the TEG suspended on the T-shirt. The upper arm and chest locations are ideally located for integration with Electrocardiogram (EKG) sensors. Both body locations produced

Fig. 8. The T-shirts with TEG devices integrated.

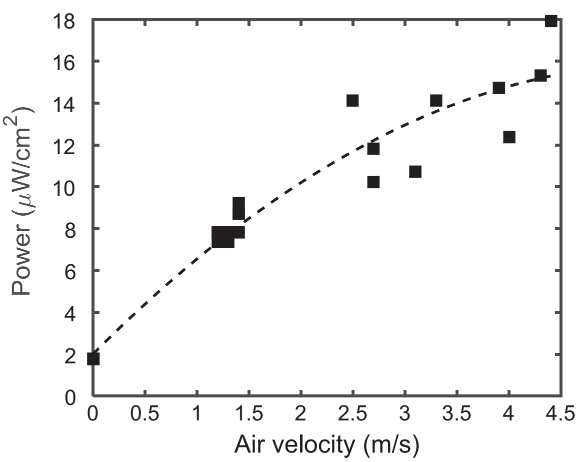

Fig. 9. Generated power versus walking/running speed from TEG mounted on T-shirt.

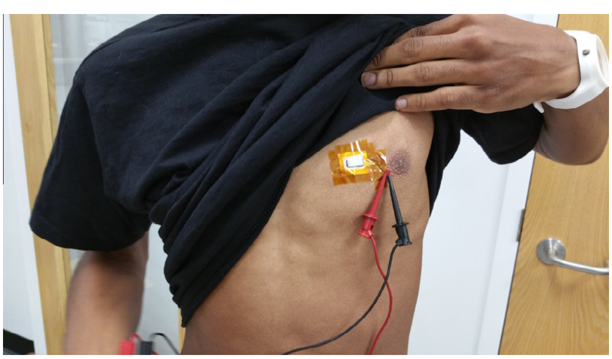

Fig. 10. A TEG device taped directly to skin over the chest area.

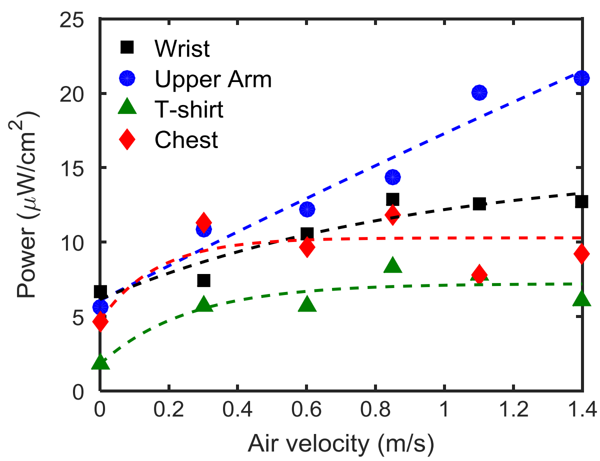

Fig. 11. Comparison of the TEG power on wrist, upper arm, T-shirt and chest.

almost similar power when the person was not moving, but the upper arm location produced more power when the person was walking.

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