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Garment-integrated thermoelectric generator arrays for wearable body heat harvesting

Linden K Allison[1] **and Trisha L Andrew**[1,2,*]

[1] Department of Chemistry, University of Massachusetts, Amherst, MA 01002, United States of America
[2] Department of Chemical Engineering, University of Massachusetts, Amherst, MA 01002, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: tandrew@umass.edu

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Abstract

Wearable thermoelectric generator arrays have the potential to use waste body heat to power on-body sensors and create, for example, self-powered health monitoring systems. In this work, we demonstrate that a surface coating of a conducting polymer poly(3,4-ethylenedioxythiophene) (PEDOT-Cl), created on one face of a wool felt using a chemical vapor deposition method was able to manifest a Seebeck voltage when subjected to a temperature gradient. The wool felt devices can produce voltage outputs of up to 120 mV when measured on a human body. Herein, we present a strategy to create arrays of polymer-coated fabric thermopiles and to integrate such arrays into familiar garments that could become a part of a consumer's daily wardrobe. Using wool felt as the substrate fabric onto which the conducting polymer coating is created allowed for a higher mass loading of the polymer on the fabric surface and shorter thermoelectric legs, as compared to our previous iteration. Six or eight of these PEDOT-Cl coated wool felt swatches were sewed onto a backing/support fabric and interconnected with silver threads to create a coupled array, which was then patched onto the collar of a commercial three-quarter zip jacket. The observed power output from a six-leg array while worn by a healthy person at room temperature ($\Delta T = 15\,^{\circ}$C) was 2 μW, which is the highest value currently reported for a polymer thermoelectric device measured at room temperature.

1. Introduction

Thermoelectric materials are a type of material with high electrical conductivities and low thermal conductivities, allowing for them to generate a thermovoltage when exposed to a temperature gradient. These materials are utilized in temperature sensors, such as thermocouples, and energy harvesters [1–5]. Thermoelectric generators (TEGs) have the ability to convert waste heat into power and are versatile enough to be able to be used in a variety of applications [6–10]. With the correct choice of materials and fabrication techniques, TEGs can be integrated into garments and provide a means for a portable and accessible power source [11–21]. Yi *et al* recently reported a textile TEG composed of poly(3,4-ethylenedioxythiophene) poly(styrene sulfonate) (PEDOT:PSS) and poly[Na(NiETT)] as the p and n types respectively. The 32-leg device was able to produce a thermovoltage of 3 mV [4]. However, many examples of body-mounted TEGs require rigid thermoelectric materials or are designed to be adhered to the user's skin. These systems are, therefore, difficult to scale-up and to integrate into a consumer's daily wardrobe. Using an all-fabric device can allow for more practical integration options and, ultimately, a more accessible product [22–28].

In established previous work, it was shown that the use of reactive vapor deposition (RVD) to vapor print persistently *p*-doped poly(3,4-ethylenedioxythiophene) (PEDOT-Cl) onto one face of commercial fabrics, such as cotton, created highly-efficient fabric thermopiles that maintained their function in the presence of sweat [29]. We utilize a vapor coating technique, so the fabrics maintain their look and feel, while also reducing the waste produced in classic solution-based polymer coating methods. Our previously reported work, as well as the work herein are the only reports of polymer-coated textile TEGs made from a vapor coating technique. Further, by integrating this one-side-coated cotton thermopile into a knitted armband, they created an all-fabric, wearable TEG that produced Seebeck voltages of up to 23 mV when worn on the body (ΔT = 30 °C). Here, we present a method for creating arrays of polymer-coated fabric thermopiles, and the design and optimization of thermoelectric garments containing these all-fabric TEGs. We report on optimizing the power outputs of a TEG by fully utilizing a wool-felt textile. We observe notable power outputs of up to 2 μW from a person wearing a three-quarter zip jacket containing a six-leg TEG array. This is the highest reported power output of a polymer-coated textile TEG [21].

2. Method

2.1. PEDOT-Cl coated fabrics

PEDOT-Cl was deposited onto wool felt in a custom-built, quartz wall reaction chamber using RVD. Iron (III) chloride was used as the oxidant and 3,4-ethylenedioxythiophene was used as the monomer in this reaction. The oxidant, substrate, and monomer were heated to 95 °C, 110 °C, and 180 °C, respectively. The depositions were giver 30 min to react at ∼100 mTorr. Further details of the deposition process have been previously detailed [29] and were followed exactly as reported for this work.

2.2. TEGs

The TEGs were all assembled using commercially available wool felt as a substrate. Silver-plated (76%) nylon (24%) fabrics and silver-plated nylon thread were both purchased from Less EMF Inc.

2.3. Electrical characterization

The power outputs from the TEG array were measured using the 'Chronoamperometry' function on an Autolab Potentiostat. The current of the devices were measured under fixed voltage values over a period of 5 min at each voltage. The measurements were done both statically at room temperature and ambient humidity, as well as on a participant with damp skin. Voltage outputs (Seebeck voltages) from body-worn devices were measured using a Fluke multimeter.

2.4. Infrared (IR) images

The IR images were taken using a FLIR camera.

3. Results and discussion

We previously reported an all-fabric TEG integrated with a wearable knit band. We chose a lateral architecture to create the TEGs, as this type of device architecture has a lower likelihood of causing thermal equilibration across each thermoelectric leg and because the dimensions and constituents of the thermoelectric legs can be independently tuned without adding additional bulk to a garment. Here, modifications were made to this previously reported TEG to increase the power outputs. The carbon fibers previously used as the n-type thermoelectric material were replaced with a more robust silver-plated nylon thread. The cotton substrate was exchanged for a wool felt, which is a non-woven material with very low thermal transport. The densely textured, microstructured surface of the wool felt increased the mass loading of the deposited PEDOT-Cl on the fabric surface, as compared to plain-woven tobacco cotton, leading to much higher surface conductivity values. The increased polymer loading on the fabric surface and higher conductivity, coupled with the decreased thermal transport across the wool felt substrate enabled the thermoelectric legs of the device to be shortened, thus increasing the power outputs of an individual thermoelectric leg without sacrificing the effective thermal gradient experienced by the thermopile.

One thermoelectric leg was comprised of a rectangle of PEDOT-Cl coated wool felt contacted to silver-plated nylon fabrics on either end and the assembly stitched onto a thin backing support fabric using silver threads (figure 1(a)). Two thermoelectric legs comprised one TEG unit. Arrays of the two-leg TEGs could be easily created by simple patching the backing fabric onto any desired textile or garment and connecting the TEGs with silver thread embroidery. The Seebeck voltage output from the two-leg TEG was first characterized using a hot/cold block test station (figure 1(b)); however, the apparent Seebeck voltages recorded using this test setup were surprisingly low at 10 μW K^{-1} (figure S1 available online at stacks.iop.org/FPE/6/044006/mmedia). In contrast, when the TEG was placed against the wrist of a participant (by inserting the TEG within a custom knit armband), output voltages as high as 130 mV were recorded at a ΔT = 13 °C, particularly when the participant's skin was wetted with lotion and/or saline (figure 1(c)). It is important to mention that the difference in output voltages for each ΔT value recorded is due to properties of different devices, not to the change in temperature. A similar observation was noted in published work [29], where the apparent output voltages of all-fabric TEGs were up to an order of magnitude higher on sweaty skin, as compared to a static, dry test station. It is important to note that PEDOT-Cl is a mixed ionic-electronic conductor, and

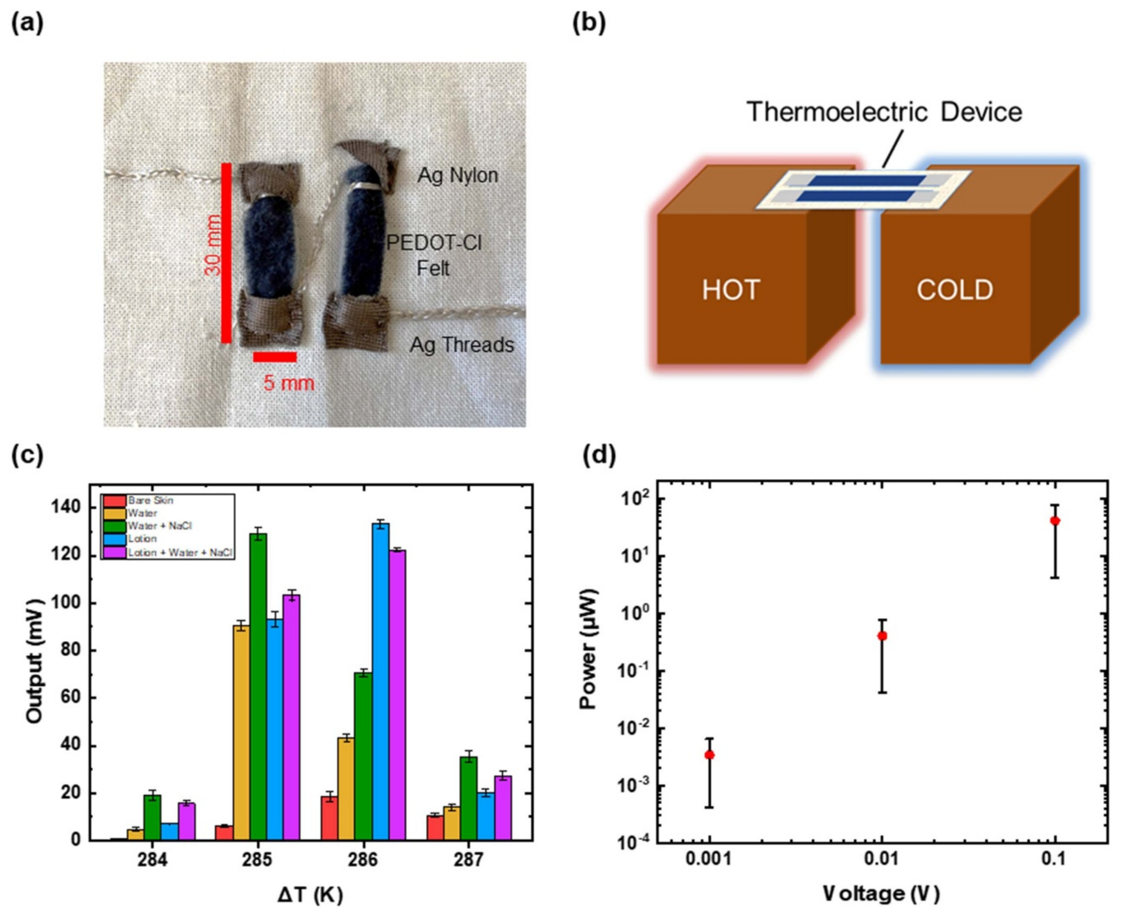

Figure 1. (a) The lateral architecture of one TEG comprised of two thermoelectric legs. (b) Test setup used to characterize the static voltage outputs of the TEGs at controlled temperature differentials. (c) Output voltages of several body-mounted two-leg TEGs. Each TEG was tested and dry skin as well as skin that was wetted with water, a 1 mM solution of sodium chloride, and commercially available lotion. (d) Power outputs recorded from the TEGs at fixed voltage values.

it is known that the increased output voltages are a reflection of the increasing ionic conductivity when the polymer is exposed to moisture [6]. Figure 1(d) shows the device power outputs at fixed voltage values. These voltage values represent the range of possible *voltage outputs* that can be produced by the TEGs upon being worn on the body. One TEG produced 3.5 μW at 100 mV, which can be considered the average voltage output of one representative TEG shown in figure 1(a).

Since our fabric-based TEGs had a lateral architecture, a thermal gradient could be imposed across each thermoelectric leg by simply folding the pliable fabric TEG over a spacer (figure 2(a)). This meant that our TEGs could be readily integrated to familiar garments at certain points, such as the cuff of a sleeve or the collar, where the TEG arrays would be naturally folded over when the user wears the garment. Folding the TEG around the fabric of the garment exposes the device to both the T_H, body heat, and T_C, ambient air without sacrificing the comfort or functionality of the garment. In conjunction with optimizing the placement of the TEG on the garment, the placement of the device on the body was also considered in order to maximize the amount of heat transferred

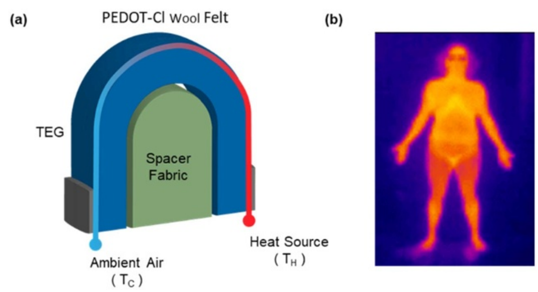

Figure 2. (a) A diagram of our lateral TEG folder over a spacer fabric such that a thermal gradient is imposed across the TEG. (b) Thermal camera image of a person.

from the heat source (the body) to the TEGs. Areas closest to the body's core, along the head, neck and torso, have lower temperature variability than those on the body's extremities, and thus lead to more stable power outputs from the TEGs. Figure 2(b) shows a thermal image of a person, the bright spots representing the hottest areas on the body.

For this work, we chose to patch two separate TEG arrays onto the collar of a fleece, three-quarter zip jacket, as depicted in figure 3(a). The placement

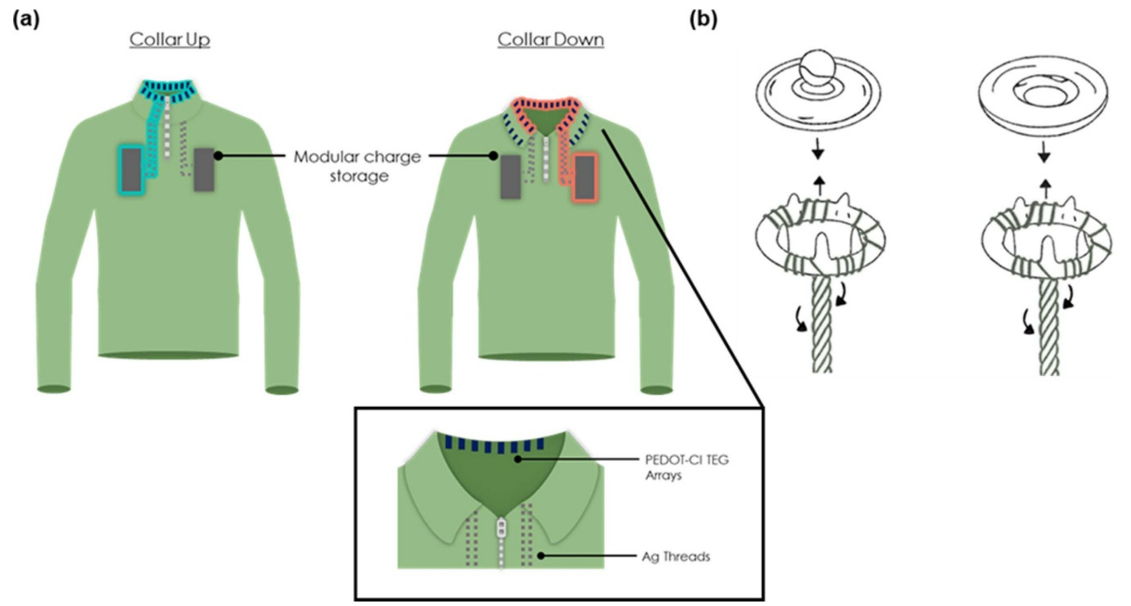

Figure 3. (a) Design of a three-quarter zip jacket integrated with two separate TEG arrays at the collar. (b) The mechanism of integrating snap buttons with silver nylon thread.

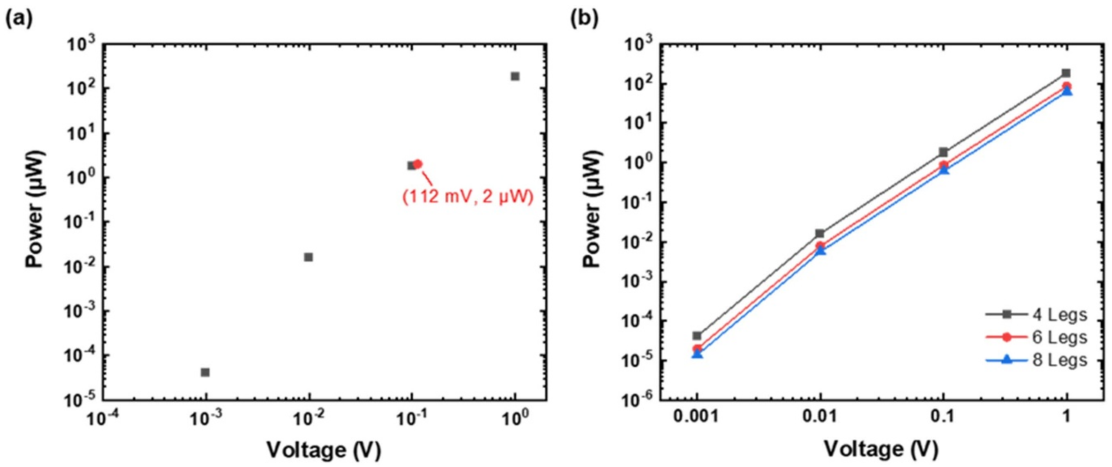

Figure 4. (a) Power outputs from an eight-leg TEG array located at the base of the collar of a three-quarter zip fleece jacket. Averaged data from three different arrays created on separate garments are presented as black squares; error bars are colored blue. The red data point represents the power and voltage output measured while the jacket was worn by a participant. (b) The power outputs from the three-quarter zip jacket as more TEGs are added to the array at the base of the collar.

on the collar allows for the TEGs to be in thermal contact with the neck and chest area, which have low thermal variability. The top of the collar had an array consisting of six PEDOT-Cl thermoelectric legs, while the base of the collar had an array of eight legs. Two separate arrays allowed for thermoelectric body heat harvesting when the jacket was worn either with the collar folded down, or with the collar folder up. The TEGs were connected in series within the array, each array was designed to quick-connect (via snap buttons) to its own modular charge storage device in the future. Silver-plated nylon threads were used to electronically interface the components and therefore create a fabric circuit. Commercially available snap buttons were used as electrical switches, allowing for a modular charge storage device to be connected/disconnected from the TEGs on demand (figure 3(b)).

Figure 4(a) shows the power outputs produced by the eight-leg TEG array at the base of the collar of the fleece zip jacket at room temperature, at fixed voltage values. The data recorded from the six-leg TEG array at the top of the collar can be found in the Supporting Information (figure S2). The power outputs were recorded at fixed voltage values, where the applied voltage values covered the apparent range of output voltages capable of being produced by our TEGs when worn on the body (see figure 1(c)). Figure 4(b) shows the power outputs as the number of TEGs in the array was increased. The power decreased as more legs were added, which is due to an increase of the overall impedance of the completed circuit, likely due to contact resistance between each of the PEDOT-Cl legs and the silver nylon fabric/thread (figure S3). It is important to note that the number of TEGs in the array should not exceed the contact area between the jacket with a wearer's neck during regular wear, as this would result in poor thermal contact between the heat source and some of the TEGs, and, therefore, a reduction in the overall efficiency of power generation.

The power and voltage output produced at room temperature by the eight-leg TEG array at the base of the jacket collar when the fleece zip jacket was worn loosely by healthy participants ($\Delta T = 15$ °C) was also recorded, shown in red in figure 4(a). On-body measurements were taken on lightly dampened skin to simulate perspiration. The output voltage of the device array worn on the body was also independently confirmed using a multimeter and measured to be 112 mV. When worn by a participant at room temperature, a $\Delta T = 15$ °C, the TEG array generated 2 μW, which is currently the highest value reported for a conjugated polymer-based TEG array. This results in a power density of around 67 μW cm^{-2} for a two-leg device calculate using the area of the PEDOT-Cl film as this is the active material. These voltage and power output values were not notably affected by the fit and looseness of the jacket on various participants and were consistently achieved after each participant wore the jacket for at least 15 min (to ensure sufficient heat transfer from the wearer's body to the TEG array). Further, due to the low thermal transport property of the wool felt substrate, which prevented complete thermal equilibration across each thermoelectric leg, the TEG array at the base of the jacket collar continuously output 112 mV even after eight continuous hours of wear.

4. Conclusion

We utilized reactive vapor deposition to coat commercially available wool felt in PEDOT-Cl, which we used to construct an all-fabric TEG. We demonstrated that a 2-legged TEG device can generate an average of 3.5 μW at an operating voltage of 100 mV. These TEGS were successfully integrated as arrays into the collar of a three-quarter zip jacket. When worn by a participant the TEGs were able to generate an unprecedented 2 μW of power at room temperatures. Our work reveals pertinent design considerations when integrating thermoelectrics into a garment and also indicates that practical power outputs can be extracted from body-worn polymer-based thermoelectric devices at room temperature. Additionally, this work emphasizes the importance of testing wearable thermoelectrics on a human body to accurately predict the potential power produced by the garment.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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ORCID iD

Trisha L Andrew https://orcid.org/0000-0002-8193-2912

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