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Analysis of Skin-Worn Thermoelectric Generators for Body Heat Energy Harvesting to Power Wearable Devices

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***Abstract*— The rapid growth of wearable electronic devices motivates investigation of powering such devices using energy harvesting, with the long-term goal of continuous operation without the need to recharge or replace batteries. In this work, we present a study conducted using a wearable device to measure the voltage, power, and energy that can be harvested continuously from human body heat using a thermoelectric generator (TEG) worn on the skin surface. Using a TEG worn on the arm, we demonstrate an average of 22.9 μW continuous maximum power delivery across three subjects, corresponding to 1.43 μW/cm^2 power density. Additionally, the large thermal gradient across the TEG when first placed on the skin provides sufficient voltage output across a matched load to enable cold start of state-of-the-art DC-DC boost converters. Overall, the results demonstrate sufficient power density and voltage output provided by centimeter-scale TEGs for operating battery-less, wearable sensor devices using body heat energy harvesting.**

I. Introduction

The motivation behind this study is the increasing popularity of wearable electronic devices evident throughout a wide range of industries from consumer to medical [1]. Common to all of these devices is the need for rechargeable or replaceable batteries. In contrast, it is possible that ambient energy harvesting, a rapidly developing area of research and development, could provide a path forward for creating fully self-sustaining and power autonomous wearable devices.

In the context of the human body, energy can be extracted from the thermal gradient present between the surface of the skin and the ambient air in most indoor and outdoor environments, whether cooler or warmer. This energy can be harvested using a thermoelectric generator (TEG), a solid-state semiconductor device that leverages the Seebeck Effect to produce electricity. Used as a generator, a TEG induces voltage at its output terminals that is a function of the thermal gradient between the side where heat is applied (hot side) and the side where heat is dissipated (cold side); both hot-cold and positive-negative output voltages are reversible, correspondingly.

The use of TEGs to extract energy from body heat to power wearable devices is a broad and active research area, with previous studies exploring applications ranging from the operation of commercially available boost converter integrated circuits (IC) when paired with TEGs [2], to the integration of TEG technology into clothing fabric and textiles [3]. However, limited data is available quantifying the continuously available output power provided by common,

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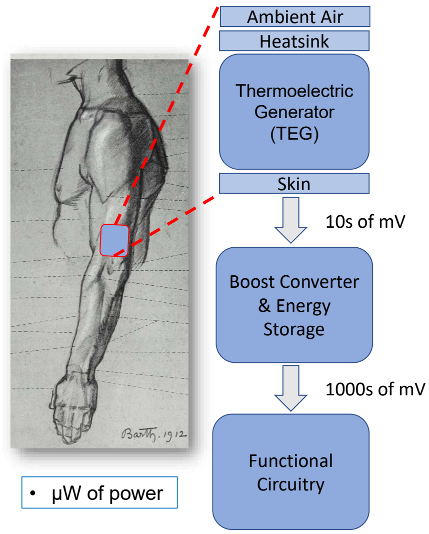

Fig. 1. A wearable device incorporates a thermoelectric generator (TEG) to power downstream functional circuitry. This work presents experimental measurements of skin-worn TEGs to determine continuously available output power and output voltage for battery-less wearable devices.

commercially available TEGs used in a body-worn context during normal daily activity.

This paper presents a methodology, wearable TEG metrology hardware, and experimental data for measuring the available output power from a body-worn TEG on the skin across multiple timescales and multiple subjects. The purpose of these experiments is to gain a better understanding of the realistic available voltage, power, and energy that can be generated from a commercial, centimeter-scale TEG worn on the arm under normal, indoor conditions.

Design and implementation details are provided for the wearable TEG measurement system, and experimental measurements from three separate subjects and multiple trials demonstrates $>10\,\mu$W continuously available output power from a skin-worn TEG, which is sufficient to meet the power requirements for many state-of-the-art wearable sensors. We also demonstrate start-up and steady-state operational TEG output voltages compatible with either commercial or recently published energy harvesting ICs. Long-term, these studies demonstrate the true viability of batteryless and energy-autonomous wearable devices powered by human body heat.

II. Wearable TEG Measurement System

A. Device Design

Wearable devices powered by thermoelectric energy harvesting from body heat [4], [5] typically use a system topol-

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ogy comparable to that shown in Fig. 1. A skin-worn TEG provides low output voltage (<100 mV), which is boosted by a DC-DC converter to IC-compatible voltage levels (≥1 V). The focus of this work is the available electrical output voltage and power of the TEG in such wearable devices, so functional circuitry is not considered directly but must be operable in the microwatt regime.

To assess available output power from a skin-worn TEG, a TEG is secured to the forearm of the wearer using a modified elastic athletic band, as shown in Fig. 2. In most indoor environments the skin surface serves as the TEG hot-side. The selected TEG (Marlow TG12-6L, 40 mm x 45 mm) is bonded on its alternate side to a small aluminum heatsink with the same contact surface dimensions as the cold-side of the TEG using thermally conductive adhesive. This assembly is retained within the band using tension from a strip of material passing over the heatsink. Cutouts are made in the fabric such that the heatsink is exposed to ambient air flow. The tension from the elasticity of the arm band keeps the hot side of the TEG in contact with the wearer's skin.

Measuring the electrical output of the TEG is accomplished by connecting it to a passive resistive-load and measuring the voltage across the load (Fig. 2). It is paramount that the total power transferred be maximized. To achieve this, the output of the TEG is loaded by an experimentally-matched resistive load to achieve maximum power transfer as described in Sec. II-B. The voltage across the load drives a voltage follower (LMC6032), which isolates the TEG output from the separately powered measurement electronics to negate measurement losses. The output of the voltage follower is input to a non-inverting amplifier with adjustable gain (LMC6032), and the amplifier output is measured using a 16-bit ADC (TI ADS1115) and stored to an SD card via a microcontroller (AtMega328).

The system is made portable by supplying power to the measurement electronics using a 5 VDC USB battery pack. The entire logging system is contained within a separate shoulder-pack and connected to the arm-band TEG assembly using a two-conductor cable. The block diagram for the complete measurement system is shown in Fig. 2.

B. Load Matching Experiment

Empirical testing was done to verify that the system delivers the maximum possible power from the TEG to the load by matching TEG source resistance and dummy load resistance. To perform this experiment the TEG was configured with a hot-plate and a heatsink with fan to maintain a ∼10°C temperature gradient across the device, chosen because of the ambient lab temperature of 22°C and a minimum stable hotplate temperature setting of 32°C. The dummy load resistance was then manually varied from 2-10 Ω in 1 Ω; this range was determined from the 4.56 Ω expected internal resistance at low temperature gradients from the TEG datasheet. Load voltage was recorded at 1 Hz, and the system was allowed to stabilize for seven minutes between adjustments of the load resistance. The average power was calculated at each load resistance interval and

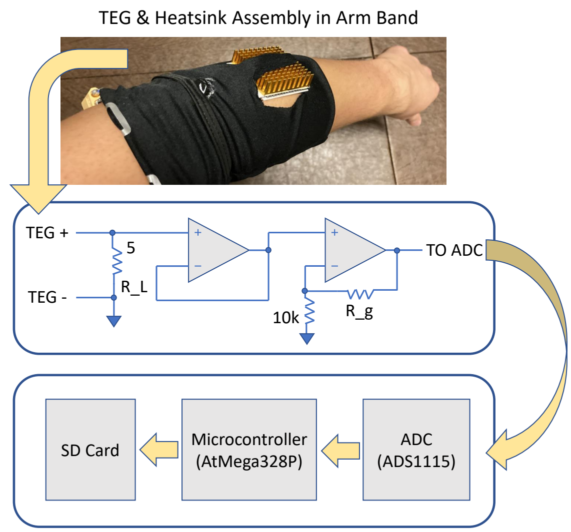

Fig. 2. Arm-worn TEG and measurement system architecture providing maximum power transfer and continuous data logging.

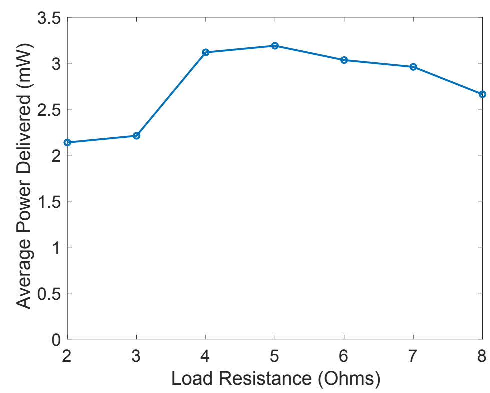

Fig. 3. Power delivered for varying load resistance is used to verify nominal TEG source resistance for load matching and maximum power transfer.

is plotted in Fig. 3. Despite the coarse resolution of 1-ohm steps for the load resistance, the trend is clearly visible showing a maximum average power of 3.2 mW delivered at a load resistance of 5 Ω. As the source resistance of Peltier-based TEGs does not change significantly with temperature differential, this load matching should be similar for a typical skin-worn temperature gradient of a few degrees.

III. Experimental Methods

To measure available output power from a skin-worn TEG, subjects were asked to wear the TEG arm band and shoulder pack containing data logger electronics for up to 4 hours at a time and to proceed with their normal indoor routine throughout the experiment. The device is worn on the left arm in the general vicinity of the elbow such that the heatsink is oriented away from the wearer's body (Fig. 2). This is intended to replicate a potential location of a TEG-powered device worn on the arm. Subjects are also requested to wear clothing that allows the heatsink to remain fully exposed to atmosphere for the duration of the test. The data logger was set to measure source-matched TEG output voltage at

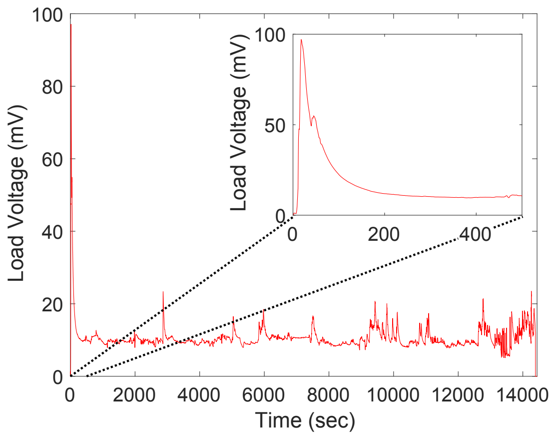

Fig. 4. Measured raw load voltage generated during a continuous 4-hour experiment with the arm-worn TEG and measurement device.

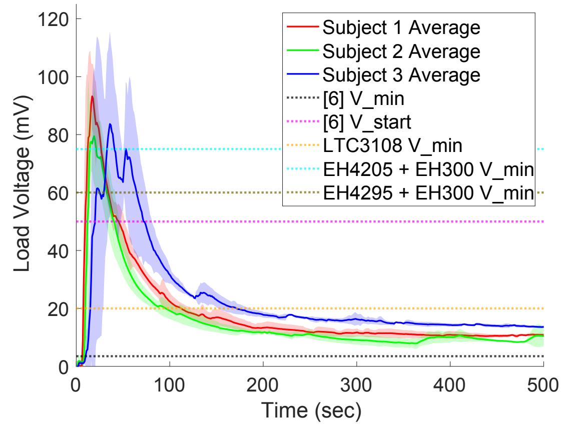

Fig. 5. Measured load voltage in cold start conditions, when the wearable device starts at room temperature. Trend lines are the average of the three cold starts per subject with the standard deviation envelope shown in the shaded region of corresponding color. Horizontal dotted lines represent minimum input continuous voltage and minimum input start-up voltages of various boost converter technologies, including both commercial and state-of-the-art published harvesters.

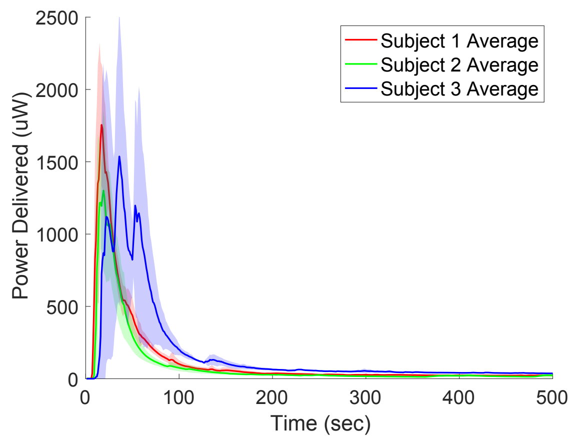

Fig. 6. Measured power delivered to load in cold start conditions. Trend lines are the average of the nine hot starts per subject with the standard deviation envelope shown in the shaded region of corresponding color.

a sampling frequency of 1 Hz, and the recording is started prior to the subject putting on the arm band; this is done to capture the performance of the TEG when it is first put on. All experimental protocols were approved by the Institutional Review Board (IRB) at Oregon State University.

The experiment was conducted on three individual subjects, where each subject was asked to perform the experiment up to three separate times on different days. Each was asked to remain indoors for the entirety of the four hour experiment. The four hour experimental duration is selected such that each experiment run provides one "cold start" test and three "hot start" tests, each of 60 minute duration. A cold start is defined as the device behavior when the measurement system, including TEG and heat sink, is at room temperature when first applied to the skin; specifically, between experiments, the device is allowed to reach ambient equilibrium for a minimum of 30 minutes prior to placement on the subject's arm. A hot start is defined as the device behavior after it has been worn continuously for a minimum of 30 minutes, at which point it has approached a steady-state equilibrium. By defining these tests as such, cold start and hot start testing can be run sequentially in a four hour period without any action required from the wearer.

IV. Results & Discussion

A. Raw Performance

Typical raw data collected from a single run with a subject is shown in Fig. 4, which plots the voltage across the source-matched load resistor with respect to time for the entire four hour duration. The inset is a zoomed version of the first 500 seconds of the test to better illustrate the cold start transient. Cold start and hot start tests are extracted in 60 minute intervals from this continuous experiment; the cold start consists of the first hour of data, and three hot start tests are derived sequentially from the last three hours of data, respectively. The aggregate experimental data consists of nine hot start tests and three cold start tests per subject across three individual subjects.

B. Cold Start Performance

The TEG showed a similar cold start response for all three subjects, where load voltage and power delivered can be seen in Fig. 5 and Fig. 6, respectively. When the armband is first put on, there is an immediate transient in load voltage that on average peaks from 83.6 mV to 93.2 mV within the first 100 seconds of operation. The voltage quickly decays toward the steady-state load voltage observed in the hot start tests, which ranges in average from 10.3 mV to 13.6 mV at 500 seconds. The nature of this result is to be expected, as the room temperature TEG and heat sink are subjected to a large thermal gradient between the heatsink temperature and the skin temperature when it is initially placed on the arm. This gradient gradually decreases as the heat sink warms up, with the transient response dominated by the thermal time constant of the TEG system.

This cold start behavior is notable because the initial peak in voltage lasting tens of seconds is useful for start-up of a downstream energy harvester IC, which for low-voltage DC-

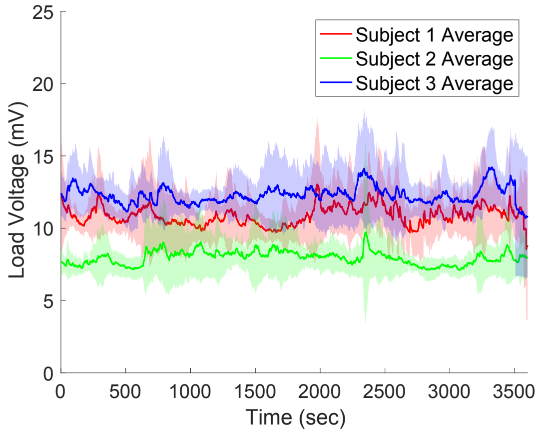

Fig. 7. Load voltage in hot start conditions. Trend lines are the average of the nine hot starts per subject with the standard deviation envelope shown in the shaded region of corresponding color.

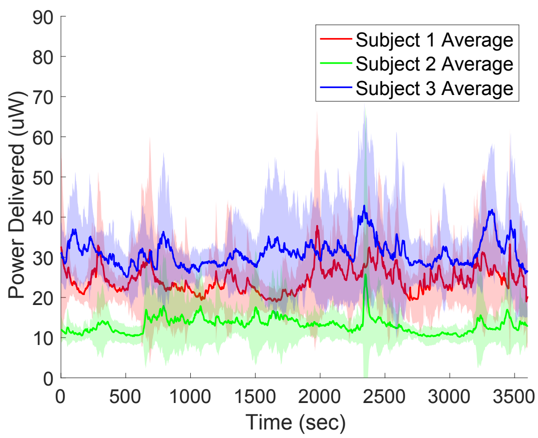

Fig. 8. Power delivered to load in hot start conditions. Trend lines are the average of the nine hot starts per subject with the standard deviation envelope shown in the shaded region of corresponding color.

DC converters typically requires a higher start-up voltage lasting at least several milliseconds, after which operation can be maintained at much lower continuous input voltage. The minimum operating input voltage and minimum start-up input voltage for several commercial boost converter technologies used with TEGs are plotted alongside cold start curves in Fig. 5 [2]. For comparison a state-of-the-art converter start-up voltage of ~50 mV and 3.5 mV minimum input operating voltage, once started, are also plotted [6]. It can be observed that all three subjects' average peak voltage exceeds the required 50 mV for startup and maintains output above the minimum 3.5 mV operating voltage once at steady-state.

C. Hot Start Performance

Hot start TEG output voltage and maximum delivered power are shown in Fig. 7 and Fig. 8, respectively, which are also consistent across subjects. Steady-state average load voltages of 7.9 mV, 10.8 mV, and 12.3 mV for each subject continuously exceed the minimum input voltage required to sustain operation of a low-voltage energy harvester (3.5mV).

TABLE I

Subject	Average Power (μW)	Average Energy (mJ / hr)
Subject 1	24.4 +/- 2.27	87.9 +/- 8.17
Subject 2	13.2 +/- 1.48	47.4 +/- 5.31
Subject 3	31.1 +/- 6.83	112 +/- 24.6
Average	22.9 +/- 3.53	82.4 +/- 12.7

The average power and average energy accumulated per hour are summarized in Table I, calculated from the hot start tests of each subject, along with overall averages. Continuously available average output power exceeds 10 μW for all subjects in steady-state operation of the skin-worn TEG. For the 40 mm x 45 mm TEG used in these experiments, average delivered power density is 1.43 μW/cm^2 across all subjects.

We note that the location of the TEG on the arm was left up to each subject, though directed to be in the vicinity of the elbow, and the ambient temperature in the indoor locations was not recorded or controlled. Intentionally leaving these variables uncontrolled has the desirable effect of providing realistic variation in environment and use, where a future TEG-powered wearable device may be put on differently every time, or where indoor spaces may be maintained at a wide range of temperatures. By allowing for these variables to remain uncontrolled, the resulting TEG performance data represents of a wider range of real-world conditions.

V. Conclusion

This paper presents a study on the continuously available energy provided from body heat using thermoelectric generators on the skin surface. A custom, wearable measurement device was used to record source-matched power delivery from a centimeter-scale TEG worn on the arm over several hours, repeated across multiple subjects. Average available power was 22.9 μW in an indoor environment, corresponding to 1.43 μW/cm^2 power density. This is sufficient for powering micropower DC-DC converters and downstream integrated circuits, and importantly the start-up and steady-state TEG output voltages are sufficient to start and maintain operation of state-of-the-art energy harvesting ICs. Long term, this work demonstrates the potential utility of body heat energy harvesting and motivates continued development of low-power, battery-less wearable electronic devices.

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