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Utilization of Commercial Peltier Thermoelectric Generators for Continuous Wearable Device Use

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ABSTRACT

As wearable technology becomes increasingly integrated in areas of healthcare and common use, the demand for sustainable, long-duration power sources has intensified. While conventional batteries impose limitations due to their finite lifespans and bulk, a promising way to address these concerns is using thermoelectric generators (TEGs), which convert temperature gradients into electrical energy. However, high-performance TEG systems often depend on specialized materials and fabrication techniques that limit scalability and widespread commercialization. Therefore, it may be beneficial to step back and test already mass-produced TEGs within this environment of sustainable wearable technology. This study tests the practicality of commercial-grade Peltier 40x40 mm TEGs for the smaller temperature differential that the human body produces. Different numbers of TEGs are tested to determine the statistical significance of the voltage output of a variable 4-6 Peltier TEGs in series, and heat sinks are then added to determine their effectiveness on the total voltage output. While there was no statistical significance of adding more TEGs to the system, there was significance shown in adding the heat sink. The results suggest that while commercial-grade TEGs are not optimal in this environment, there needs to be a change to the system rather than the TEGs themselves, as TEGs cannot improve to a great extent due to the smaller temperature differential. This represents a significant milestone in the direction of future research on the path to sustainable, worn technology.

INTRODUCTION

As wearable technology becomes increasingly integrated into daily life, the demand for self-powered, reliable devices has grown rapidly. Devices that monitor physiological signals, such as heart rate or temperature, require a constant and stable energy source, yet traditional batteries are often bulky, short-lived, and inconvenient for continuous use. The challenge of continuous wearable charging has sparked significant interest in harnessing human body heat as a renewable, ever-present source of energy through wearable thermoelectric generators (1). The human body represents a constant, untapped source of thermal energy, offering significant potential for sustainable power generation in wearable systems. By converting the natural temperature differential between the body and the surrounding environment into electrical power, these generators offer a promising solution for low-power biomedical devices. However,

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despite advances in materials and design, commercial thermoelectric generators still face limitations in efficiency, voltage stability, and user comfort when applied to wearable formats (2).

Effective wearable thermoelectric systems using commercially available thermoelectric generators, enhanced through accessible structural modifications such as heat sinks and capacitor-based energy management, will produce a continuous and stable voltage output suitable for long-term electrocardiographic monitoring. The purpose of this research is to argue the fundamental design requirements of wearable thermoelectric generators, incorporate voltage and thermal enhancement strategies to overcome performance limitations while maintaining its commercial viability, and ultimately demonstrate meaningful impact through reliable on-body integration for continuous biomedical monitoring.

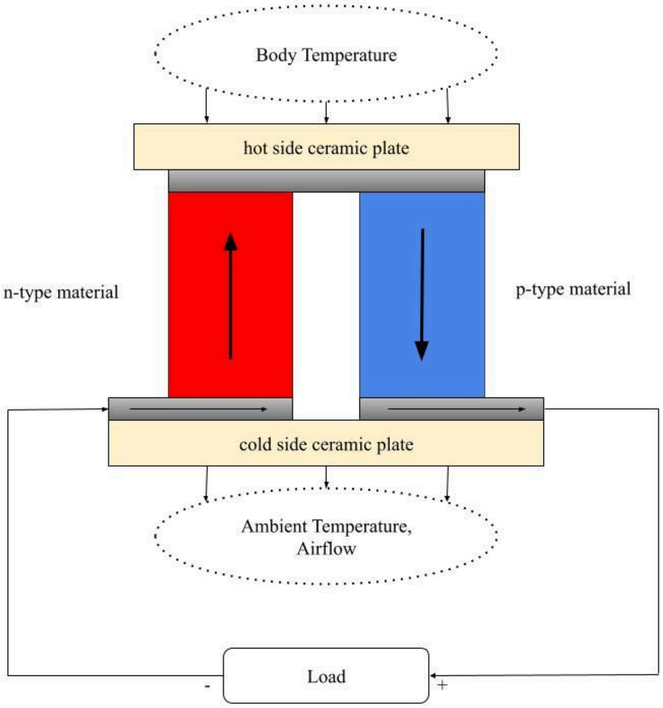

Figure 1. Schematic representation of a wearable thermoelectric generator illustrating heat transfer and voltage generation. Adapted from Siddique et al. (2017).

Thermoelectric generators (TEGs) use n-type and p-type semiconductor materials. The most common n-type and p-type materials are Bismuth Telluride (Bi2Te3) and Bismuth Antimony Telluride (Bi0.5Sb1.5Te3) respectively (2). When a thermal differential is placed upon the thermoelectric generator, the n-type electron excess and p-type electron holes move toward the cold side of the ceramic plating, creating electricity that runs through the copper wire to the load.

Early thermoelectric devices were rigid and designed for industrial applications, such as harvesting waste heat from factory machinery, making it impossible for them to conform to curved surfaces or maintain consistent contact with skin, which limited their potential for wearable applications (2). When tested with human body heat, these industrial thermoelectric generators (TEGs) proved unsuccessful in providing sustainable power (3). Although thermoelectric generators show functionality in industrial contexts, their direct application to wearable devices was not feasible without substantial design modifications such as flexibility that could fit the curved human body.

These limitations prompted researchers to investigate naturally occurring thermal gradients and human body heat was identified as a reliable energy source for the usage of TEGs, which could enable a continuous voltage source without the use of batteries. Experiments measured the thermal gradient between the human body and the surrounding environment, showing that even small differences in temperature could be converted into usable electrical energy (2).

Furthermore, prototype wearable devices, such as those for continuous electrocardiographic monitoring, were successfully powered using only body heat; this showed that low-power biomedical electronics could operate for extended periods without battery replacements, confirming the viability of human body heat as a steady and dependable energy source (4).

Currently, designs are limited by a low thermal differential produced by modern TEGs and unstable voltage output. Commercial thermoelectric modules show low power output under small temperature gradients, and their voltage fluctuates with environmental changes or body movement, making them unsuitable for continuous monitoring without modifications (5). Small temperature differentials and environmental variability create voltage instability. Even with good skin contact, unmodified TEGs cannot reliably power devices, demonstrating the need for systems that use structural and thermal management modifications.

Thus, there is still a necessity for adequate skin contact due to those requirements' limiting of the instability of the voltage output of wearable TEG designs. Controlled laboratory and on-body testing of wearable thermoelectric generators showed that the temperature differential available across the device was typically limited to approximately 2-5 K under common indoor conditions, increasing to 5-10 K in cooler outdoor environments (5), reflecting a relatively small thermal gradient between the human skin and ambient environment. Even during extended wear, changes in ambient temperature and airflow caused frequent fluctuations in the thermal gradient, resulting in inconsistent voltage output. Because thermoelectric voltage is directly proportional to the temperature differential, these findings demonstrate that wearable thermoelectric generators operate within a thermally constrained environment that inherently limits voltage production. Even high-performance thermoelectric materials cannot fully compensate for small and unstable gradients (1). This establishes a boundary condition for wearable thermoelectric research and explains why recent investigations have shifted toward system-level optimization rather than material enhancement alone (5).

Further investigations into low-power biomedical wearables reported that body temperature variability caused by motion, posture changes, and physiological regulation introduced frequent voltage drops in thermoelectric-powered systems, particularly during long-term monitoring scenarios (4). These results extend the thermal limitation argument by connecting environmental and physiological variability to practical device performance. Voltage instability caused by natural bodily changes reduces the reliability of continuous monitoring systems, reinforcing the need for wearable designs that account for real-world conditions rather than idealized thermal models. Together, these studies indicate that voltage limitations are dynamic, influenced by both user behavior and environmental exposure.

In response to these inherent constraints, researchers have implemented structural and thermal management innovations designed to enhance heat transfer and preserve temperature differentials. Wearable thermoelectric systems that incorporated external heat sinks demonstrated improved convective heat dissipation on the cold side of the device (6). This enhancement preserved the temperature differential across the thermoelectric elements and led to measurable increases in voltage output during both stationary and ambulatory testing (7). These findings indicate that voltage output can be improved through passive thermal management strategies. By increasing heat rejection efficiency, heat sinks counteract ambient temperature effects that would otherwise reduce the thermal gradient, highlighting the role of external structural components in improving electrical performance without modifying the thermoelectric material itself (7).

Despite the addition of improved structural design and thermal management, voltage instability remains a practical concern due to fluctuating environmental and physiological conditions. As a result, researchers must expand beyond generation-focused strategies and implement system-level electrical solutions to stabilize output. Wearable thermoelectric systems incorporating capacitor-based energy storage were shown to accumulate energy during periods of higher thermal gradient and supply stabilized voltage during periods of reduced output, enabling more consistent operation of biosensing electronics (1). Therefore, voltage instability can be mitigated through energy buffering rather than increased generation alone. By decoupling energy harvesting from energy consumption, capacitor-based systems allow wearable biomedical devices to maintain functionality despite intermittent or fluctuating power input.

Beyond reliability, on-body thermoelectric integration enhances user mobility and autonomy. Experimental wearable systems powered solely by body heat demonstrated stable operation during normal daily activity, including walking and light motion (5). Therefore, energy harvesting can function passively in real-world conditions, allowing users to engage in daily routines without actively managing device power while reducing physical encumbrance and improving comfort, increasing the likelihood of long-term adherence in clinical and consumer health applications. This improvement in usability directly supports broader healthcare goals of preventative monitoring and decentralized medical observation.

Mechanical comfort further influences user acceptance and long-term integration. Research incorporating flexible substrates and textile-based thermoelectric modules showed that conformable designs significantly improved wearability while maintaining functional energy output (8). Moreover, flexible architectures allowed devices to contour to natural body curvature, reducing pressure points and minimizing thermal discomfort. Complementary investigations into stretchable thermoelectric systems demonstrated that compliance reduced interfacial resistance while simultaneously enhancing comfort during extended wear (9). These structural improvements address one of the primary barriers to wearable adoption: the trade-off between device performance and physical comfort. By aligning mechanical design with human ergonomics, thermoelectric wearables become more viable for everyday integration rather than limited experimental use.

At the industry level, on-body thermoelectric integration contributes to a broader transition toward self-sustaining electronics and sustainable energy harvesting. The reduction of disposable battery usage decreases electronic waste and aligns wearable device development with global sustainability initiatives. Additionally, the ability to power sensors autonomously expands the design space for medical and consumer health technologies, enabling thinner, lighter, and more distributed sensing networks. Textile-integrated thermoelectric systems suggest the possibility of embedding power generation directly into clothing (8).

Taken together, the integration of thermoelectric generators onto the human body produces a dual-layered impact. For users, TEGs enhance autonomy, comfort, and reliability in continuous monitoring; for the biomedical and wearable technology industries, TEGs support sustainable design, regulatory feasibility, and the expansion of distributed health technologies. As thermoelectric systems continue to improve in voltage output and mechanical adaptability, their integration has the potential to redefine how wearable devices are powered, shifting the paradigm from externally maintained electronics to self-sustaining human-centered systems.

Although significant progress has been made in the development of wearable thermoelectric generators through improvements in structural design, thermal management, and energy stabilization, these innovations represent intermediate steps rather than final solutions. The integration of thermoelectric systems onto the human body introduces complex and dynamic challenges related to comfort, thermal variability, and power reliability that cannot be fully addressed through isolated design improvements. Continued innovation is therefore necessary to refine how TEG systems interact with the body, adapt to changing physiological and environmental conditions, and deliver stable power over extended periods. Advancing this field requires not only incremental enhancements to existing technologies but also a more holistic approach that considers user experience, system level integration, and real world deployment constraints. In the broader context of sustainable energy and long term health monitoring, further research into accessible and scalable wearable thermoelectric solutions is essential for enabling continuous, noninvasive biomedical monitoring and reducing reliance on conventional power sources. By building upon current advancements and addressing their remaining limitations, future work can help translate wearable thermoelectric generators from experimental devices into reliable tools for widespread clinical and personal health applications.

METHODS

This study used an experimental method using a Keithley 2401 sourcemeter and multiple 40x40 mm Peltier TEGs. The hypothesis in the experiment predicted that the Peltier TEGs in series powered by the heat differential between human body heat and the surrounding environment, if arranged correctly, could power a low-power wearable electrocardiograph. The hypothesis also predicted that the use of a heat sink on top of the TEGs would increase the voltage output substantially. The hypothesis was tested by collecting the room temperature in which the experiment was conducted, along with the temperature of the human test subject on whom the TEGs were placed; then, testing the voltage output over a time of five minutes for 4, 5, and 6 TEGs on the human test subject, along with a 6TEG experiment with heat sinks. Each TEG complex, the TEGs were placed in series. The voltage outputs were then simulated to test whether or not it would charge a 5.5V capacitor whose capacitance differed between 10µF, 22µF, 47µF, and 100µF with a voltage controller set to discharge the capacitor until 3V at a resistance of 1k ohms.

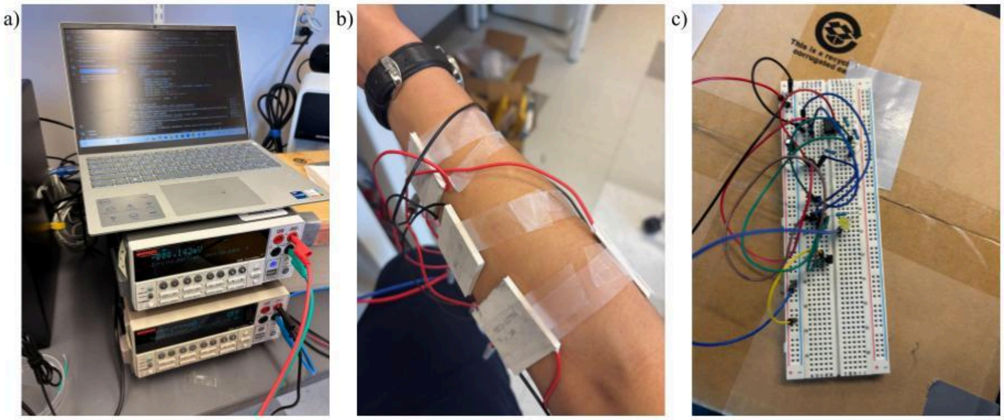

Figure 2. Systems used in the study. The Keithley 2401 Sourcemeter (a), the thermoelectrics attached to the arm for the experiment (b), and the capacitor-based system which was integrated with the thermoelectrics (c).

A total of four distinct experiments were conducted, each corresponding to a certain number of TEGs, along with the use of a heat sink. At each point, the time after the start of the data collection for that trial was recorded, along with the voltage output of the TEG complex at that time. A python script ran to specifically find the Keithley 2401 sourcemeter was run, and data was transferred to an excel spreadsheet that was later used for assimilation of the data. Instrumentation involved the Keithley 2401 sourcemeter, a thermometer for both the room and human body temperature recorded, and a computer to run both the script and the mathematical simulation afterwards on the data.

This calculation is done as such:

$$V_C(t) = V_S(1 - e^{(-t/RC)})$$

where V_C is the current voltage of the capacitor. Since the resistance (R) and the Capacitance (C) are set as 1k ohms and between 10-100µF, then we can run a mathematical model demonstrated by Figure 5 to show the charging of the capacitor under a certain time period.

To ensure validity of the experiment, all experiments were done with the same temperature differential, with the room temperature, which was isolated, being set to match a differential of 17K with that of the human body temperature during testing. The human test subject used consented to the study. They are biologically male, age 18, 163.83cm tall, and used their arm as the testing site. As seen in Figure 2a, the TEGs were taped onto the human arm with tape. When heat sinks were added, the heat sinks were placed directly onto the TEGs, with the system being taped onto the arm as a whole. For the heat sinks, pressure on the heat sinks against a non-heat-conducting surface was used to create the same environment as the TEGs without heat sinks. Statistical significance was assessed using a t-test over the different TEG complexes and their voltage output after stabilization, which the results showed to have happened near the end of data collection for each trial. By adapting the temperature differential during the experiment to reach the same differential and providing the same time variable for each trial, this experimental design allows replication by other researchers aiming to evaluate the feasibility of using industrial grade Peltier thermoelectrics to power wearable devices using the heat differential between environmental conditions and the human body.

RESULTS

The results of this experiment do not support the hypothesis that wearable thermoelectric systems using commercially available thermoelectrics with the necessary systematic modifications, can produce a stable and continuous voltage output suitable for long-term electrocardiographic monitoring.

The results for the voltage output of the TEG systems can be seen here as:

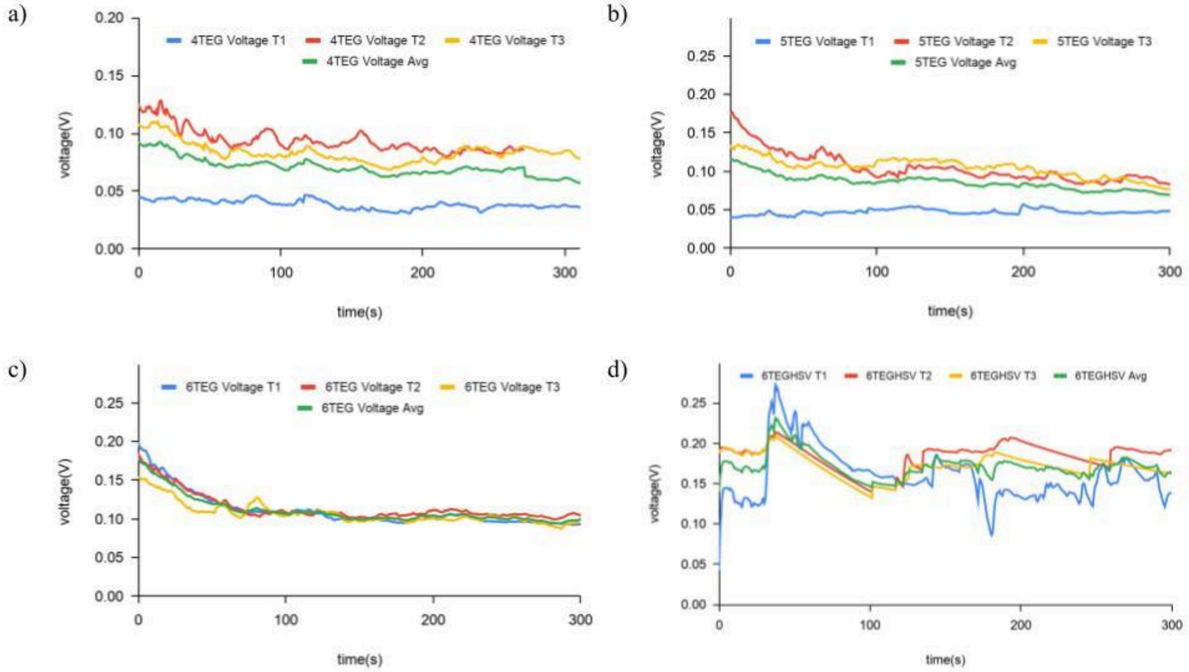

Figure 3. Voltage Output of TEG systems. Collected from 4 TEGs (a), 5TEGs (b), 6TEGs (c), and 6TEGs with a heat sink added (6TEGHSV) (d). Each Trial is separated into T1, T2, and T3, with an average line showing the average voltage output of each system.

There is a large difference between the TEG systems in Figures 3a, 3b, and 3c without the heat sinks, where the voltage decreases from the initial starting amount and the TEG system with the heat sink, Figure 3d, which although has a large increase at the start, the average voltage among the trials at the start remains largely the same throughout. This is much more clearly seen when graphing all the average voltages with figure 4:

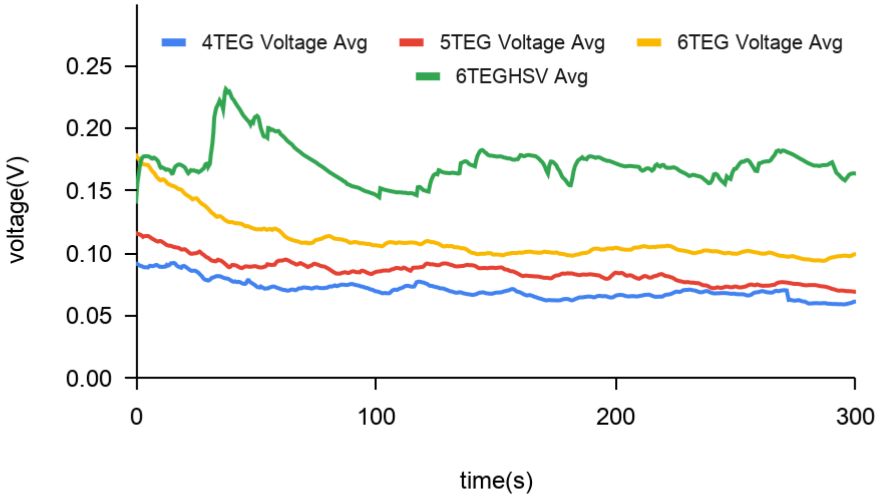

Figure 4. The average voltage output of three trials were collected to compare results.

In figure 3d, the 6TEGHSV data stays relatively the same except for a large outburst of voltage around 30-50 seconds. The relative voltage to the starting voltage also remains the same throughout with the heat sinks. However, without the heat sinks, we see the TEG output voltage decreases slowly before stabilizing at a voltage lower than the initial value.

Using the following equation mentioned before, $V_C(t) = V_S(1 - e^{(-t/RC)})$, we can calculate the increasing capacitance of capacitors of different microfarad values, shown figure 5:

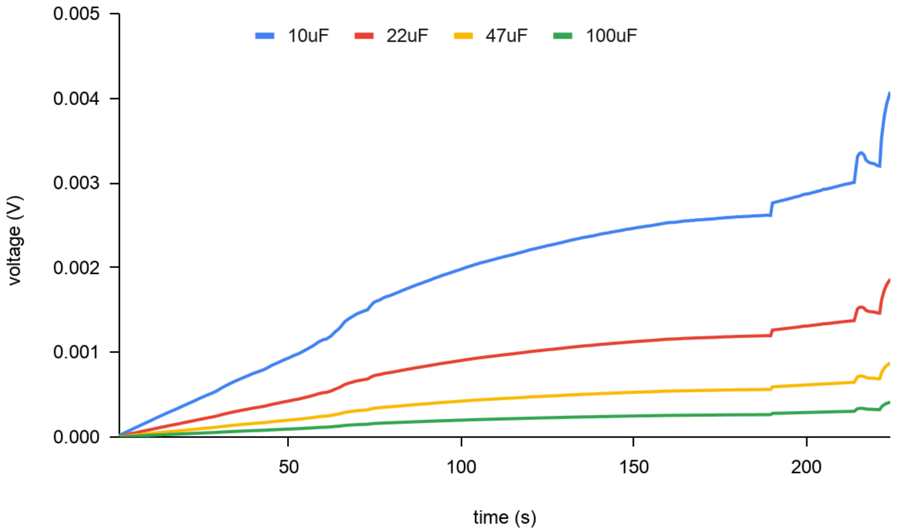

Figure 5. Voltage accumulated in each of the capacitors during the time they were charged for by the 6TEG with heat sink complex.

There is no change in the voltage seen due to no discharge in the capacitors because they have not reached 5.5V. This means that the voltage output in the 5 minute period because the capacitors only discharge when reaching 5.5V. Using the time that each charged to, however, we can estimate the amount of time that each would take to charge up to 5.5V. Since the data collection for the charging stopped at 224.1738224 seconds, we use the following equation to find how long each charging session would be for each capacitor:

$$V_C = V_S(1 - e^{(-t/RC)}),$$

which is then plugged into the spreadsheet in order to run the simulation and gain a perspective on the charging of the capacitors. The capacitors being charged had so little voltage input that it is physically impossible for the capacitors to be charged. Therefore, the TEGs are unusable in this effect.

Comparing the 0.16-0.18 V limit that the Peltier modules hit to the ink-dosed modules' power output from Kim et al., 2014, which can power a ECG at 70uW with a boost converter, whereas the presented TEG system could only power 26uW, producing a much lower power output. This does not meet the standards of 30uW for even a ultra-low power ECG. This power output is also not realistic enough to charge the capacitor to 5.5V in a reasonable time period, as seen in Figure 5.

The TEG charging significance can also be calculated using two-tailed t-tests (table 2), which further implies that using the heat sink data for the capacitor charging simulation was the right choice. The t-test data was taken from the last 30-60 seconds of the data where on the graphical data we see a stabilization of the voltage measurements, as seen with table 1:

Independent Variable	Trial 1	Trial 2	Trial 3
4TEG	0.03725415968	0.08410165317	0.08409102937
5TEG	0.04668909746	0.08890874556	0.08614372794
6TEG	0.09500647857	0.1041789465	0.09580746492
6TEGHSV	0.156798819	0.186789687	0.1717239783

Table 1. Averages for the last 30-60 seconds for each independent variable.

Comparisons	Mean 1 (V)	Mean 2 (V)	P-Value	Significance
4TEG vs 5TEG	~0.06848	~0.07391	0.806	Not Significant
5TEG vs 6TEG	~0.07391	~0.09833	0.115	Not Significant
4TEG vs 6TEG	~0.06848	~0.09833	0.113	Not Significant
6TEG vs 6TEGHSV	~0.09833	~0.17177	0.0013	Significant

Table 2. Two-tailed T-test Data for Comparisons between TEG System Data. Means are calculated with T1, T2, and T3 from Table 1.

The p-values between 4, 5, and 6 TEGs are ~0.8, ~0.15, and ~0.13 respectively. Because the p-values do not come very close to 0.05, we can determine that the data is insignificant and there was not much of a significant change in those trials. However the p-value is statistically significant between the 6 TEG trials with and without the heat sink. Therefore, the usage of a heat sink statistically is much more power-efficient.

DISCUSSION

The results of this investigation suggest that while thermoelectric energy harvesting is a promising pathway for wearable biomedical systems, the current generation of commercially available thermoelectric generators (TEGs) is not sufficient to meet the performance requirements of practical, continuous-use devices. Across the tested configurations, increasing the number of TEGs used from 4 to 6 did not produce a statistically significant improvement in voltage output, indicating that an increase in quantity alone does not overcome the fundamental efficiency limitation that the commercially available TEGs have, especially when dealing with low heat differentials such as the one between the body and the surrounding environment. The charging of the capacitor was also a mathematical model which did not account for external environmental factors within or outside of the testing facility.

The integration of a heat sink, however, did produce a statistically significant improvement in performance, reinforcing the idea that thermal management plays a more critical role than simple electrical scaling in determining system output.

These trends, however, might emerge from the limited sample size. Only using 4-6 TEGs in the experiment should be changed to a larger range of TEGs if the experiment would ever be redone. The TEGs would take up a large portion of the body, especially when being reattached after trials, and therefore not be a “wearable” prototype, as that title suggests it is portable and easily reattached. Therefore, this constrained our experimental design in the form of our sample size, and so we chose to use only 4-6 TEGs.

They might also emerge from instability of the TEG attached to the body. TEGs may have been pulled away or toward the body due to gravity during each experiment, and the movement of the subject whose body was used to maintain the TEG’s heat differential may have hindered its voltage output. Therefore, some trials may have been skewed depending on the movement and placement of the TEGs on the arm. The use of only one test subject also further limits the results of the study and its reproducibility due to the varying body composition between individuals.

Even with those limitations, it does become clear that relying on these TEGs limits the overall feasibility of wearable energy harvesting systems. Commercial TEGs are typically designed for industrial or high-gradient heat recovery applications, where large and stable temperature differentials exist. When applied to the human body, however, the available thermal gradient is small, dynamic, and highly sensitive to environmental conditions. This mismatch results in suboptimal energy conversion, voltage instability, and diminishing returns even when additional modules are added. Although improvements such as heat sinks or better physical contact can allow for a small optimization, the underlying material properties and device architecture of commercial TEGs constrain their ability to operate efficiently in wearable contexts.

To move beyond the limitations identified in this study, it becomes clear that the continued optimization of commercially available thermoelectric generators is no longer sufficient for wearable applications. The results show that performance gains from simply increasing module count are negligible under constrained thermal gradients, while meaningful improvements arise primarily from changes in heat management rather than electrical scaling. This finding suggests that the bottleneck in this area of research is not in system size or configuration, but in the suitability of current commercial materials and device architectures for low-temperature differential environments.

As a result, future progress must shift toward the deliberate design and synthesis of thermoelectric materials tailored specifically for low-grade heat harvesting. Rather than adapting technologies originally developed for industrial waste heat recovery, wearable applications require materials engineered to operate efficiently under small, unstable temperature differences. This points toward the previously discussed research directions, including the development of thermoelectric materials engineered for enhanced carrier transport and reduced thermal losses at small temperature differentials, as well as composite systems that integrate organic and inorganic components to improve flexibility without significantly compromising electrical conductivity. In parallel, ongoing work in thin-film and mechanically compliant thermoelectrics focuses on improving conformal contact with the skin, thereby reducing interfacial thermal resistance and addressing one of the primary inefficiencies identified in wearable configurations.

However, this study also suggests that the material itself is not the only problem, but rather there must be a change in the system of the wearable TEG itself. Since the human body heat temperature differential is not much energy to work with, no matter the material, redesigning the system around the TEG would be able to increase efficiency much more than incremental steps in improving materials. This would include approaches such as engineered heat-spreading layers, optimized interface materials, and structured heat dissipation pathways.

At the same time, each improvement in either the system or materials used to create the TEG must take into account the commercial availability of the suggested product. Since wearable TEG applications include smartwatches and other wearable devices that are hugely marketable, the commercial side of the product must be discussed as well.

These findings conclude that wearable thermoelectric energy harvesting cannot be realized through reliance on incrementally improving TEG materials or simple system-level adjustments alone. Instead, progress depends on a coordinated redesign of both material systems and thermal architectures, developed specifically for the constraints of the human body environment. The evidence suggests that the field is approaching a threshold where optimization of existing technologies yields diminishing returns, and meaningful advancement will require thermoelectric solutions that take into account the system as a whole, rather than a simple redesign of the TEG's materials itself.

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