Comparative Analysis of Peltier Devices and Flexible Heater Strips for Enhancing Bandwidth in Thermo-Active Soft Actuators

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Soft actuators are a new generation of robotic actuators designed for safer and more adaptable physical human-robot interaction, that can be triggered by various stimulating mechanisms, including pneumatic, electric, electromagnetic, light, magnetic, and thermal sources. Among the different types of soft actuators, thermoresponsive ones that utilize heat as the stimulus show great potential due to their ability to deliver a relatively high force-to-size ratio without the need for external air pumps, tethers, high voltage sources, or complex designs. However, a major drawback of such actuators is their limited bandwidth. Traditional methods rely on Joule heating for actuation, with the actuator deflating when the heat source is turned off and ambient temperature takes over. Recently, the Peltier mechanism has been introduced as an alternative approach for active heating and cooling. This research article presents a comparative analysis of the Peltier and Flexible heater mechanisms in terms of the bandwidth and energy consumption of phase-change thermo-active soft actuators. The study aims to assess the potential of Peltier-based actuation in addressing the bandwidth limitations observed in traditional soft actuators. The findings reveal that Peltier-based actuation can significantly improve actuation speed in thermoresponsive soft actuators. However, it is important to note that the performance of Peltier-based actuators decreases after a few cycles unless additional measures, such as the use of an external fan, are implemented. This increase in performance comes at the cost of higher energy consumption, which should be carefully considered in practical applications.

Keywords: Soft robotics; Peltier; Thermo-active actuator.

1. Introduction

Thermo-active soft actuators are a rapidly evolving technology making use of thermal energy to do mechanical work [1]. The response to heat is mapped into bending, twisting, or stretching [2, 3]. The ability of these actuators to perform such complex movements in response to thermal stimuli makes them a highly attractive option for a variety of applications [3] including medical devices [4, 5][6], and energy harvesting [7, 8] revolutionizing the field of soft robotics. [9]

In soft robotics ,thermo-active soft actuators offer several advantages over traditional actuation technologies. Soft robots are better suited for tasks that require delicate movements, such as handling fragile objects or interacting with humans [10, 11]. Thermo-active soft actuators can be designed to be highly sensitive to changes in temperature, allowing them to respond quickly to environmental changes and perform complex tasks with ease [12].

In the medical field, thermo-active soft actuators offer the potential for new and innovative medical devices [13]. For example, they could be used in the development of self-regulating catheters that adjust to changes in the body's temperature [14] or in the creation of micro-robots that could navigate through the body to deliver drugs to specific areas [15, 16]. Furthermore, thermo-active soft actuators have potential applications in energy harvesting [17]. They can be used to generate electricity from waste heat, such as in industrial processes, or to harvest thermal energy from the environment, such as in solar energy conversion [18].

Despite their promising potential, the current state of the art thermo-active soft actuators have a few limitations hindering their widespread adoption. firstly, the slow response time, [19, 20] which is attributed to the slow thermal dynamics of the materials used in the actuators [21], and is coupled with a reliance for ambient cooling. As a result, they are not suitable for high-speed actuation applications [22] and their actuation cycles are asymmetrical, with deactuation taking much longer [12]. This poses a significant barrier to the potential use of these devices in areas such as robotics and other industrial applications where high-speed motion is essential [23].

Moreover, the low bandwidth of these devices also presents a limitation on their functionality. The bandwidth of an actuator refers to its ability to execute a wide range of movements [24] and respond promptly to sudden temperature changes [25]. A low bandwidth limits the overall functionality of the device and restricts its ability to execute complex movements, which may be necessary in some applications [26].

Therefore, it is crucial to address these limitations and develop more efficient and effective heating and cooling mechanisms for thermo-active soft actuators.This will result in faster response times and higher bandwidth, enabling them to perform more complex and sophisticated movements.This will unlock their full potential in various applications, including robotics, medical devices, and energy harvesting.

To address these challenges, researchers have proposed various solutions, including the use of different materials, geometries, and actuation methods [27, 28]. One promising approach is the use of Peltier devices [29, 30], which are semiconductor devices that can be used for both heating and cooling by exploiting the Peltier effect. Peltier devices are compact, lightweight, and do not require any moving parts, making them an attractive option for actuation systems. While Peltiers have many advantages, they also have some limitations for active cooling applications. Peltier devices have a relatively low coefficient of performance [31], which is a measure of the cooling power output per unit of electrical power input. This means that they are less efficient than other cooling technologies, such as compressor-based refrigeration systems [32].In addition, the cooling capacity of Peltier devices is limited by their size and thermal properties [33]. They can only cool a small area and are not suitable for large-scale cooling applications [34]. Peltier devices require a significant amount of electrical power to operate, which can be a limitation in battery-powered or low-power applications [35]. Also, Peltier devices have a limited temperature range in which they can operate effectively [36]. They are not suitable for very low or very high temperature applications [37]. Furthermore, Peltier devices generate a significant amount of heat on the hot side of the device, which must be dissipated to prevent overheating [38]. This can be a challenge in some applications where space is limited or where heat dissipation is difficult, such as soft robotic applications [39, 40].

Phase-change soft actuators are a type of thermo-active soft actuator that utilize a fluid undergoing a phase transition to drive motion in response to thermal stimuli. This actuation principle is becoming increasingly popular, with both elastomeric and flexible membrane designs being introduced to the literature. While these actuators typically employ stimuli such as traditional Joule heating, there is a growing trend towards the implementation of Peltier junctions. The performance of Joule heating in these systems is relatively predictable in terms of transient time. However, the heating and cooling efficiency of Peltier devices, when applied to soft actuators, is subject to a variety of external factors, such as ambient temperature and contact resistance. Although control systems and arbitrary heat sinks can be integrated to moderate temperature at the steady state, a comprehensive understanding of the transient performance of these devices is essential. This is particularly true in the context of soft actuators, where developing intricate solutions that leverage the unique advantages of Peltier heating and cooling is critical. Our research endeavors to bridge this knowledge gap by examining the transient behavior of Peltier devices in comparison to traditional Joule heating, providing insights that could propel the design of more responsive and efficient soft actuators.

In this research article, we investigate the feasibility of using Peltier devices as a solution to the low bandwidth problem of thermo-active soft actuators. We conducted four sets of experiments using a elastomeric sample made of a mixture of Ecoflex 00-50 [41, 42, 43, 44] and Novec 7000 phase-change fluid[45]. The sample was placed inside a cylinder beneath a piston, and the entire system was placed on either a Peltier device or a flexible heater strip. The experiments were designed to compare the performance of the Peltier device and the flexible heater strip in terms of heating and cooling speed, power consumption, and overall bandwidth.

The present work is structured as following: Section 2 details the methodology employed to conduct a comparative analysis between the Peltier effect and traditional joule heating. A set of experiments were designed to evaluate and compare their respective performances. The obtained results are presented in Section 3, which also provides a detailed discussion of the findings, followed by a succinct conclusion in Section 4.

2. Methodology

As previously mentioned, the Peltier device and heater strip differ fundamentally in their heating mechanisms: Joule heating versus Peltier/Seebeck effect. This leads to differences in their cooling mechanisms, where a heater strip can be cooled by simply turning it off and allowing ambient temperature to affect the system, whereas a Peltier device requires reversing the direction of electrical current to remove heat from the system. In an ideal scenario, a Peltier device would instantaneously adjust the temperature of each side. However, in practice, it takes time for each side of the device to reach its target temperature. Additionally, the Peltier device's function is based on the temperature difference between its two sides, rather than the absolute temperature values. With time, the temperature on both sides of the device will increase due to the accumulation of internal heat.

This effect can significantly impact the functionality of thermo-active actuators, particularly those utilizing phase-change materials. If the cold side of the Peltier device's temperature surpasses the phase change material's transient temperature, the actuator will fully expand and cease to function. Incorporating a fan adjacent to the Peltier device can help dissipate heat and prevent the accumulation of internal heat. However, it is important to note that operating a fan consumes energy, which must be taken into account when considering the system's energy efficiency. Our study involved sets of experiments which focused on analyzing the bandwidth of the thermo-active actuator, as well as to compare the energy efficiency.

2.1. *Experimental Setup*

2.1.1. *Bandwidth Experiments*

Fig. 1 shows the experimental setup for the bandwidth comparisons of a Peltier device across four cases. These cases include (i) an ideal case using two dedicated Peltiers for active heating and cooling, (ii) a flexible Joule heater for active heating and ambient cooling, (iii) a less than ideal case using a Peltier without external active cooling, and (iv) a quasi-ideal case using a Peltier and integrated blower-style fan for thermal management. In all cases, the ambient temperature was set to 25°C.

A 40x40mm dual-stage Peltier was used for the bandwidth experiments with a 40x40mm aluminum heatsink (as shown in Fig. 1). The heatsink aids the thermal management of the device, ensuring that the Peltier can effectively heat for more heating and cooling cycles. The current remained constant throughout all cases, and the voltage was capped. Next, the four cases will be explained in further detail.

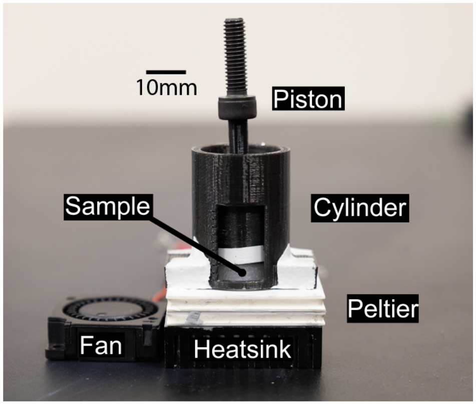

Fig. 1: Experimental setup for bandwidth experiments (depicting case (iv))

Small cylindrical samples were prepared with Ecoflex 00-50 and 20% ethanol by volume and set to cure. Curing with ethanol allows this sample to form microcavities that hold the phase-change fluid. After curing, these cavities were rejuvenated with Novec 7000 overnight until they reached full saturation. The samples were then placed in a cylinder-piston apparatus which converts expansion of the sample to linear actuation. By having the radial expansion limited, the sample forces the piston mass up through axial expansion as heating occurs. The movement of the piston was recorded with a camera to obtain elongation of the sample. Surface temperature readings were captured top-down by a thermal camera to obtain temperature values of the top surface of the Peltier in real-time. Data points from both cameras were captured every 5 seconds.

Due to the inevitable imperfections of Peltier devices, the ideal case is not practical. To analyze the potential effects of the ideal case (i), our study utilized two Peltier devices, with one dedicated to heating and the other dedicated to cooling.

During the experiment, it was observed that it took about 50 seconds for the flexible heater to reach its maximum elongation, which refers to its vertical expansion while its radial expansion was limited. To ensure consistency across all cases, the heating process was sustained for approximately 50 seconds before moving the sample onto a cold Peltier. This was done to allow the cooling process to determine the bandwidth while keeping the heating duration constant.

In order to allow the Peltiers to rest between actuation cycles and prevent overloading, it has been deemed necessary to interconnect two distinct power supplies. This measure ensures the efficient operation of the Peltier devices by maintaining a stable current flow through them. To achieve this objective, a constant current of 2 Amperes was applied to each active Peltier unit, while the voltage capped at 7 Volts during its operational phase.

The flexible heater case (ii) uses a 30x40mm thin flexible polyimide heater to represent Joule heating. However, this demonstrates Joule heating from a planar surface (to be similar to the other cases of this study) which varies from previous work that utilizes conductive coils internal to the elastomeric samples. The current was held constant at 0.755 Amperes and voltage capped at 18.5 Volts before being removed after one full actuation to allow ambient cooling for de-actuation.

While in some applications an adjacent fan can be used, in some other applications it is impractical to create a system with a fan [46]. The less than ideal case (iii) only has the Peltier with the heatsink attached. Each heating and cooling period was 50 seconds long, with 10 seconds dedicated to swapping the direction of the current. The current was held constant at 2 Amperes and voltage capped at 7 Volts before being removed during the final cycle once the Peltier began to overheat (hot side $> 100°C$).

The quasi-ideal case (iv) utilizes a 30x30mm blower-style fan placed next to the heatsink (Fig. 1). This case attempts to replicate the repeatability of the ideal case through enhanced thermal management, while still keeping the application practical and low power ($<$ 2.5W). Similarly to the previous case, each heating and cooling period was 50 seconds long with a 10 seconds swap period. The current was held constant at 2 Amperes and voltage capped at 7 Volts. This case can increase the amount of actuation cycles that could be obtained and analyze the effects of external active cooling on the linear actuation.

2.1.2. *Power Efficiency Experiment*

Fig. 2 shows such experimental setup for the power consumption comparisons made between a flexible Peltier device flexible polyimide heater. The top of this design was created with Dragonskin-10, a much stiffer silicone, to act as a strain-limiting layer, while the body of the bellows is Ecoflex 00-50. The bellows-style design is bonded to each respective heater with Sil-Poxy to embed the heaters for completely flexible designs. Therefore, both the top and bottom of the designs act as strain-limiting layers and allow the bellow to expand linearly into a rectangular prism. A silicone tube was cured in the top layer of silicone to allow the injection of Novec-7000 without damaging the cube walls.

This experimental setup aimed to investigate and compare the performance of a thermo-active actuator based on a flexible Peltier and a similar system based on a flexible heater in terms of achieving maximum elongation and the associated power consumption. Specifically, the study evaluated the rate at which maximum elongation was attained and the power required to achieve this elongation using the aforementioned actuators. The amount of Novec 7000 injected was 0.3mL for all trials. Data points were captured every 4 seconds.

2.2. *Measurements*

Elongation values were processed from the camera data and measured with ImageJ [47]. All temperature and elongation data were plotted in a Jupyter Notebook [48]. The derivative of the elongation in millimeters was used to obtain the elongation rate in millimeters per second. The mechanical power ($P(t)$) was calculated by taking the product between the gravitational force of the piston (F) and the elongation rate ($v(t)$) in Eq. (1).

$$P(t) = F \cdot v(t) \tag{1}$$

Next, the maximum electrical input power is calculated by taking the current for a case and multiplying by the capped voltage. The maximum electrical input energy (E_{in}) was then obtained by multiplying by the amount of time the corresponding device was active. The mechanical power was integrated using the composite trapezoidal rule to obtain the mechanical energy, and then was divided by the electrical energy to obtain the minimum efficiency (η) using Eq. (2).

$$\eta = \frac{\int P(t)dt}{E_{in}} \tag{2}$$

The efficiency was then used to create an efficiency ratio by using Min-Max normalization across all cases [49].

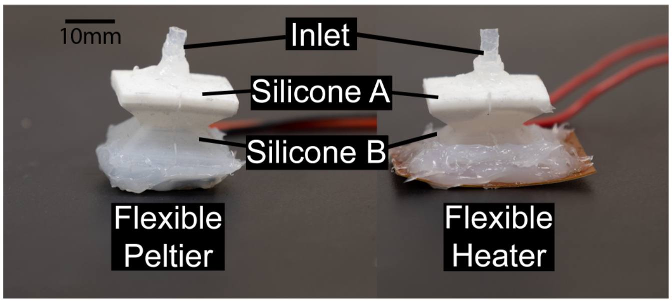

Fig. 2: Experimental setup for power efficiency experiments. Silicone A is Dragonskin-10 and Silicone B is Ecoflex 00-50. Dragonskin-10 has a shore hardness of 10A acting as a strain-limiting layer, while Ecoflex 00-50 has a shore hardness of 0.5A, allowing for expansion.

2.3. *Data Analysis*

The present study identifies a practical issue with the Ecoflex and trapped microbubble-based sample preparation technique, whereby the phase-change fluid experiences evaporation after several hours to days. This evaporation significantly restricts the cycling capability of the actuators and is a common problem in other comparable methods, as reported in previous studies [50]. To mitigate this limitation, the study explores an encapsulating approach utilizing a bellows-style hollow design. Specifically, the Novec 7000 is directly injected into the primary cavity of the encapsulating system and pools near the heating surface to effectively increase the heat conductance and address the evaporation issue.

2.4. *Technical Specifications*

2.4.1. *Bandwidth Experiments*

A 40x40mm dual-stage Peltier (arcTEC CP68475H-2) was used for the bandwidth experiments with a 40x40mm aluminum heatsink (as shown in Fig. 1). The quasi-ideal case (iv) utilizes a 30x30mm blower-style fan (5V Brushless DC fan) placed next to the heatsink (Fig. 1).

Small cylindrical samples of dimentions (r = 7.5mm; h = 5.75mm) were prepared with Ecoflex 00-50 (Smooth-On, Macungie, PA, USA) and 20% ethanol by volume (vaporization temperature $T_{vap} = 78.37°C$) and set to cure at 60°C for 4 hours. After curing, these cavities were rejuvenated with Novec 7000 ($T_{vap} = 34°C$) (Sigma Aldrich, St. Louis, MO, USA) overnight until they reached full saturation (0.25mL). The samples were then placed in a cylinder-piston apparatus which converts expansion of the sample to linear actuation. The movement of the piston was recorded with a camera to obtain elongation of the sample. Surface temperature readings were captured top-down by a thermal camera (FLIR C5, Teledyne FLIR, Wilsonville, OR, USA) to obtain temperature values of the top surface of the Peltier in real-time. Data points from both cameras were captured every 5 seconds.

2.4.2. *Power Efficiency Experiment*

For the comparison consumption experiment , 20x20x2.5mm flexible Peltier device (TEGWAY, Korea) and a 30x40x0.5mm thin flexible polyimide heater. The top of this design was created with Dragonskin-10 (Smooth-On, Macungie, PA, USA), a much stiffer silicone, to act as a strain-limiting layer, while the body of the bellows is Ecoflex 00-50. The bellows-style design is bonded to each respective heater with Sil-Poxy (Smooth-On, Macungie, PA, USA) to embed the heaters for completely flexible designs.

3. Results and Discussion

Cases (i) and (ii) depict the two extremes of elongation when it comes to thermo-active phase change actuators (Fig. 3). Case (i) shows symmetric actuation and de-actuation cycles from the active cooling capabilities of the Peltier, although small variations are noticeable. Alternatively, case (ii) can be represented as traditional Joule heating and shows the long delay after elongation where current is removed from the system and ambient cooling takes over.

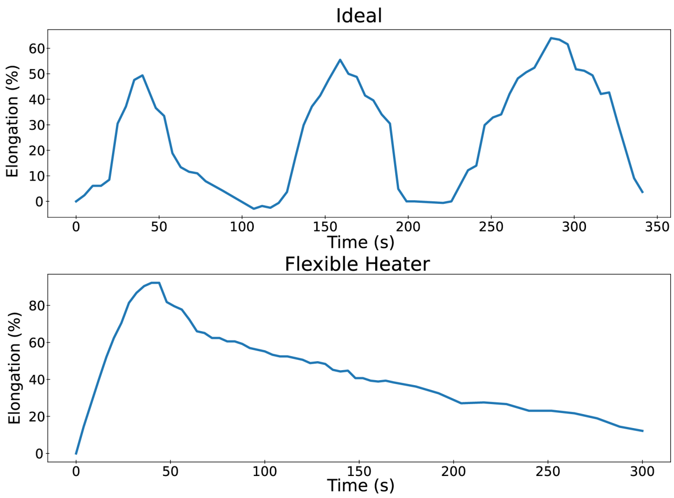

Fig. 3: Elongation curves of the ideal (case i) and flexible heater (case ii) scenarios.

An additional noteworthy observation inferred from the elongation behavior of the ideal scenario is that the elongation and cooling time progressively increased throughout the cycles. This phenomenon can be attributed to the buildup of internal heat within the sample, which allows for a greater degree of elongation upon heating and subsequently necessitates an extended time period for the de-actuation of the sample. The findings clearly demonstrate that the implementation of an ideal scenario can enhance the bandwidth of the thermo-active actuator by approximately 350%. Nevertheless, as previously mentioned, it is worth noting that achieving such an ideal case in practice is not practically feasible.

Case (iii) demonstrates the gradual heating of the Peltier body when heat is not pumped away from the heatsink (Fig. 4). With only the heatsink, the sample was able to go through two and a half actuation cycles before it remained above the vaporization temperature of the phase-change fluid at its both sides. It can be inferred that the cycling frequency surpasses the actuator's bandwidth, leading to insufficient time for the Peltier to cool the actuator before the start of the subsequent cycle. Consequently, heat accumulates within the actuator, impeding its ability to retract. As a result, during each cycle, the elongation experienced during the cooling phase (i.e., negative rate) is lower than that during the heating phase (i.e., positive rate). This trend persists until the actuator eventually ceases elongation after several cycles.

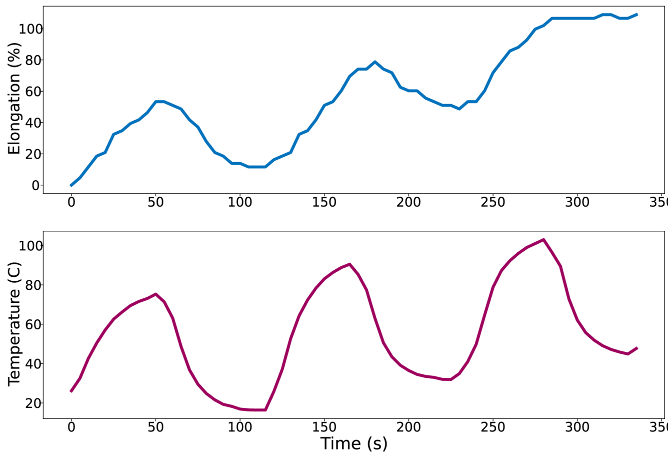

Fig. 4: Temperature and elongation curves of the Peltier with no fan (case iii).

Case (iv) shows the capabilities of the low-power fan blowing ambient air through the heatsink fins (Fig. 5). Both the elongation and temperature curves reflect a more stable actuation cycle with temperatures cooling lower than 22°C over multiple cycles. Only three cycles are shown in the graph, but the sample could continue actuating until the phase-change fluid depletes. In contrast to the situation observed in case (iii), the introduction of a fan can potentially enhance the actuator's bandwidth in this case. This increased bandwidth would enable the Peltier to adequately cool the actuator before the commencement of the subsequent cycle, thereby impeding the accumulation of heat and prolonged elongation.

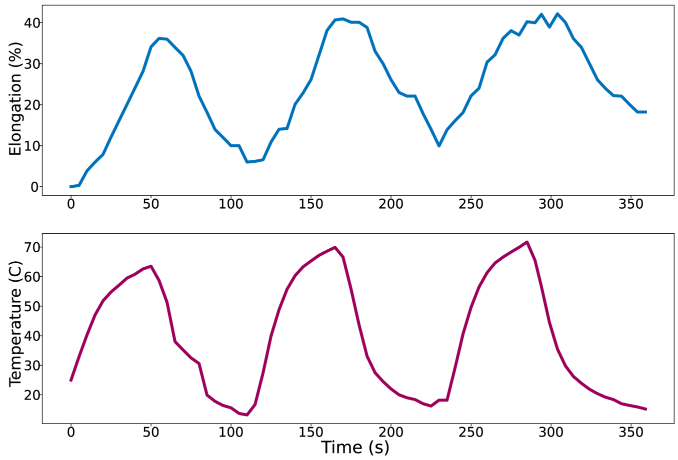

Fig. 5: Temperature and elongation curves of the Peltier with fan (case iv).

Analogous to the fan/nofan comparison, a correlation can be made with muscle tension production, where the signal (Peltier -> Action Potential) is akin to the action (Elongation -> Muscle Tension). However, in muscle tension production, incomplete relaxation of the muscle due to the occurrence of multiple signals can result in a 'staircasing' effect or unfused tetanus.(Fig. 6).

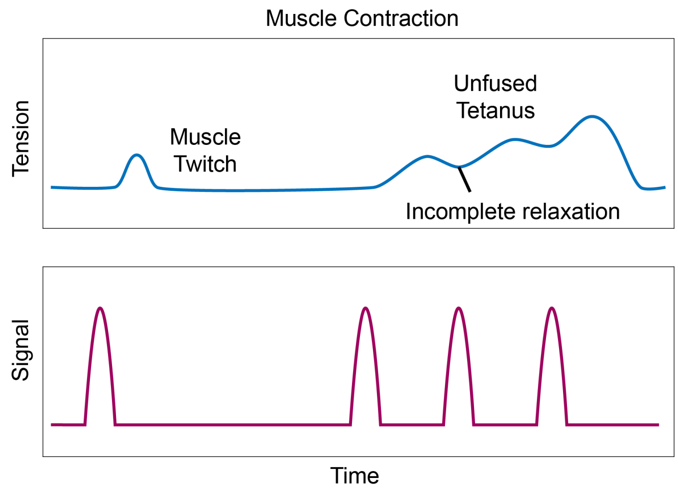

Fig. 6: Depiction of muscle contraction and accumulated action potentials depicting unfused (incomplete) tetanus.

Case (iii) demonstrates the detrimental effects of inadequate thermal management, leading to an inability to cool both the Peltier and the sample effectively. This inadequacy causes heat to accumulate inside the actuator, resulting in a 'staircasing' effect in elongation, similar to unfused tetanus in muscle tension production [51, 52]. In contrast, case (iv) exhibits significantly reduced 'staircasing' in elongation, even at lower temperatures, which can be compared to the 'treppe' phenomenon. The 'treppe' effect involves repeated stimulation leading to increased tension production and more efficient muscle contractions. Furthermore, despite case (iii) displaying the highest efficiency ratio of electrical to mechanical energy, it fatigues much faster than other cases. The rapid onset of fatigue, combined with inadequate thermal management, makes case (iii) an unsustainable solution. These findings underscore the importance of appropriate thermal management in actuation systems, as it plays a critical role in maintaining the system's long-term functionality and efficiency. Therefore, while case (iii) initially displays high efficiency, its tendency to fatigue rapidly and the occurrence of inadequate thermal management lead to long-term instability. On the other hand, case (iv) demonstrates the importance of effective thermal management, with significantly reduced 'staircasing' and improved efficiency in elongation, making it a more sustainable and reliable solution.

Fig. 7 shows the elongation rate of the four cases in millimeters per second and Fig. 8 shows the mechanical power calculated over time with Equation 1.

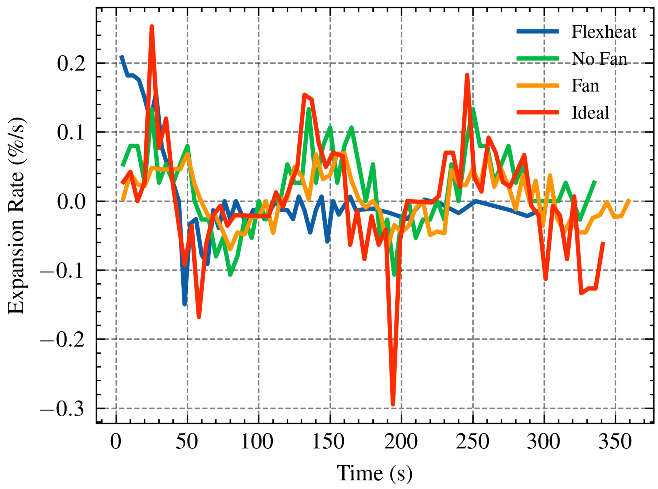

Fig. 7: Elongation rates across the four experiments

The data presented in the graphs demonstrates that during the initial stages of the heating process, the elongation rate of the heater is the highest, reaching approximately 0.2 mm/s. Subsequently, the rate progressively decreases until it ultimately settles at a value near zero, reflecting the sluggish nature of ambient cooling processes. However, when Peltier devices are employed, the elongation rate exhibits a sinusoidal pattern, with the amplitude of oscillation varying between 0.04 mm/s for case (iii) and 0.1 mm/s for cases (i) and (ii). This behavior implies that the incorporation of a fan results in a slight reduction of the velocity amplitude. Consequently, this aspect of heat management is beneficial in curbing heat accumulation within the actuator and, therefore, limiting its elongation rate.

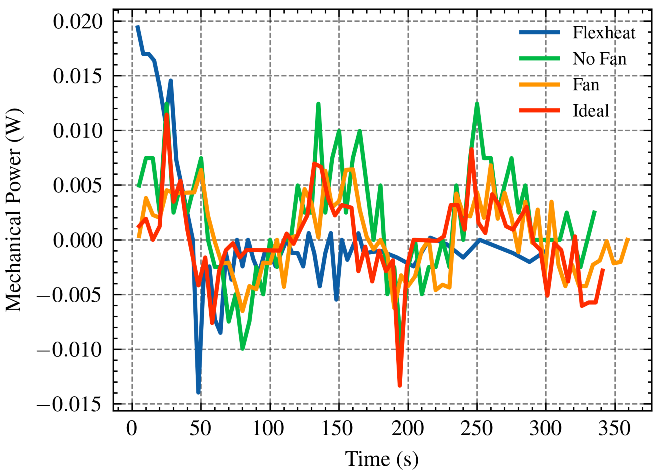

Fig. 8: Mechanical power across the four experiments

Analysis of the mechanical output powers reveals that the heater case demonstrates the highest absolute value during the heating process. Furthermore, the negative portions of the mechanical output powers in all cases result from the opposing directions of the forces due to weight and velocity. A comprehensive summary of the input and output energy across all cases during the heating process, along with their respective energy efficiency ratios, has been provided in Table 1.

The efficiencies in the present study were computed using the quotient of the output mechanical energy and the input electrical energy, which were subsequently normalized by the maximum value observed in the absence of a fan (i.e. case (iii)). It should be emphasized that the primary objective of this investigation is to compare the performance of Joule heating and Peltier effect, rather than to determine the exact energy efficiency of each case. This is due to the simplified nature of the mechanical work calculation employed, which does not take into account the non-linearities arising from ambient effects and frictional forces.

Table 1: Energy and Efficiency of each bandwidth test

-	**Ideal**	**Flexible Heater**	**Fan**	**No Fan**
Mechanical Energy (J)	0.0113	0.0648	0.0891	0.5855
Input Energy (J)	5600	520	4819.8	3705
Efficiency ratio (%)	0.0128	0.7888	0.1169	1.0

The addition of the fan dramatically reduces the efficiency of the electrical to mechanical conversion, but allows the soft actuator to actuate for many more cycles. This ability to prolong the actuation cycles is from a decrease in the temperature difference between the two sides of the Peltier (ΔT). Alternatively, this means the case with no fan gets hotter faster, and relies more on the ambient cooling that takes place. This results in increasing the mechanical work output and overall bandwidth while being limited to the minimal amount of actuation cycles.

The power density experiment presented in Fig. 2 provides a compelling demonstration of the efficacy of the hollow design of the phase-change fluid elastomeric structure, which incorporates a completely flexible Peltier unit. During the experiment, a selected input power was applied, and the resulting expansion was recorded between the flexible Peltier and the flexible heater sample, as depicted in Fig. 9.

The findings indicate that the flexible Peltier unit required less than half the input power of traditional Joule heating across various elongation rates. Notably, while using a comparable amount of Novec 7000 as the previous set of experiments, the hollow design of the structure facilitated faster actuation of the Peltier device, obviating the need for overnight sample soaking while also featuring a one way inlet. Additionally, the experiment demonstrates that the Peltier device can attain higher elongation rates with less input power than traditional Joule heating.

It is important to note that the employment of Peltier technology imposes a limitation on the maximum elongation attainable, which is approximately 80% of the capacity that can be realized by the heater. This is due to the fact that prolonging the heating duration in Peltier devices prior to reversing its direction will result in the degradation of semiconductor materials, particularly in the absence of an adequate thermal management system, such as a fan.

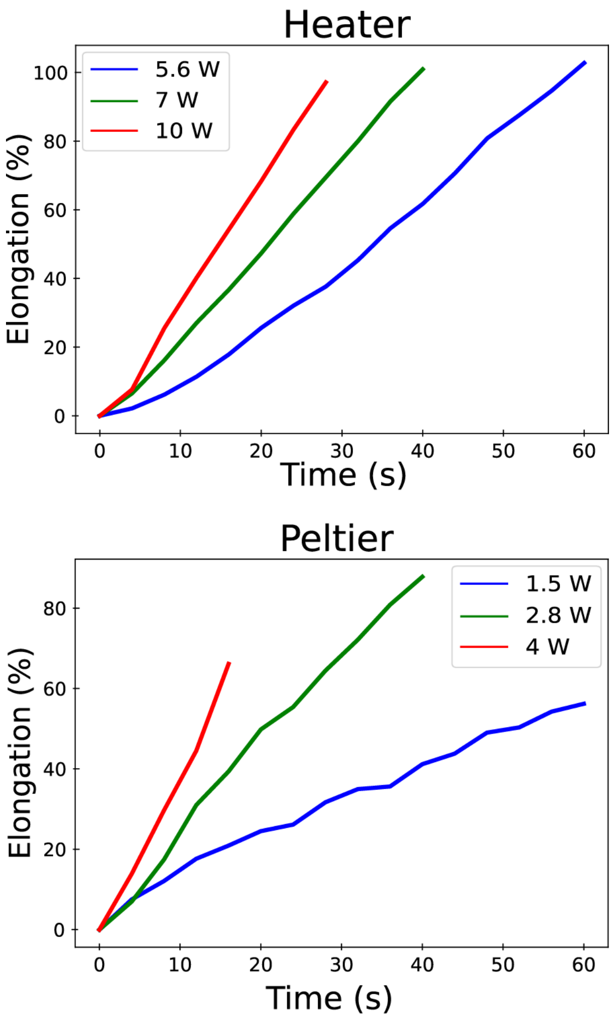

Fig. 9: Flexible Peltier vs flexible heater elongation curves at different power input.

4. Conclusion

This article provides a comprehensive comparative analysis of transient behavior between Peltier-based actuation and traditional Joule heating as stimulus mechanisms for thermo-active soft actuators. The particular focus of the study centers around phase-change thermo-active actuators, which rely on the remarkable volume expansion that occurs when a liquid undergoes a transition into a gas state.

In these phase-change actuators, the actuation process involves raising the temperature of the liquid, causing it to transition into a gas phase and leading to a substantial increase in volume. To return the actuator to its original state, the gas is subsequently cooled down, either through exposure to ambient temperature or through a combination of Peltier-based cooling and the assistance of a fan. This cooling process allows the gas to revert back to its liquid form, resulting in the deflation of the actuator.

By comparing the performance of Peltier-based actuation with traditional Joule heating methods, the study aims to evaluate the effectiveness of Peltier-based approaches in achieving rapid actuation and deflation in phase-change thermo-active soft actuators.

In conclusion, our research findings confirm that active cooling, specifically using a Peltier device, results in more than three times the speed compared to using a heater alone. However, this increase in speed comes with two significant drawbacks. Firstly, active cooling consumes additional energy, leading to increased energy consumption. Secondly, the accumulation of heat on one side of the actuator causes permanent inflation after just a few cycles of inflation and deflation. To address the issue of accumulated heat, the inclusion of a fan proves to be highly beneficial, significantly improving cycling performance in terms of speed and durability.

Surprisingly, in terms of energy consumption and efficiency, the Peltier device without a fan emerges as the most efficient option among all the cases. It outperforms the use of a flexible heater and even surpasses the efficiency achieved by incorporating a fan. This unexpected result stems from the fact that while the addition of a fan increases overall energy consumption, it does significantly contribute to the output mechanical energy. Therefore, utilizing the Peltier device not only enhances the actuator's bandwidth but also improves energy efficiency. However, it is important to note that the limited number of cycling repetitions remains a significant impediment when solely relying on Peltier devices. Based on our findings, future research should focus on improving heat dissipation in Peltier-based thermo-active soft actuators with minimal energy requirements. Addressing this challenge will enable the development of more efficient and durable actuation systems, expanding the potential applications of Peltier technology in soft robotics.

The innovative approach that was presented in Fig. 2 underscores the tremendous potential for developing novel, efficient actuation systems that harness the benefits of Peltier devices while minimizing power consumption, enhancing flexibility, and increasing speed of actuation. This design remains completely flexible while maintaining actuation performance as opposed to Yoon et al.[53] which integrated a thin copper fin for uniform heating throughout the cavity. It is noteworthy that our proposed design is dependent on gravity pooling the phase-change fluid on top of the heating stimuli for fastest actuation. Additionally, the cooling methods employed can be expanded further for temperature regulation while cycling actuation. Sogabe et al.[54] shows submerging phase-change actuators in climate-controlled liquid further enhances actuation performance and control. This ties into the many specific considerations of employing Peltiers over Joule heating, as it eliminates the effects of gravity, uniformly heats the entire body, and maintains direct control of environmental temperature.

Further assessment is imperative to determine the optimal shape and geometry of the proposed system. Moreover, the potential benefits of interconnecting multiple actuators in a networked configuration to augment either the output force or the operational bandwidth ought to be explored. This can involve a detailed investigation of the mechanical and electrical properties of the individual components, as well as the collective behavior of the integrated system. The effectiveness of different control algorithms, sensing mechanisms, and feedback loops must also be evaluated to ensure precise and stable operation of the actuator network. Such endeavors can significantly advance the applicability and utility of the proposed technology in various domains, including robotics, physical interactions with humans, and biomedical engineering.

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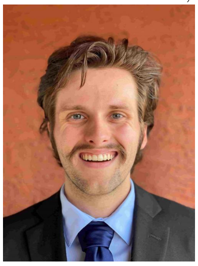

Trevor Exley started at the University of North Texas in 2017 and has since received his B.S. and M.S. in biomedical engineering, and a focused minor in mechanical engineering. His research focus is in the fields of biomedical instrumentation, biomechanics, and machine learning. For his Master's thesis he targeted Parkinson's disease by evaluating the predictive capabilities of quiet standing data while working with the Biomedical AI Lab.

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