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# Utilizing the Peltier effect for actuation of thermo-active soft robots

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**Abstract**

The field of soft actuation methods in robotics is rapidly advancing and holds promise for physical interactions between humans and robots due to the adaptability of materials and compliant structures. Among these methods, thermally-responsive soft actuators are particularly unique, ensuring portability as they do not require stationary pumps, or high voltage sources, or remote magnetic field. However, since working principles of these actuators are based on Joule heating, the systems are inefficient and dramatically slow, especially due to their passive cooling process. This paper proposes using the Peltier effect as a reversible heating/cooling mechanism for thermo-active soft actuators to enable faster deformations, more efficient heat transfer, and active cooling. The proposed actuator is composed of a thin elastic membrane filled with phase-change fluid that can vaporize when heated to produce large deformations. This membrane is placed in a braided mesh to create a McKibben muscle that can lift 5 N after 60 s of heating, and is further formed into a gripper capable of manipulating objects within the environment. The effectiveness of the proposed actuator is demonstrated, and its potential applications in various fields are discussed.

Supplementary material for this article is available online

Keywords: soft robotics, thermo-active actuators, peltier effect

(Some figures may appear in colour only in the online journal)

## 1. Introduction

Soft robotics is a rapidly growing field that has gained significant attention in recent years due to its potential for enabling *physical* human–robot interactions (*p*HRIs) in a safer and more efficient manner compared to traditional rigid robots [1, 2]. One of the key advantages of soft robotics is the use of materials with a relatively low Young's modulus (<1 GPa) [3], which allows them to deform and conform to their surrounding environments. This ability to adapt to their surroundings, combined with their low reflected inertia [4], make soft robots ideal for *p*HRI as they can operate in close proximity to humans without posing a significant risk of injury [5, 6].

Furthermore, the flexibility of the material used in soft robotics also allows for the development of robots with embodied intelligence [7, 8]. Embodied intelligence refers to the ability of a robot to perceive and understand its environment through its physical interactions with the world, rather than relying solely on sensors and algorithms [9]. Soft robots, with their ability to deform and adapt to their environment, are better equipped to exhibit embodied intelligence, which enables them to handle complex and unpredictable scenarios more effectively [10, 11].

Soft robots are not limited to just *p*HRI applications. Their versatility and embodied intelligence also make them suitable for a range of other applications, including exploration

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of natural environments [12, 13], handling of delicate objects [14], and even in medical applications such as minimally invasive surgeries [15, 16]. The potential of soft robotics is vast and holds great promise for the development of safer, more efficient and adaptable robotic systems in a wide range of fields.

Thermo-active soft actuators are a type of soft actuator that have gained significant interest due to their high force generation per unit weight and low power requirements [17]. In contrast to pneumatic soft actuators that rely on stationary pumps and accompanying accessories [18, 19], polymeric/elastomeric soft actuators that demand exceedingly high voltage (ranging from 20 KV to 400 KV) necessitating a stationary power supply [20, 21], magnetically actuated soft materials reliant on external magnetic fields [22, 23], and Liquid crystal photo-driven soft actuators that depend on external light sources [24, 25], thermo-active soft actuators present a promising alternative that offers portability. Thermo-active soft actuators eliminate the need for external pumps, high voltage sources, magnetic fields, or light sources. Recent studies have also directed their attention towards modifying the actuation technology employed in McKibben muscles [26, 27]. Traditionally, these muscles have relied on pneumatic actuation, but emerging research has explored alternative stimuli, including heat, to drive their movement [28]. However, the main limitations of this technology include their very low bandwidth and the inefficiency of the heating and cooling processes [29]. Traditional resistive heaters have been commonly used as the sole heating source for soft actuators, relying on Joule heating (i.e.$I^2R$) to generate heat [30]. However, these devices are characterized by their inefficiency, as the cooling process is passive and can only occur once the current is removed [31].

To address these limitations, various thermo-active soft actuators have been developed that utilize shape memory alloys (SMAs) or shape memory polymers (SMPs) [32]. SMAs have the unique ability to restore their shape after deformation through thermal or electrical charges, making them ideal for actuation in soft robotics. However, they have slow actuation cycles due to the conversion of heat to mechanical energy [33]. SMPs have a similar working principle to SMAs but offer more versatile actuation methods, including light and moisture [34]. Despite these advantages, these types of thermo-active soft actuators still face the challenge of inefficient cooling [35].

Induction is another approach of generating heat. However, there are several disadvantages associated with using induction heating for pneumatic artificial muscles. Induction heating requires the use of an external power source, such as a high-frequency electromagnetic field. This means that the actuation of artificial muscles using induction heating is dependent on the availability of an external power source. Also, induction heating can generate significant amounts of heat, which can be detrimental to the performance and durability of the artificial muscles [36]. The high temperatures generated during induction heating can cause the artificial muscles to lose their shape and structural integrity, leading to reduced actuation capabilities and a shorter lifespan.

Peltier junctions [37] have emerged as a promising alternative to Joule and induction heating as a reversible thermo-active stimulus for controlling soft actuators. Peltier junctions are solid-state devices that work based on the Peltier effect, which is the transfer of heat between two materials when an electrical current is passed through them. When a current is passed through a Peltier junction, one side of the junction becomes cold, while the other side becomes hot.

Peltier junctions can be used to control the temperature of soft actuators, which can lead to reversible and controllable actuation. The reversible nature of Peltier junctions allows for repeated actuation cycles, making them a promising alternative to other heating techniques that can cause irreversible damage to the soft actuator.

Moreover, Peltier junctions offer several advantages over Joule and induction heating [38]. They do not require an external power source or the use of electromagnetic fields, which simplifies the actuation process and reduces the risk of damage to the soft actuator. Additionally, Peltier junctions have a faster response time than induction heating, which makes them suitable for dynamic applications that require rapid actuation.

This paper proposes using Peltier heating as a reversible heating mechanism for thermo-active soft actuators to enable faster deformations, more efficient heat transfer, and active cooling. The proposed actuator is composed of a thin elastic membrane filled with phase-change fluid that can vaporize when heated to produce large deformations.

The organization of the paper is as follows: in section 2, the working principle of the soft actuator is explained. The methodology and design considerations for the different applications are outlined in section 3. Section 4 presents the discussion and conclusion.

## 2. Working principle

Our actuation principle is based on two primary components: a phase-change material and Peltier-based heating and cooling. The phase-change material changes state from liquid to gas when heated above its vaporizing temperature and from gas to liquid when cooled below its condensation temperature. The balloon will contain the phase-change material, and the Peltier effect will be utilized to heat and cool it.

Historically, fluorocarbons [39] have been the preferred choice for phase-change fluids due to their low boiling points, with perfluorocyclohexane being an example with a boiling point of 51 °C, as noted in a study by Kato in 2016 [40]. However, the use of fluorocarbons has become limited due to their adverse impact on the ozone layer. In order to address this issue, Novec-7000, an engineering fluid with a vaporization temperature of 34 °C, has emerged as a promising alternative [41, 42]. Novec-7000 has been found to be effective in managing thermal systems while being environmentally friendly.

A Peltier device, also known as a thermoelectric cooler, is a type of solid-state cooling device that uses the Peltier effect to transfer heat from one side of the device to the other. The Peltier effect is a phenomenon where an electric current is

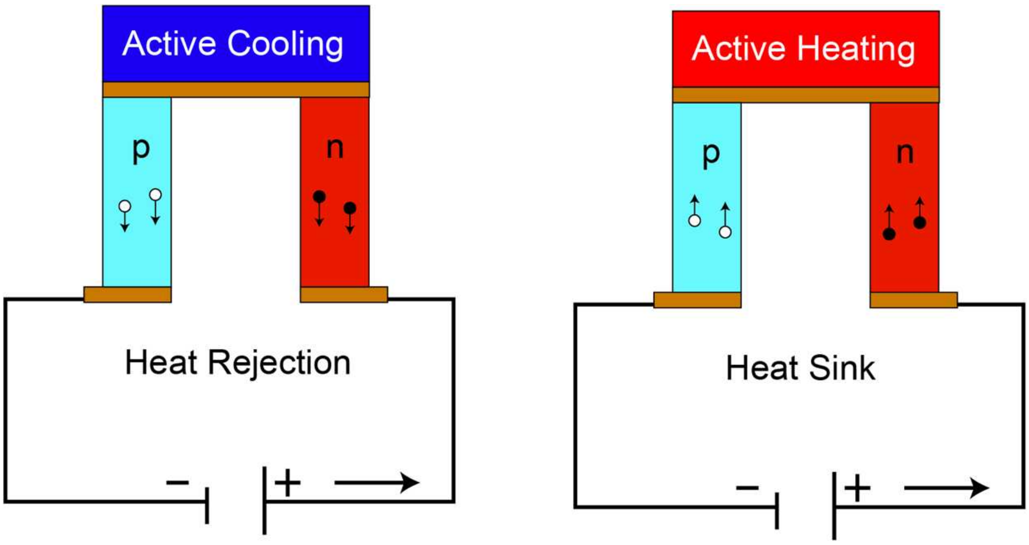



**Figure 1.** Operation principle of Peltier with one p-type and one n-type thermoelement depicting the active cooling and heating capabilities when the current is reversed.

passed through a junction of two dissimilar conductors, causing heat to be absorbed or released at the junction depending on the direction of the current.

A Peltier device typically consists of a series of thermocouples made of two different types of semiconductors, typically doped with different impurities to create a p-type and an n-type material [43]. The thermocouples are arranged in a series, with one end of each thermocouple connected to a metal plate that serves as the cold side, and the other end connected to a different metal plate that serves as the hot side. When a DC electric current is applied to the Peltier device, as shown in figure 1, it causes electrons to move from the p-type material to the n-type material, or vice versa, depending on the direction of the current. This movement of electrons causes heat to be absorbed or released at the junctions between the two types of material, depending on the direction of the current. As a result, the cold side of the Peltier device becomes colder while the hot side becomes hotter, allowing the device to transfer heat from one side to the other. The amount of heat transferred depends on the current flowing through the device, the number of thermocouples, and the temperature difference between the hot and cold sides.

During the heating phase, the Peltier effect will be used to raise the temperature of the phase-change material above its vaporizing temperature. As a result, the phase-change material will change from a liquid to a gas, causing an increase in volume inside the balloon, which will result in the expansion of the balloon. During the cooling phase, the Peltier effect will be used to lower the temperature of the phase-change material below its condensation temperature, causing the phase-change material to change from a gas to a liquid. This will result in a decrease in volume inside the balloon, leading to the contraction of the balloon.

The proposed actuation principle has several advantages over traditional actuation methods. The use of a phase-change material allows for reversible and controllable actuation, while the use of Peltier-based heating and cooling provides precise temperature control, enabling multiple actuation cycles when the phase-change material is encased in a thin membrane. Additionally, the use of an enclosed balloon made of soft and elastic materials allows for safe and flexible actuation, making it suitable for various soft robotic applications.

## 3. Methodology

The methodology employed in this study is comprised of several key steps that were taken to fabricate the thermo-active actuators, characterize the materials and Peltier devices used, develop the actuator body design, and design approaches for the actuator's application. Specifically, these steps involve (A) the fabrication process of the actuators, (B) the characterization of the materials and Peltier devices utilized, (C) the iterative development of the actuator body design, and (D) the exploration of various design approaches for the actuator's application. These methods will be discussed in detail in the subsequent sections of this article.

### 3.1. *Fabrication*

The Fabrication process of the silicone composite utilized in the study involved several key steps. Firstly, a mixture of Ecoflex 00–50 and Ethanol [44] was prepared by mixing for 2–3 min, as depicted in figure 2. During this mixing process, no effort was made to remove small air bubbles, as they were found to increase the total elongation of the Ecoflex. A mold for the silicone to cure in was created using CAD software and printed using a 3D printer. The prepared mixture was then poured into the mold and cured inside a climate chamber at 45 °C for at least 1 h. The silicone was left in the climate chamber overnight to allow for the evaporation of ethanol from the silicone. To rejuvenate the silicone, it was then soaked in

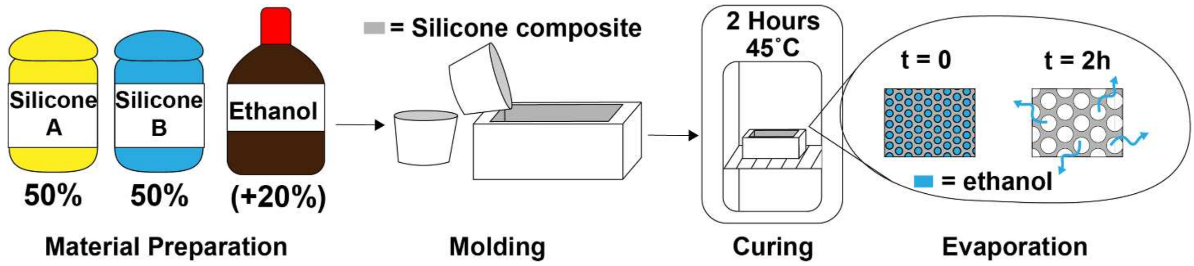



**Figure 2.** For material preparation, 50% Ecoflex 00–50 part A is mixed with 50% Ecoflex 00–50 part B, then 20% by volume of ethanol is added before stirring and pouring into desired mold. The mold is placed in a climate chamber at elevated temperatures to speed up the curing process which allows the liquid ethanol to expand within microbubbles that are formed before escaping the silicone matrix.

Novec-7000 for a period of 30 min to 2 h, depending on the volume of silicone, in order to fully saturate the silicone with Novec-7000.

The use of a stretchable main shell to house the phase-change fluid was investigated for actuation purposes. This approach builds on previous work with elastomeric structures containing phase-change microcavities. However, a shift was made towards a thin membrane (balloon) design similar to HaPouch [41] to create larger cavities. The change in design was motivated by several reasons. Firstly, it allowed for higher repeatability due to the phase-change fluid being encapsulated after multiple actuation cycles and having a shelf-life of about four days without evaporation. Secondly, the new design closely resembled traditional pneumatic soft actuators, allowing for further simplification of the internal channels. Most importantly, the speed of localized heating and cooling of the Peltier junctions increased dramatically when placed on the side of the balloon where the phase-change fluid pooled.

### 3.2. Characterization

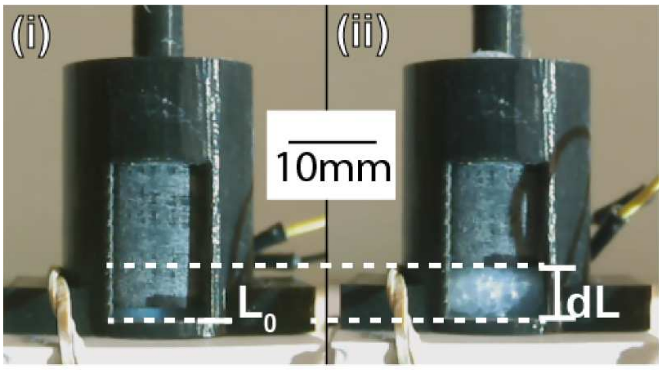
The characterization involved multiple steps of testing the materials and their effects of the actuation properties. Initially, the actuation properties of the materials were investigated using external heating via Peltier devices. Data was collected using captured images and temperature sensors, depending on the specific test setup. The collected data was then processed and analyzed to determine the most effective material specifications and actuation properties. Finally, the identified material specifications and actuation properties were integrated into the core design to improve the overall performance of the actuator. Additional details regarding the specific methods and procedures employed for characterizing the materials will be discussed in the following.

The aim was to investigate the deformation behavior of a soft body material, which was prepared using a specific mixing protocol. To accomplish this, videos were captured of the material's expansion and subsequently analyzed using ImageJ software [45]. The experimental setup consisted of a hollow cylinder design, as depicted in figure 3(a) with a weighted plunger (5 g) sanded smooth to minimize friction on the silicone as it expands. The larger Peltier was used and operated at 2.5 amps for 30 s, and the resulting elongation was recorded.

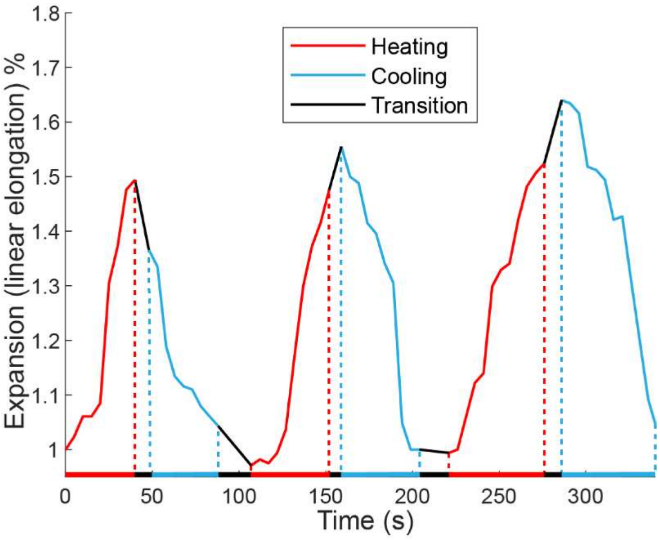
The soft body material was prepared using a mixture of 50% Ecoflex 00–50 part A and 50% Ecoflex 00–50 part B. Additionally, ethanol at different volume percentage levels was added to the mixture before stirring and pouring it into a desired mold. The mold was then placed in a climate chamber at elevated temperatures to expedite the curing process, which allowed the liquid ethanol to expand within microbubbles formed before escaping the silicone matrix.

In order to investigate the impact of varying percentages of ethanol on the expansion of silicone, a set of experiments was conducted. The silicone samples, each having a cylindrical shape with a height between 3.8–4.0 mm and a diameter of 15 mm, were fully immersed into Novec-7000 until saturation after being prepared with varying ethanol concentrations by volume. To measure the expansion of each sample, the 3D printed cylindrical apparatus was utilized, with its 5 g weighted plunger that was carefully designed to hold the sample onto the Peltier without impacting its elongation ability (figure 3(a)). This experimental setup allowed us to easily capture the elongation of each sample and measure it using ImageJ software [45].

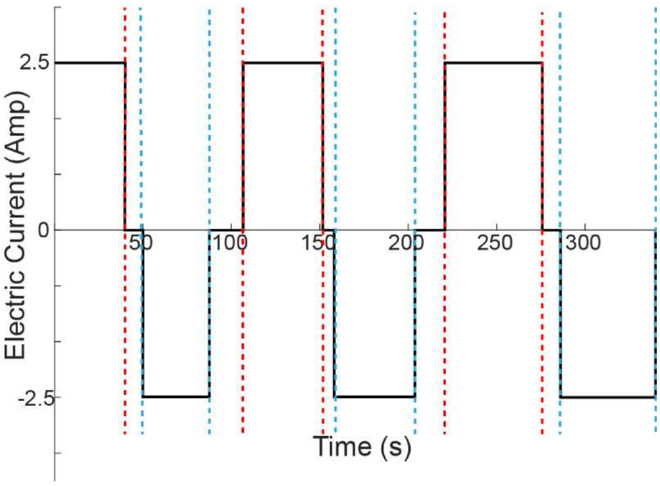
The experiment involved subjecting the silicone samples to heat on the arcTEC CP68475H-2 Peltier device, in accordance with the conditions outlined in table S1, with a current of 2.5 A applied for a duration of 30 s each. As in a similar study [46], the resulting data revealed that the optimal concentration of ethanol required to increase silicone expansion due to phase-change fluids was 20%. Moreover, it was discovered that there was no significant increase in expansion beyond an ethanol concentration of 20%, and the saturation point of the mixture was identified to be approximately 31%. These findings provided valuable insights into the effects of ethanol concentration on silicone expansion, which are crucial for optimizing the use of phase-change fluids in practical applications. It was determined that the optimal concentration of ethanol has a saturation point, beyond which any additional ethanol concentration did not produce significant expansion in silicone. By knowing the saturation point of the mixture, we can use ethanol more efficiently, avoiding any unnecessary wastage of excess ethanol. Consequently, the findings of the experiment




(a)

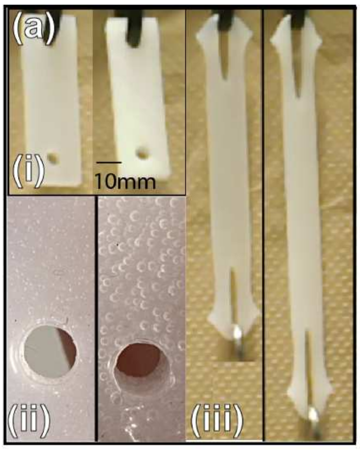



(b)

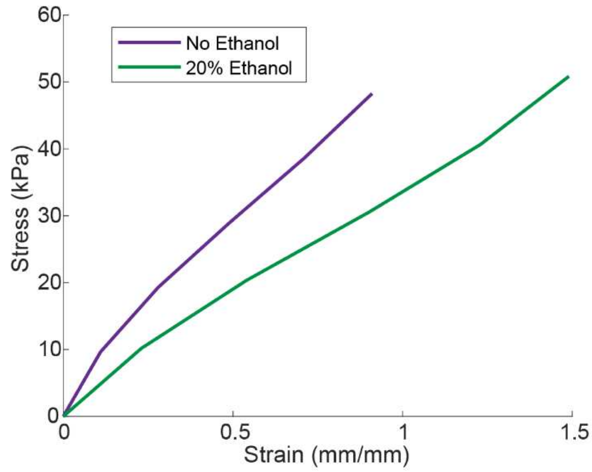



(c)

**Figure 3.** (a) Cylinder elongation of Ecoflex 00–50 with 20% ethanol from heating with the Peltier (i) initial length (3.9 mm), and (ii) fully expanded (7.7 mm) after 60 s at 2.5 Amps, (b) elongation plotted for repeated actuation cycles using a dedicated heating and cooling Peltier. The sample used was cylindrical with a 4 mm height and 15 mm diameter, and cured with 20% ethanol by volume and 5% zinc oxide by mass of only Part A and Part B silicone, and (c) corresponding currents of the heating and cooling Peltier from the previous graph.




(a)




(b)

**Figure 4.** (a) Samples of 0% (left) and 20% (right) ethanol were prepared and (i) suspended. (ii) Bubbles were prevalent in the 20% sample, and (iii) a 500 g mass was attached to record the elongation, and (b) stress–strain curve for the samples.

can help in cost savings and improve the performance of the final design of the actuator.

Silicone was not used to house the phase-change fluid in the McKibben and the gripper. However, the addition of ethanol in the curing process increased the silicone's ability to stretch. Therefore, the same curing process was still used for the fabrication of the gripper. To demonstrate the increased ability of the silicone, an experiment was conducted using two rectangular cured silicone blocks—one without ethanol and one with 20% ethanol. The stress and strain were measured for each block by attaching a mass of 0.5 kg off of one side of the silicone, as shown in figure 4. The results of the experiment showed that the 20% ethanol silicone was able to achieve over 50% more strain at the highest stress level taken, as shown in figure 4. The use of ethanol in the curing process thus improved the silicone's mechanical properties, enhancing its ability to stretch under stress.

To study the enhanced efficiency of phase-change activation and deactivation, we prepared a sample with a composition of 20% ethanol by volume and 5% zinc oxide by mass. The selection of zinc oxide was based on its superior ability to retain Novec-7000. Specifically, we opted for a 5% mass of zinc oxide in order to maximize Novec-7000 retention while minimizing any adverse effects on overall stiffness (figure S2).

However, the use of a single Peltier to rapidly cycle the activation and deactivation of the phase-change process proved to be time-consuming, as the Peltier needed time to cool down between activations. It took around 5 min for each cycle to complete. To overcome this issue and reduce the cycle time to under 2 min, two larger Peltiers with 40 × 40 mm heatsinks were used in tandem, as specified in table S1. During the activation and deactivation cycles, images were captured every 5 s, and a transition period was allowed, during which the sample was moved from one Peltier to the other. The transition period caused a change in elongation of the sample, which could be attributed to exposure to room temperature and the ambient heat of the previously activated Peltier.

The graph presented in the study demonstrated that the Peltier was capable of fully activating and deactivating the sample in approximately 40 s, and this process could be repeated several times consecutively. As it was illustrated in figures 3(b) and (c), It was observed that the maximum and minimum elongation of the sample increased with each cycle, as expected, due to the increasing deformations of the silicone after each activation. Further improvements could be made to the process by utilizing more advanced Peltiers or implementing active cooling methods. Such improvements may eliminate the need for using two Peltiers, and further reduce cycle times. Overall, the study provides valuable insights into the activation and deactivation of phase-change with increased efficiency. The use of a sample containing 20% ethanol by volume and 5% zinc oxide by mass, and the use of larger Peltiers with heatsinks in tandem, demonstrate a significant reduction in cycle time, improving the efficiency of the activation and deactivation process. These insights have implications for optimizing the use of phase-change materials in our soft actuators, leading to more efficient and cost-effective designs.

The maximum temperature achieved at each level of supplied electric current and the corresponding duration required for each level of electric current are shown in figure 5. The data indicates that the maximum temperature is not increasing proportionally with an increase in electric current supplied to the Peltier. However, as more electric current was supplied to the Peltier, the duration required to reach the maximum temperature was decreased. It is important to note that there is a limit to the maximum current that can be supplied to the Peltier due to thermal limitations, beyond which the Peltier may be damaged or overheated. Therefore, it is necessary to carefully optimize the level of electric current supplied to the Peltier for efficient operation and to prevent damage to the device.

In addition to the observations made in figure 5, another interesting finding can be seen in figure 6. It was noticed that the slope of the temperature change during the transition periods (i.e. when the Peltier switches from hot to cold and vice versa) increases from negative to positive as the number of activation-reactivation cycles increases. This phenomenon could be due to the accumulation of internal residual heat in the phase-change material over time. As the material is exposed to the ambient temperature during the transition period, it tends to expand rather than contract, which causes the slope of the temperature change to become steeper.

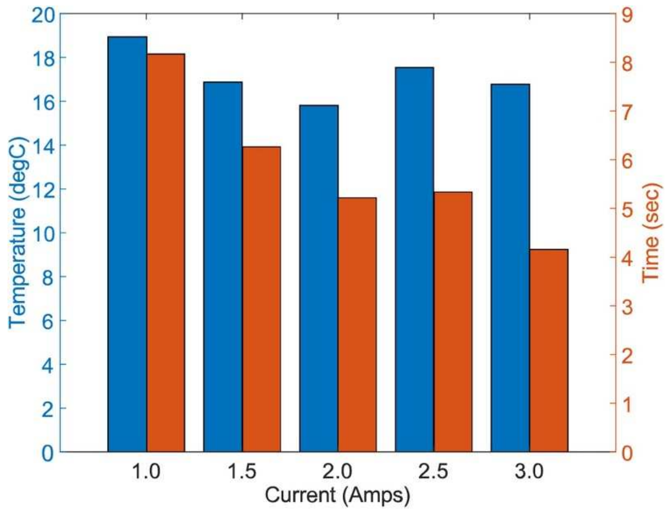



**Figure 5.** Maximum temperature of the hot side of the Peltier and the occurrence time at each level of supplied electric current.

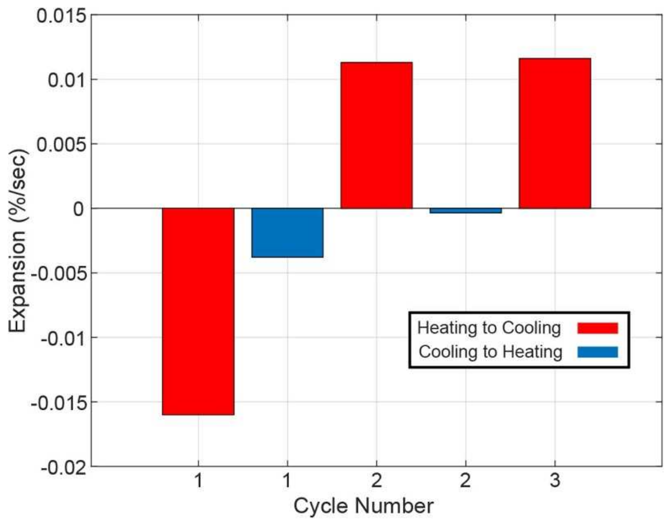



**Figure 6.** Slope of temperature changes (figure 3(b) during each transition period over different activation-reactivation cycles).

This observation highlights an important consideration when designing and using Peltier-based soft actuators with phase-change materials. The accumulation of internal residual heat can affect the efficiency and accuracy of the device over time, especially during the transition periods. Therefore, it is crucial to account for this phenomenon and implement appropriate measures to mitigate its impact, such as incorporating additional cooling systems or adjusting the activation-reactivation cycle times.

A dual-Peltier system can be implemented to increase the speed of actuation and decrease the lag time between actuation cycles. However, even with heatsinks attached, the Peltier

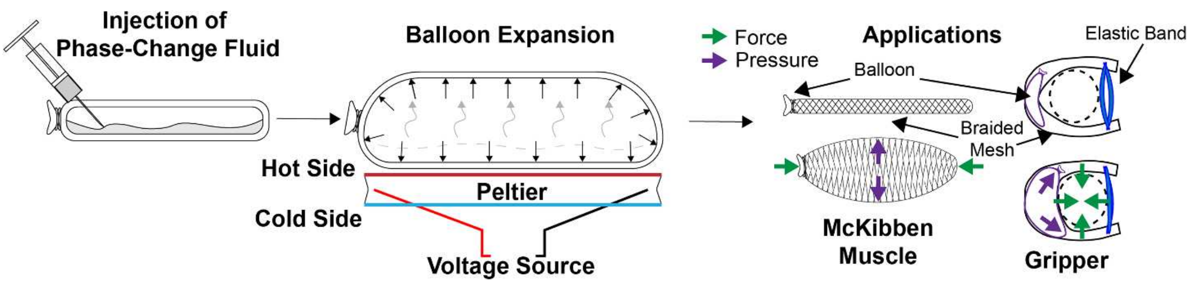



**Figure 7.** The phase-change fluid is injected into a balloon, to then be heated with the Peltier unit. Once heated, the fluid changes phases from liquid to vapor, and the internal pressure of the cavity increases leading to actuation. The first application depicted is a McKibben artificial muscle, which shortens as the internal pressure increases, producing a linear force and small contraction deformation. The second application is a gripper, which utilizes a McKibben muscle coated with silicone, and bent into a horseshoe shape by an elastic band, which conforms to a cylindrical object once the McKibben bulges from an increase in pressure.

units take much longer to cool once they are on for a single actuation cycle (about 20 s).

### *3.3. Design*

In this study, two different designs were developed to demonstrate the capabilities of the technology: a McKibben artificial muscle and a soft gripper. These applications were chosen to exhibit the high force generation, increased bandwidth, and versatility of the working principle.

For the McKibben artificial muscle, a thin-nitrile membrane was cut to a length of 70 mm, with 40 mm designated for the phase-change cavity and 30 mm slack for tying off. Then, 0.4 ml of Novec-7000 was added to the balloon before it was tied off. To enhance contraction, the edges of the McKibben were melted in a circular pattern and flared open. An external layer of silicone was created using Ecoflex 00–50 and ethanol for maximum elongation (figure 7). The silicone layer cannot be cured while in contact with the thin membrane, and therefore, it must be cured in stages. For example, the two-part mold can be cured first, followed by adding the balloon and sealing it off. Alternatively, a casing can be cured, tied closed, and then cured in silicone.

For the soft gripper, a McKibben was coated with a thin layer (<1 mm) of Ecoflex 00–50 and cured inside a climate chamber at 45 °C for 30 min. A second layer was added, and the McKibben was cured again under the same conditions. The two-layer design increased the stability of the silicone layer and the friction of the silicone when used as a gripper. A prepared balloon was inserted into the McKibben, and a rubber band was pulled taut between the two ends and fixed to the McKibben with thin copper wire. This elastic band created an artificial curvature for the McKibben body. Once the phase-change component was heated, the McKibben expanded and applied radial pressure to any object central to the arc of the gripper. This resulted in a horseshoe-like appearance of the gripper. A thin copper wire was passed through the top and bottom sections of the gripper in the middle of the length of the McKibben, creating a strand of wire fixed to both sides. This allowed for the Peltier to be tied to the McKibben by twisting the wire strands together, which allowed the Peltier to have as direct contact with the balloon as possible. The two ends of the gripper were tilted upwards at a small angle to ensure that any liquid Novec-7000 would settle near the Peltier. Finally, a thin fishing line was tied to both ends and near the Peltier to lift and guide the gripper.

To study the application of Novec-7000 in artificial muscles, a nitrile balloon filled with the fluid was placed inside a braided mesh, forming a McKibben artificial muscle as shown in figure 8(a). The muscle's top end was attached to a hook, while a mass of 500 g was attached at the bottom, creating a weight load. To actuate the muscle, a small Peltier device (as listed in table S1) was attached to the bottom of the McKibben using an elastic band. The Peltier was positioned in such a way that the phase-change fluid pooled around it, greatly increasing the actuation time of the muscle. Upon applying a current, the McKibben artificial muscle, which had a total mass of 15.71 g with the Peltier, was able to lift the 500 g mass by 13.59 mm. The current was then reversed, causing the muscle to relax and return to its original length. This experiment was conducted to demonstrate the similarity between the movement of the artificial muscle and a muscle contraction. The results indicated that the McKibben artificial muscle had the potential to lift significant loads using the phase-change fluid, showing its potential in practical applications.

The gripper (with a mass of 22.68 g, including the Peltier) was designed to grab and lift objects. To demonstrate its capabilities, a video was taken (snapshots are depicted in figure 8(b)) of the gripper lifting a 100 g mass. Aerial views of snapshots (figure 8(c)) highlight the gripper's ability to conform to the object's shape, aided by the silicone external layer that increases friction and alters the compliance of the braided mesh. The horseshoe design of the gripper requires the object to be small enough to fit within its arc. The Peltier device, attached to the bottom of the gripper with an elastic band, heats up and causes the braided mesh to straighten, which in turn forces the two ends of the gripper to push together. The resulting forces, combined with the friction between the silicone and rubber band, allow the gripper to grab and hold onto the object. In theory, reversing the current would cool down the phase-change fluid, causing the gripper to relax and release the object. However, there are two main drawbacks to this design. Firstly, the attachment of the Peltier creates a nonplanar heat transfer surface, which is highly inefficient. Secondly, by the

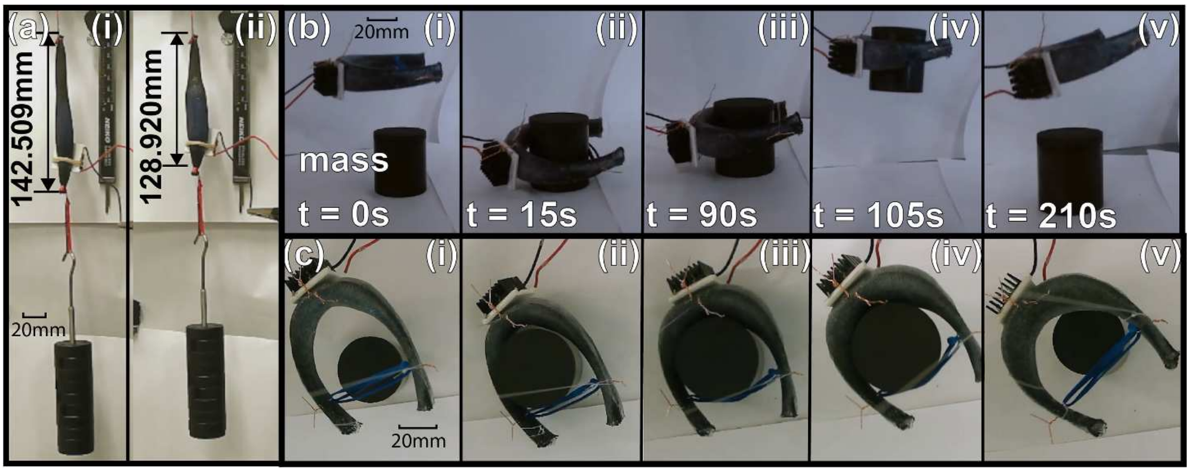



**Figure 8.** Implementation of the (a) McKibben artificial muscle ($m = 15.71$ g with Peltier) using 0.4 ml of Novec-7000 in a nitrile pouch lifting a 500 g weight, (i) resting and (ii) actuated ($\Delta L = 13.59$ mm). McKibben artificial muscle with silicone membrane implemented as gripper ($m = 22.68$ g with Peltier) (i) descending, (ii) surrounding 100 g mass, (iii) closed around 100 g mass, (iv) lifting, and (v) dropping with corresponding timestamps and views. Heating was initiated at $t = 10$ s ($I = 2.25$ A) and stopped at $t = 115$ s.

time the full actuation occurs, both sides of the Peltier are above the transition temperature of the phase-change fluid, requiring additional external cooling to release the object in a timely manner. These issues suggest the need for further optimization and improvements to the design to make it more practical for real-world applications.

## 4. Discussion

This paper proposed the usage of the Peltier effect as a reversible heating/cooling method for thermo-active soft actuators based on phase-change material to enable faster deformations, more efficient heat transfer, and active cooling, as compared to Joule heating or induction-based heating methods. The actuator proposed in this study was composed of a thin elastic membrane filled with phase-change fluid that could vaporize when heated to produce significant deformations. The membrane was placed in a braided mesh to create a McKibben muscle that was capable of lifting 5 N after 60 s of heating. Moreover, this muscle was further developed into a gripper that could manipulate objects in the environment. This is compared to previous technology which reports 0.2% efficiency and 70 s full actuation time, but relies on ambient cooling and has asymmetrical de-actuation [29]. However, there are still many considerations and shortcomings to implementing Peltier technology, which will be discussed alongside the strengths below.

After running thermal graphs on each Peltier, it was found that optimal current would be around 35% of max current for 15–20 s. This will keep the power from being too high from the internal resistance increasing as the Peltier is heated. Any longer or using more current eliminates the Peltier's capability for active cooling without an external cooling source. The Peltier's active time can be increased by utilizing heatsinks, however, the heatsinks will still accumulate heat over time that must be dissipated, removing the Peltier's capability of active cooling. Therefore, to decrease the amount of time the Peltier needs to be powered, the heat transfer to the actuator must be improved. One of the main issues with the heat transfer of the actuator was the low thermal conductivity of silicone, along with the Novec-7000 air bubbles expanding within. The silicone expanding creates pockets of air that further reduce the thermal conductivity of the silicone body. This low conductivity resulted in the heating of the soft actuator to be heavily concentrated at the contact surface of the Peltier, which causes localized expansion at the Peltier junction interface. Previous studies utilizing resistive heating [29, 42] experience this problem on a smaller level, as the soft body is built around the axis of an inner coil, and the heating/expansion occurs radially. This finding led to much lower aspect ratios with relation to the Peltier surface for the application design. A possible solution, is implementing thermally conductive nanoparticles which would increase the thermal conductivity, leading to shorter heating cycles and further elongation. Additionally, the silicone has issues binding to surfaces excluding silicone. A working solution to keep the silicone pressed against the Peltier is to apply pressure on the silicone, which is counterproductive when trying to get the silicone to actuate. Some minor success was found by simply tying the silicone to the Peltier using thin metal wire. A possible solution is finding a way to bind the actuator to the Peltier to increase heating contact area, or create planar surfaces along the actuator that cannot expand for the heating interface.

To remove the variable of thermal conductance, the experiment shifted to completely removing the silicone, by filling a balloon with a small amount of Novec-7000 and placing it in contact with a Peltier. This experiment showed a drastic increase in actuation and deactuation cycles from 90 s down to 30 s when compared with Novec-7000 infused silicone.

This speed was decreased noticeably by placing the balloon inside a braided mesh, as the heat had to transfer through the McKibben to reach the balloon. Additionally, the balloon saw a significant increase of Novec-7000 retention compared to the silicone body. The thin membrane of the balloon is all the heat has to move through to boil the Novec-7000, decreasing the time needed to actuate the balloon down to around 10 s. This allows for the ability to de-actuate the balloon using the same Peltier immediately after actuation with no rest time. Furthermore, this heating interaction needs to be optimized to allow for reversibility and active cooling in more applications/designs.

We were able to create simplistic structures using the thin-membrane design for the applications. The general principle lets the user direct expansion through the introduction of design parameters such as strain-limiting layers.

In conclusion, the design choice of using the thin membrane (balloon) to store the phase-change liquid removed the poor thermal conductivity of silicone, vastly increased the longevity of the Novec-7000 in the order of days opposed to minutes, and removed the need to adhere the expanding silicone body directly onto a Peltier. Additionally, it simplified the application designs to resemble pneumatic soft actuators.

Overall, Peltiers are inefficient once the power source is removed, as both the hot side and cold side begin to equalize as they are exposed to the ambient temperature. This paper focuses on the Peltier effect, but there may also be applications in soft robotics where the opposite effect, the Seebeck effect, may be beneficial such as energy harvesting [47].

This study demonstrates the promising implementation of Peltier devices as the heating stimuli of thermo-active soft actuators, which can allow for active cooling and enhanced control. Future works include optimization of design and heating, and targeting thermoelectric devices that utilize organic materials, which could be integrated to soft actuators. Additionally, a control system should be integrated for the Peltiers, as heat transfer becomes more efficient if you incorporate the passive heating of the Peltier after current is removed for the actuation process.

## Data availability statement

No new data were created or analysed in this study.

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