Phase-Change McKibben Actuator for Artificial Muscle

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1. Abstract

Actuators are common mechanisms that are used in robotics systems to perform movements. In the subfield of soft robotics, one conventional method to operate actuators is through a pneumatic system. However, another method to create movements is through the use of phase change actuators. This report introduces an attempt to combine the use of fluid and boiling to create a type of McKibben soft actuating muscle that is operated using the phase-change of water, which expands the actuator radially while contracting axially, and vice versa. This new actuator aims to prove the effectiveness of using phase change to operate a soft actuator to reduce the system of tethering tubes and compressors. There are two distinct tests in this report that lead to the phase-change McKibben muscle: the pneumatic muscle tests the concept of folding the inner tube while not attaching it to the ends of the muscle, and the phase-change muscle tests the concept of boiling water within the inner tube to produce actuation. The results show that for the phase-change McKibben muscle, the actuation frequency after preheating the liquid was 1 cycle per 1.5 minutes. The muscle was able to lift 42.183 N of force within 30 seconds and was able to return to its original state after boiling. This supports that the concept of using phase change to operate a McKibben actuator is possible.

Keywords: McKibben soft actuator, artificial muscle, phase-change.

2. Introduction

2.1 Background Research

Conventional soft actuators are generally categorized into three types: pneumatics, hydraulics, and SMA. Pneumatic and hydraulic actuators are operated using fluid pressure; the actuators have fast movement but require a system of tethering tubes and compressors or pumps that allow pumping and extracting the operating fluid in tandem with a pneumatic chamber network to guide the actuators' directions of movement. Shape memory alloy (SMA) actuators are operated using heat, which converts the alloy back to its pre-deformed shape. SMA's are slower to actuate and require methods of deformation prior to heating. Actuators are defined by their generated force per unit area, which means SMA's have a higher force per unit area ratio than pneumatics due to SMA having a smaller diameter.

In 2017, the Department of Mechanical Engineering at Columbia University developed a type of soft artificial muscle that utilizes the phase-change of ethanol [1]. Ethanol was distributed throughout the solid silicone elastomer matrix, which was then introduced to a heat source to reach ethanol's boiling point. The result was the expansion of the elastomer matrix due to phase change from liquid to gas, increasing volume, as shown in Figure 1. The actuator was shown to be able to lift a maximum weight of 6000 times that of its own. However, the actuation frequency of the matrix was extremely low, reaching a full cycle after around three minutes [1].

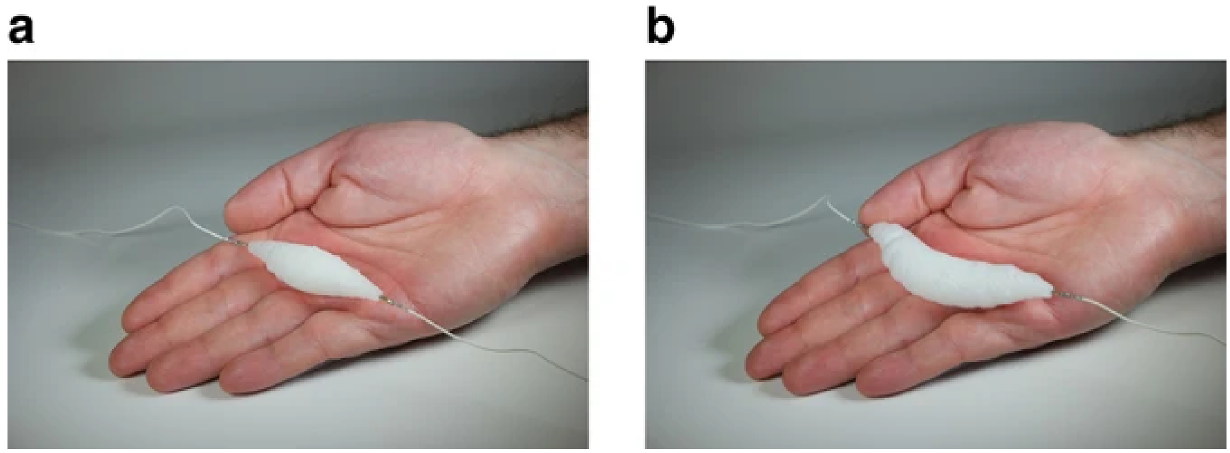

Figure 1. Soft artificial muscle composed of ethanol distributed throughout the solid silicone elastomer matrix [1]

In 2018, the Department of Mechanical Engineering at the University of Texas at Dallas conducted research on the effect of subcooling on pool boiling heat transfer using a copper microporous coating [2]. In the research, a resistive heater with a surface coated with microporous copper powder was submerged underwater. The coating allows liquid to boil at a very high heat flux, creating a vapor bubble. But since the liquid was in a subcooled state, the vapor condenses back into a liquid state quickly after boiling. The record of the experiment for both plain copper and HTCMC is shown in Figure 2.

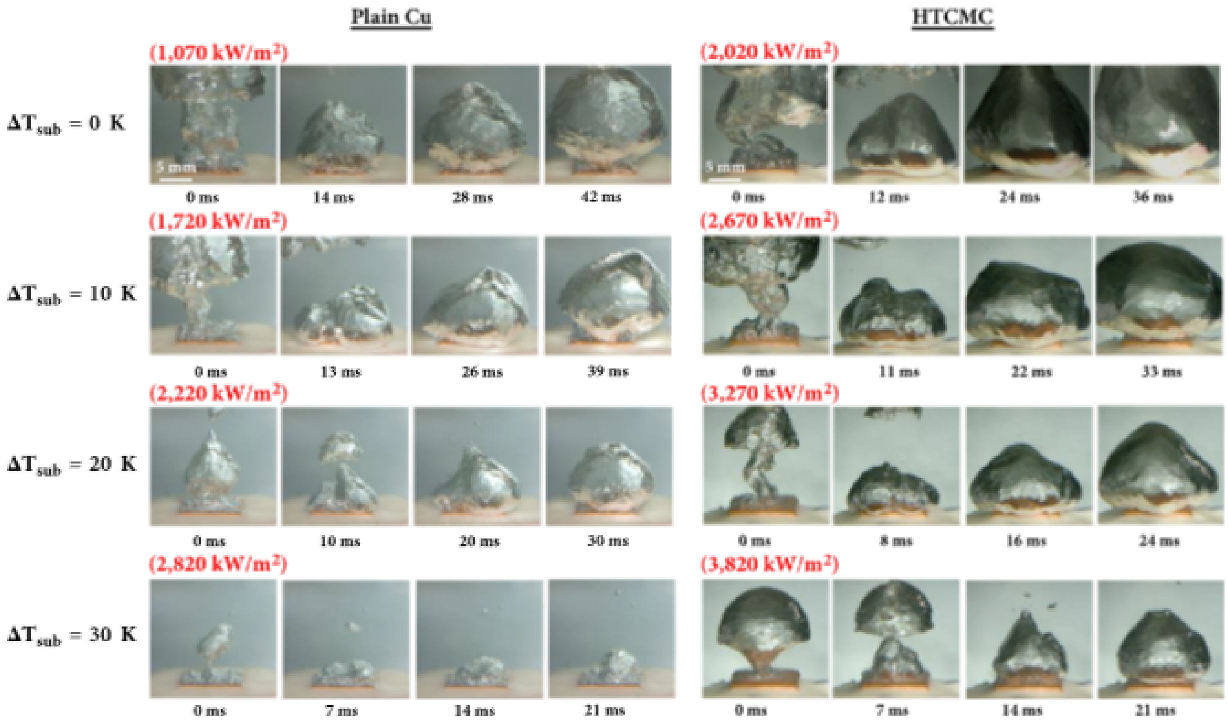

Figure 2. Comparison of plain copper and coated copper surfaces heat transfer at different subcooled temperatures [2]

The process of creating the phase-change soft actuator is similar to creating a pneumatic McKibben artificial muscle in Figure 3, where a contractible sleeve is wrapped around an elastomer tube, which allows radial expansion and axial contraction [1]; instead of using pneumatics, the phase-change actuator uses the expansion of gas from boiling liquid to operate and the elastomer tube will be foldable inside the contractible sleeve to allow compression of the gas back into liquid. Using the concepts described above, this phase-change soft actuator is intended to keep the water inside subcooled and create vapor bubbles in the subcooled water by introducing heat using a resistive heater. The formation of the vapor results in the expansion of the actuator radially, which contracts its length axially via a contractible sleeve. When the heater stops supplying heat to the water, the muscle is expected to return to its pre-boiling state immediately.

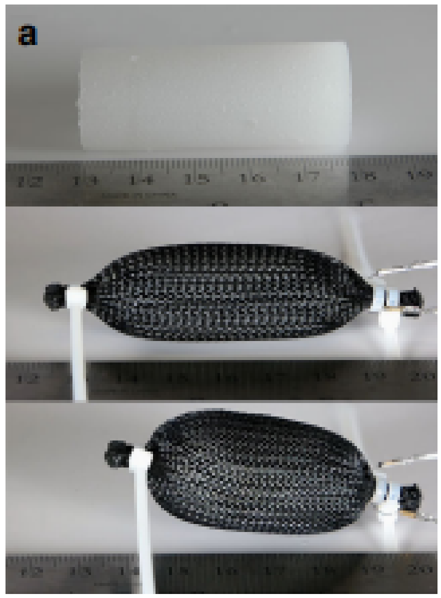

Figure 3. An example of a soft actuator showing radial expansion and axial contraction [1]

2.2 Resistive Heater

The resistive heater used for the phase-change actuator is the 20 ohms CCR-375-1 Stripline Chip With Cover Resistors by Component General as shown in Figure 4 [3]. The heater has a length and width of approximately 10 mm, which makes it ideal for small artificial muscles. The heater can achieve a maximum power of 350 W, a resistance of 20 ohms, a resistance tolerance of ± 5%, and thermal conductivity of 401 W/mK [2]. A thermocouple was installed in a 10x10x3 mm copper block soldered to the heater to collect the temperature data for monitoring. A copper surface with sintered high-temperature thermally conductive microporous coating (HTCMC) was then soldered onto the thermocouple copper block. The HTCMC surface allows higher critical heat flux to increase boiling efficiency [2]. This allows the resistive heater to boil water quickly for the phase change actuator. Epoxy helps encase the heater body, except the heating surface, along with the thermocouple and electrical wires that supply power to the heater from contact with the operating liquid.

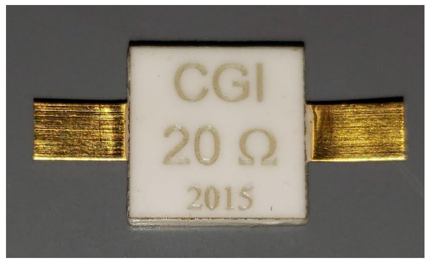

Figure 4. Component General 20 Ohms Resistive Heater

2.3 High-Temperature Thermally Conductive Microporous Coating (HTCMC)

Increased surface roughness of the copper surface on the resistive heater can increase the heat flux for the nucleate boiling system [4]. A microporous surface has cavities that can trap vapor, creating larger sites for bubble growth. However, under a prolonged period of boiling, the effectiveness of the roughed surface decreases [4]. For the resistive heater, a copper surface will be sintered with copper particles to create roughness on the surface, called a microporous coating or HTCMC similar to Figure 5 shown below.

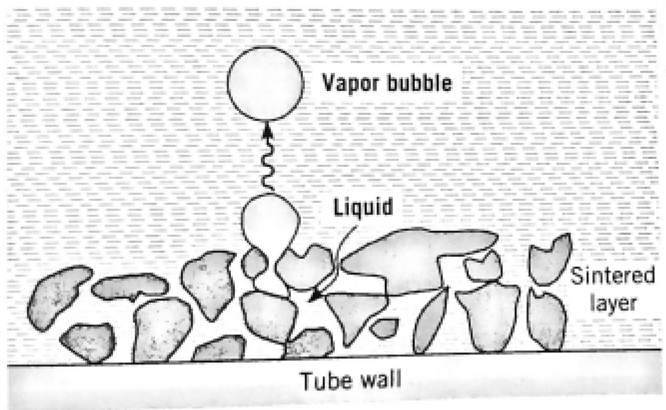

Figure 5. Surface enhancement in augmentation of nucleate boiling [4]

3. Pneumatic Muscle Test

A pneumatic McKibben muscle was created to simulate the pressure building up inside due to vaporization expansion and to prove the concept of folding the inner tube and letting it freely floats inside the muscle is compatible with the phase change muscle. A deflated and folded 4-inch rubber ball with a needle valve from iBodyCare (Appendix A) was inserted inside a 2-inch contractible sleeve. The two ends of the sleeve were tied with ¼-inch hose clamps connected with two ⅛-inch hooks to create a pulling joint on the muscle. The folds of the ball allow the ball to have a maximum expansion difference, allowing maximum contraction difference on the contractible sleeve. Unlike conventional soft actuators that have the inner tubes attached to their hooks, the hose clamps and the hooks do not tie the rubber ball for this pneumatic muscle, allowing it to freely move within the sleeve for maximum inflation. An air compression system was built to simulate the frequency of actuation of the muscle. When the muscle reaches maximum inflation, a relief valve was opened to reduce the pressure, causing the muscle to return to its original position. This allows the muscle to contract and expand at different frequencies. The testing air pressure for the muscle was measured to be at 10 psi with the actuation frequency of 3 cycles per minute. The resulting maximum contraction length of the muscle, ΔL, was 2 inches, giving the strain of the muscle, $\Delta L/L$, to be 0.2.

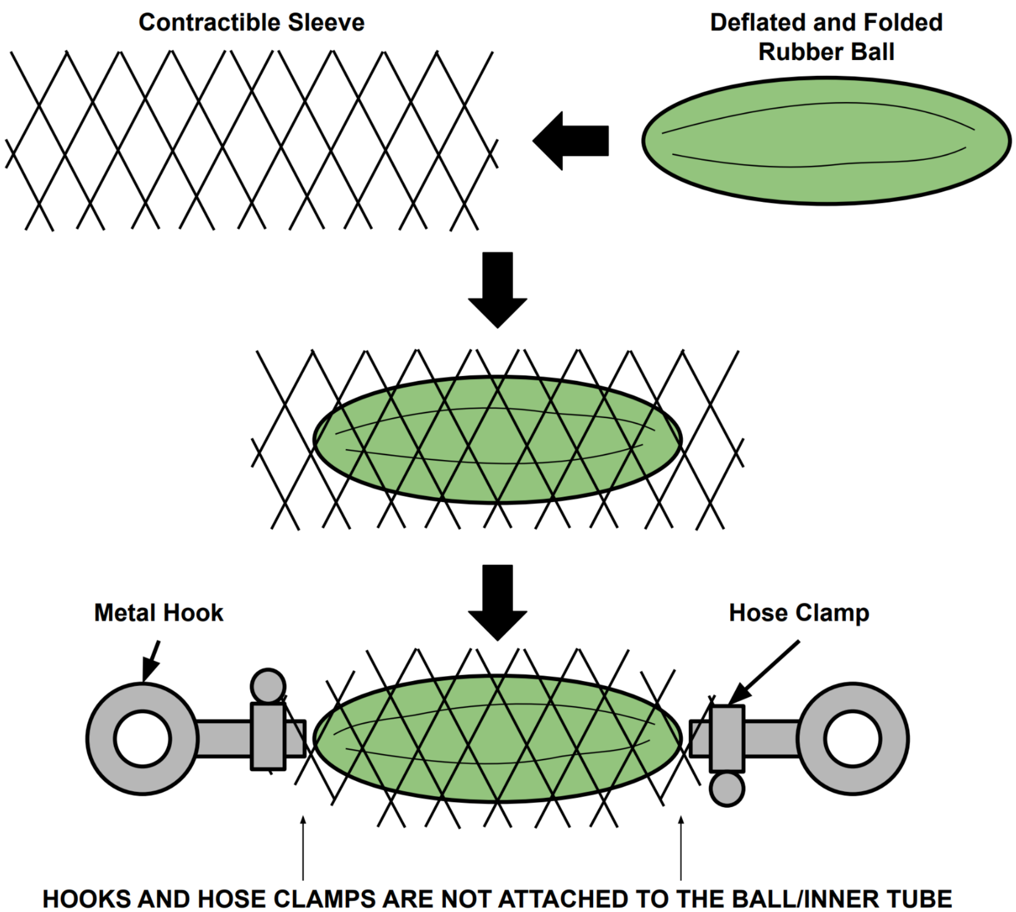

Figure 6. Pneumatic McKibben muscle development process

Figure 7. (Top) The pneumatic McKibben at its relaxed/expanded state and (Bottom) its contracted state

The pneumatic muscle shows that the ball was able to unfold itself when pressure was supplied. Since the ball was not attached to the hooks of the muscle, the ball was able to freely expand inside the contractible sleeve. This means that the contractible sleeve can be as long as we want without much affecting the properties of the muscle. Because the ball can freely move, it always moves to the position within the contractible sleeve where it has the maximum expansion difference, allowing maximum contraction in the muscle. The only thing that would prevent the ball from expanding too much or from overinflating is the maximum radial expansion of the contractible sleeve itself, which can be changed to different sleeves depending on the functionality of the muscle.

A lifting arm was made to test the strength of the muscle. The muscle was connected to the installed hooks on the crane to lift a few wheels each weight 1 kg. The crane system can only handle a maximum of 2 kg of weight, but by test estimation, the muscle can handle a lift of around 4-5 kg.

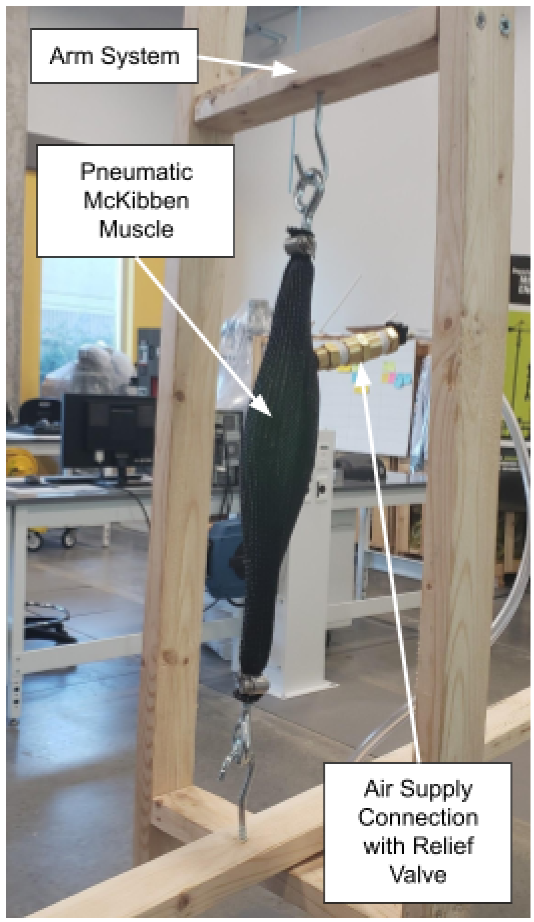

Figure 8. The crane system to test the strength of the McKibben muscle

A relief valve was installed onto the air supply connection. The relief valve was made from a plastic ball valve connected to a plastic T-joint pipe via ¼-inch silicone tubings. One end of the

T-joint pipe was connected to the needle valve while the other end was connected to the air supply with an installed pressure regulator to predetermine the inlet pressure into the pneumatic muscle. The schematic of the relief valve system is shown in Figure 9.

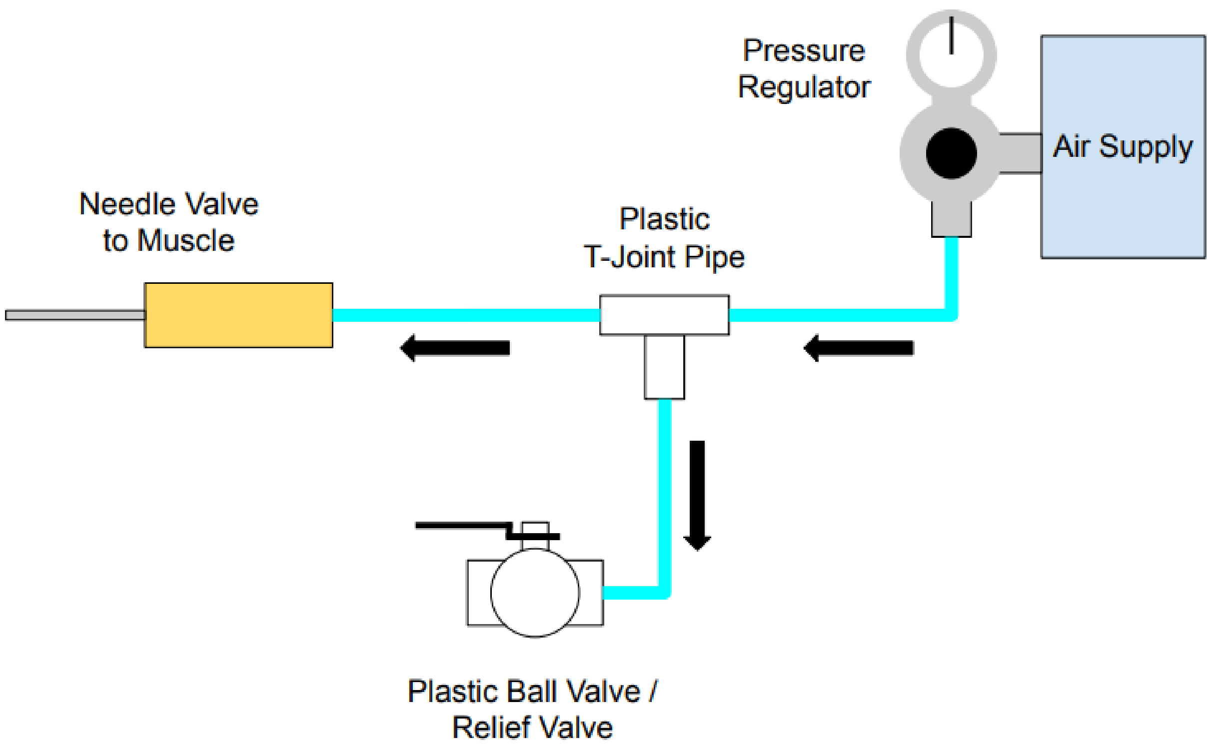

Figure 9. Schematic of the relief valve system to an air supply

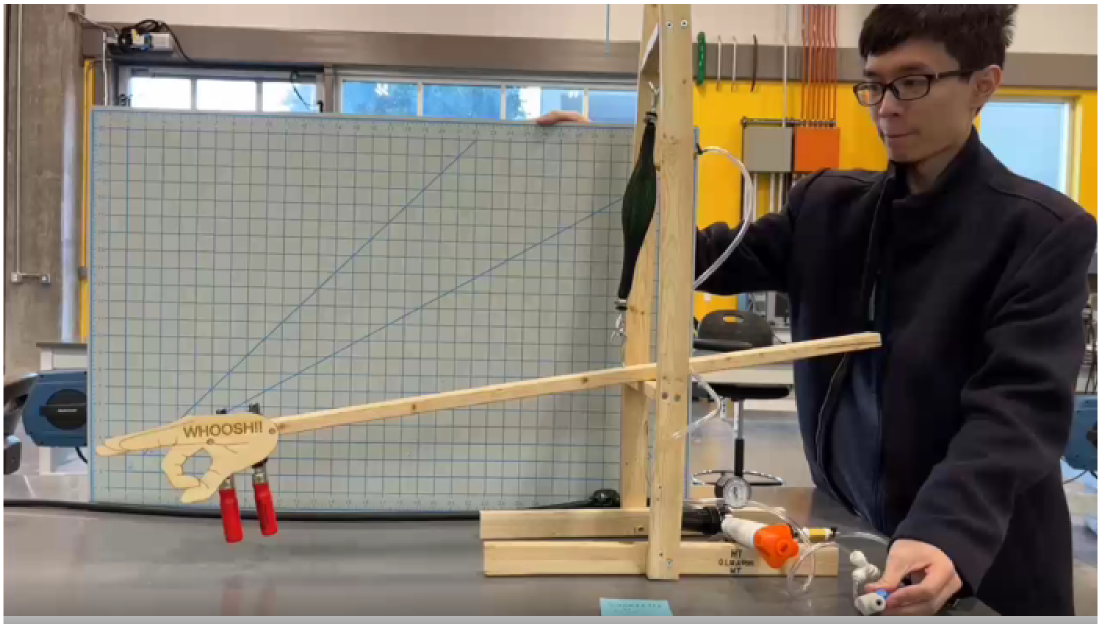

Figure 10. Tan Hoang operating the actuation frequency of the pneumatic muscle using the relief valve (left hand)

4. Phase-Change McKibben Muscle

4.1 HTCMC Resistive Heater Cap Fabrication

The resistive heater was prepared with a layer of Cu-HTCMC by using copper powder with a particle size of 67 µm [2]. The copper powder was mixed with a special thinner and spread over a 1 cm x 1 cm block of plain copper and left dried. The sample then was sintered in a furnace at high vacuum and then cleaned with 5% acetic acid by sonication and rinsed with distilled water. Wires and thermocouples were soldered onto the heater. The sample was then encased in epoxy resin, exposing the HTCMC surface. The finished heater was connected to a silicone-based bottle cap and coated with more epoxy resin to reinforce, glue, and provide a waterproof coating to the heater and the silicone cap.

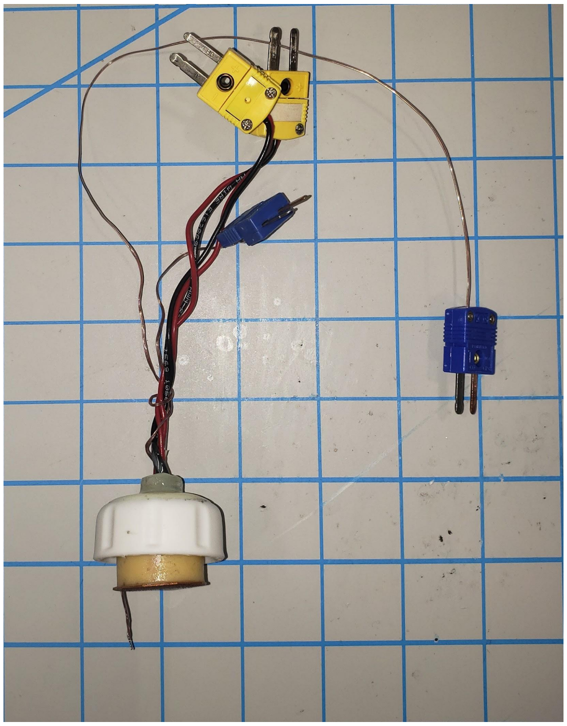

Figure 11. HTCMC Resistive Heater installed on a silicone-based cap with thermocouples and wires

4.2 Phase-Change McKibben Muscle Fabrication

To reserve the project budget, a silicone milk storage bottle from Momcozy (Appendix B) was used as the inner tube of the McKibben muscle. Silicone was chosen because of its high melting point and high-pressure resistance, which is ideal for boiling liquid inside. The HTCMC resistive heater was installed onto the cap of the silicone pouch and was made sure that the cap was watertight using epoxy resin. The silicone pouch was then folded to decrease the initial volume and inserted into a contractible sleeve before distilled water was poured until the liquid reaches the mouth of the bottle, leaving little to no air bubbles inside. The heater cap was then carefully threaded onto the pouch and ensured a tight connection. Epoxy resin was used to ensure the waterproofing of the muscle and maintain the heater cap structure due to high pressure from vapor expansion. Hooks were then installed onto the contractible sleeve but not the silicone bottle, allowing the bottle to freely move inside.

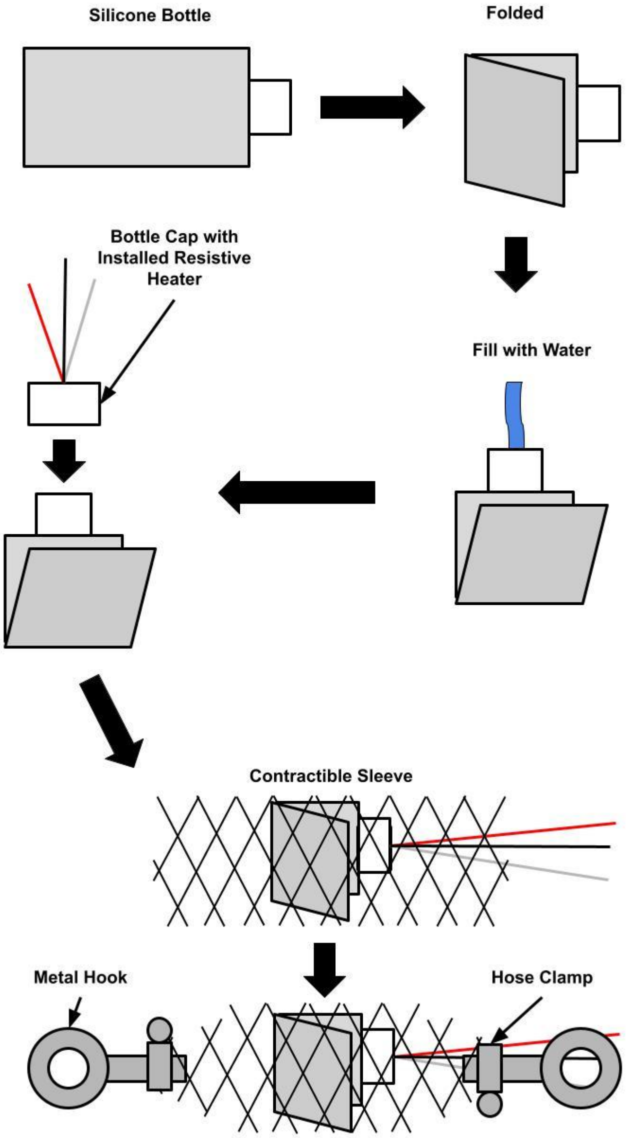

Figure 12. Phase-Change McKibben Muscle development process

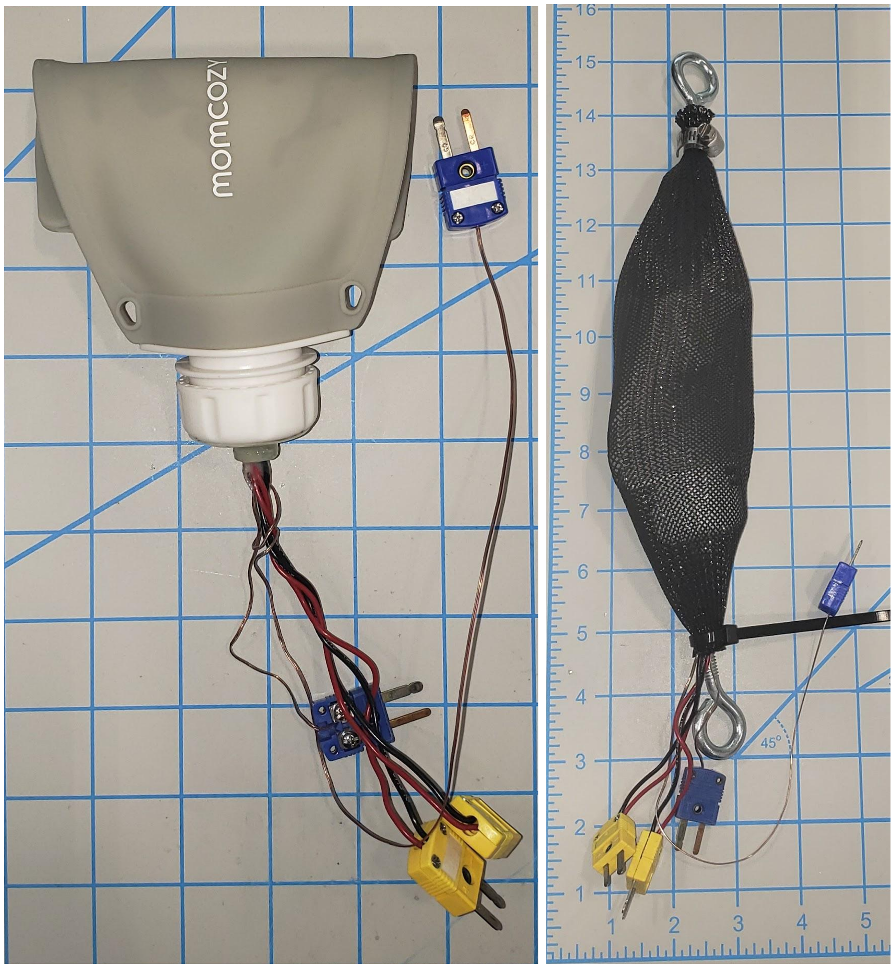

Figure 13. (Left) The folded and water-filled silicone bottle with threaded heater cap and (Right) the fully assembled phase-change McKibben muscle

5. Boiling Test Procedure

An actuation cycle of a muscle is the cycle in which the muscle contracts at the maximum length and then relaxed to its original state once. For each actuation cycle in this test, the heater has a starting supply of 1W in power to create a steady state for a computer system to acquire accurate data of the experiment before immediately supplying 200W in order to reach the critical heat flux (CHF) which generates vapor quickly. Before starting the test, the heater must first preheat the water to increase the efficiency of the phase-change McKibben muscle before determining the actuation frequency. At the initial liquid temperature of 40℃, the McKibben muscle completes its preheating phase when the muscle starts to contract approximately 2 minutes after getting 200W. The final liquid temperature after the preheating phase was 117℃. After reaching a maximum contraction, the power was turned off and the muscle was able to be relaxed to its original position, allowing the liquid to cool down at the same time. The initial preheating of the liquid gives the actuation frequency of 1 actuation cycle per 2.5 minutes.

After the preheating phase, the test begins by repeating the power supply sequence used in the preheating process with a steady supply of 1W, an immediate jump of 200W, and shutting off the power after reaching maximum contraction. Two tests were performed after preheating.

6. Data Analysis

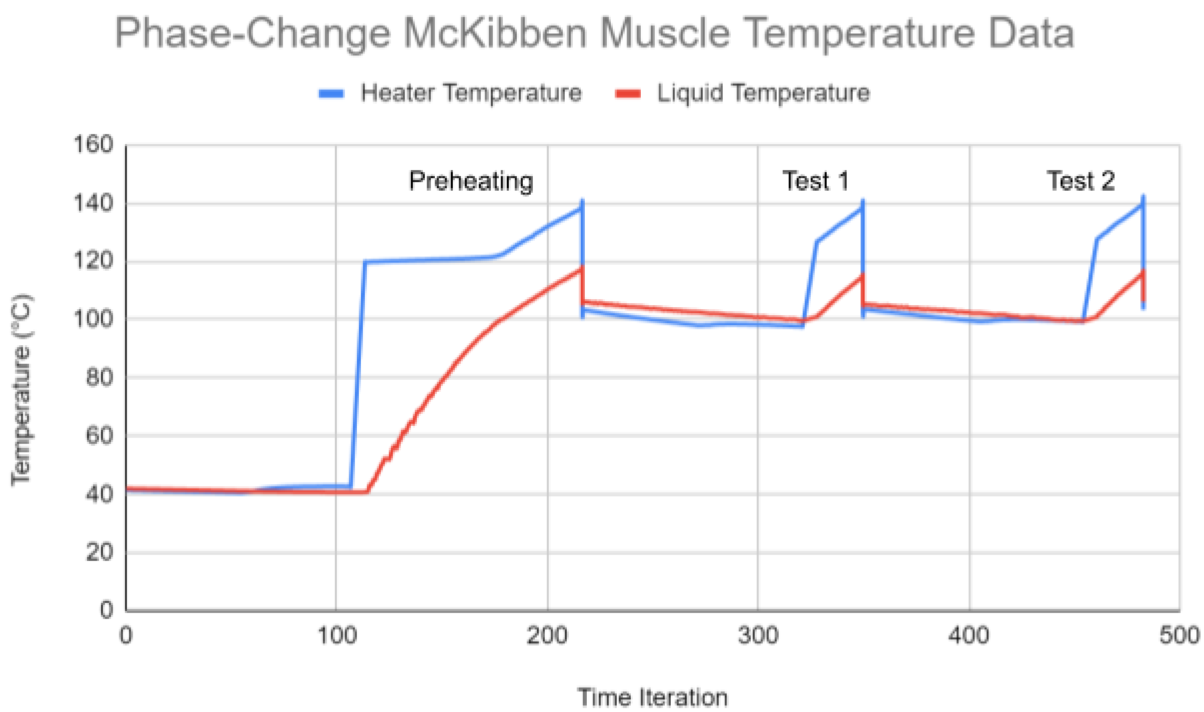

Figure 14. Phase-Change McKibben Muscle Temperature Data

The data in Figure 14 shows that upon supplying the heater with 200W, the temperature of the heater immediately increases from 40℃ to 120℃ at time iteration 100 at preheating phase. Initially, it is expected that the heater would form vapor before the water reaches boiling temperature. However, since the water was not degassed to remove any incompressible gases, the phase-change muscle requires a temperature higher than the boiling temperature of water in order to create vapor and contract. And since the water is sub-cooled, it takes a very long time for the water to reach and beyond boiling temperature. After the preheating phase, the water reaches 117℃, which was then cooled down during the muscle relaxation to 106℃ at time iteration 225. During Test 1, the heater was supplied with 1W for a steady state before getting

200W at iteration 325. Since the water was already preheated, this increases the efficiency of the muscle, reducing the heating time from 125 during the preheating phase to 25 during Test 1. The power was turned off at iteration 350 before rerunning 1W for Test 2. Test 1 and Test 2 show a similar data trend:

- Optimal actuation frequency = 1 cycle per 1 minute and 30 seconds
- Test lifting force = 42.183 N or approximately 4.3 kg of weight
- Muscle contraction length, ΔL = 1.5 inches
- Muscle strain, $\Delta L/L$ = 0.167
- Liquid amount = 50 mL

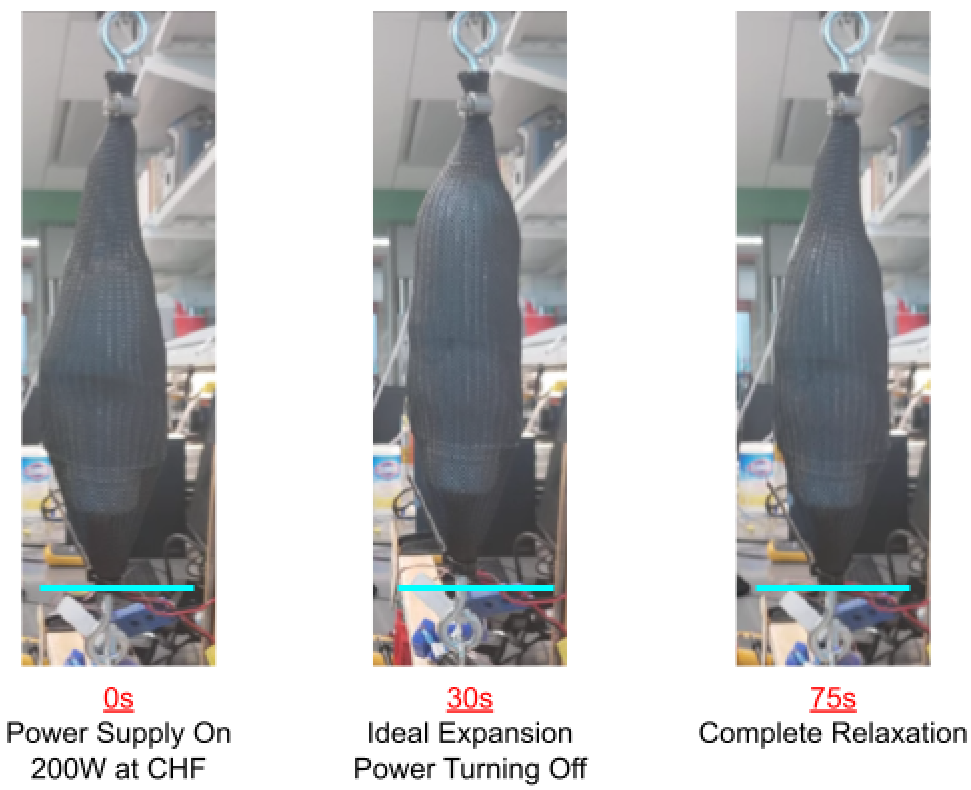

Figure 15. Prototype phase-change McKibben muscle test close-up view

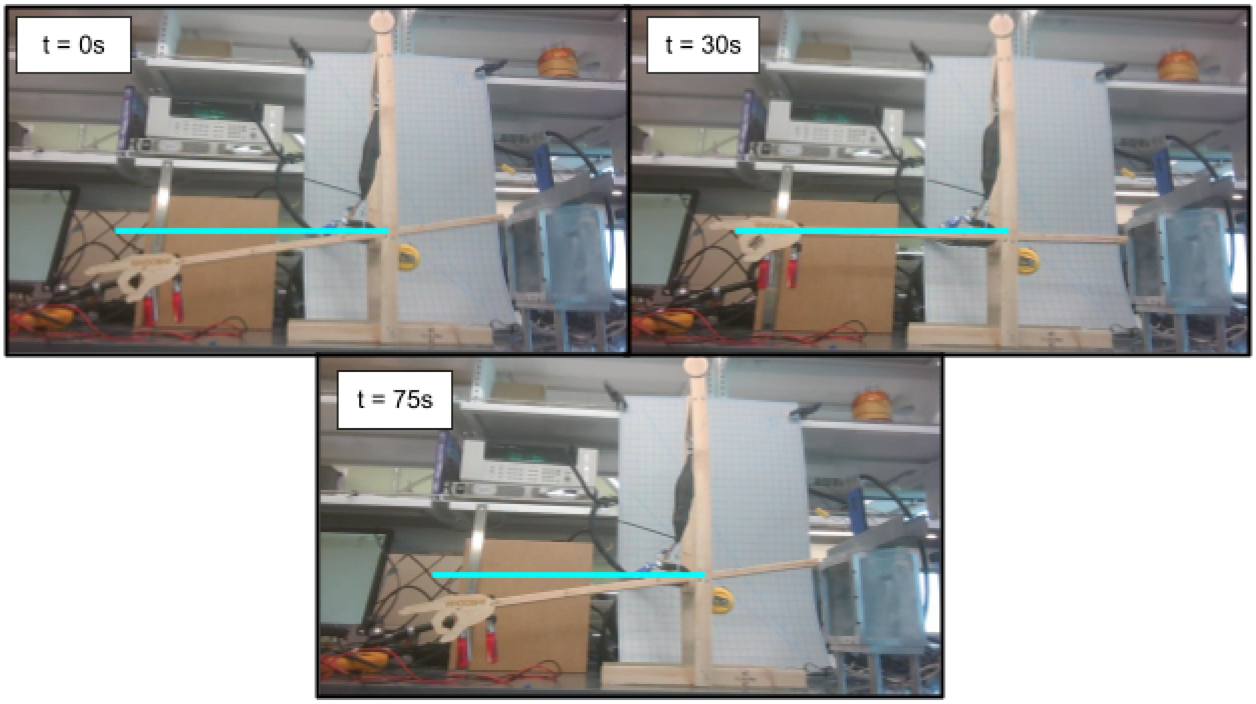

Figure 16. Prototype phase-change McKibben muscle test side view

The result shows that the phase-change McKibben muscle reaches ideal contraction in 30 seconds after supplying power, with a maximum strain of $\Delta L \approx 1.5$ inch. Upon a drop in power and heating temperature, the muscle demonstrates a slow relaxation state of 45 seconds. The test has shown that the idea of actuating a soft McKibben muscle using vaporization and an electric heater works for future soft robotics applications, this dramatically reduces the use of compressed air systems in soft actuators.

Because the silicone bottle was folded and let to move freely within the contractible sleeve, the bottle was able to expand and fill in the internal volume of the sleeve when pressure builds up, as shown in Figure 15 at t = 30s. This produced total expansion throughout the entire sleeve, maximizing the axial contraction difference of the muscle.

7. Potential Improvements

- A smaller silicone pouch is needed to maximize the expansion rate of the contractible sleeve, improving the contraction length of the muscle.
- Strong and watertight development of the muscle to prevent damage from high vapor pressure and water leakage.
- Investigate potential procedures to degas residue gaseous impurities in the water to maximize boiling efficiency.
- Investigate and incorporate cooling procedures to decrease relaxation time while not increasing heating time.

8. Conclusion

The phase-change McKibben muscle demonstrates the concept that a soft actuator can be operated using a phase change from liquid to gas and vice versa using boiling heat transfer at critical heat flux. The 9-inch by 2-inch muscle was able to lift a test force of 42.183 N, which equates to 4.3 kg of weight. The actuation frequency is not as fast as conventional pneumatic McKibben muscle but is still quick at 1 actuation cycle per 1.5 minutes after an initial preheating. Several improvements can be made to increase muscle efficiency such as degassing of the water or a smaller but stronger silicone inner tube. In conclusion, the phase-change muscle is considered a viable option for future soft robotics developments and potential applications.

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Appendix A

YOUR 4-INCH FITNESS MINI BALL
HAS ARRIVED!
LET'S ACHIEVE SOME GOALS TOGETHER!
INFLATE OR DEFLATE WITH A PUMP TYPICALLY USED FOR A BASKETBALL.
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Appendix B

Why choose Momcozy Silicone Milk Storage Bags?

Momcozy is a fast-growing brand focusing on baby feeding and breastfeeding mom nursing. We innovate and offer high-quality mom&baby products in the global market to provide comfort and meet needs.

Can be used multiple times - durable silicone storage milk bag, cost-effective

- Knob Lid Design - Strong Seal
- Multifunctional Compatible Storage
- Material One-piece Molding - No Break
- Easily Pour Milk from Breast Pump,100% Leak-proof
- The capacity is 250ml above, the container is marked with a scale, the best-recommended capacity is 250ml, it not bursting the bag during freezing and heating

User's Guidance

Step 1

Wash in boiling water for 2-3 minutes before use

Step 2

- Unscrew the Knob Cover and pour milk, no more than 250ml is recommended.
- Effortlessly pour milk from the breast pump.

Step 3

- Tighten Knob Cover, 100% leak-proof.
- Record time with label and store in refrigerator

Reusable Silicone Storage Bag

- Food grade silicone material, BPA-FREE
- Can also be made into an ice pack or hand warmer bag

Multifunctional Compatible Storage

- Momcozy Silicone Milk Storage Bag can store liquid, juice, complimentary food, etc.
- You can easy turn it into a mud bag or other storage bag

Compatible with Bottle Warmers

- Put the silicone milk storage bags in warm water to warm the milk.
- Please remove the stopper carefully before heating to avoid gas expansion. After heating, pour the milk into the bottle to drink

Easy to Clean

It can be boiled in water for 2-3 min, and put it upside down to dry

BREAST MILK STORAGE GUIDELINES - Provided by CDC

BREAST MILK STATUS	Room Temperature below 77°F / 25°C	Refrigerator 40°F/4°C	Freeze below 0°F/-18°C
Freshly Breast Milk	Up to 4H	Up to 4 Days	6 months best max 12 months
Thawed Time	1 - 2 H	Up to 1 Day	Never refreeze breast milk after thawing
Tips 	1. Please use the above stored breast milk within 2 hours after thawing 2. If fresh breast milk is not consumed within 4 days, please freeze breast milk immediately 3. The breast milk in the milk storage bag should not exceed 80% to avoid the expansion and damage of the milk storage bag when the breast milk is frozen 4. You need to use a frozen ice pack for storage when you go out. The storage time should not exceed 24 hours. When you arrive at the destination, you need to use/refrigerate/freeze immediately. Do not use it after more than24 hours.		






	Momcozy Smart Baby Bottle Warmer	Momcozy S9 Pro Breast Pump	Momcozy Silicone Milk Storage Bags - Purple	Momcozy Silicone Milk Storage Bags - Red Bean Paste	Momcozy TEMP-Sensing Discoloration Breastmilk Storage Bags - 50pcs	Momcozy TEMP-Sensing Discoloration Breastmilk Storage Bags - 120pcs
BPA FREE	✓	✓	✓	✓	✓	✓
Capacity	11OZ	180ML/6oz	250ML	250ML	180ML	180ML
Quantity	1pcs	1/2PCS	5PCS	5PCS	50PCS	120PCS
Material	Plastic	Food-grade Silicone & Plastic	Food Silicone	Food Silicone	PE & PET	PE & PET
Recommended Uses	Fast Warming/Food Heating/Steaming /Thaw/24H Keep Warm/Material Selection	Longest Battery Life; LED Display with 2 Modes & 9 Levels	Can Storage Milk/Juice/Complementary Food Ice / Warm Water (can be used for ice packs or warm hands) etc.	Can Storage Milk/Juice/Complementary Food Ice / Warm Water (can be used for ice packs or warm hands) etc.	Can Storage Milk/Juice/Complementary Food Ice / Warm Water (can be used for ice packs or warm hands) etc.	Can Storage Milk/Juice/Complementary Food Ice / Warm Water (can be used for ice packs or warm hands) etc.

Product information

Technical Details

Package Dimensions	8.39 x 4.61 x 3.35 inches
Item model number	milkbag
Material Type	Silicone
Item Weight	15.5 ounces

Additional Information

ASIN	B09R4N59G3
Customer Reviews	281 ratings 4.8 out of 5 stars
Best Sellers Rank	#2,780 in Baby (See Top 100 in Baby)