All-Soft Material System for Strong Soft Actuators

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Abstract— **In this paper, we present an improvement to a recently developed thermally responsive silicone-based actuator. The actuator is made of silicone with dispersed solvent droplets and expands when the droplets undergo a liquid-gas phase transition, which is achieved at low voltages using an embedded Joule heater. In previous work, the embedded heater was a nickel-chromium spiral-shaped Joule heating wire. In the present work, we replace the wire with a silicone-based conductive composite to create a fully soft actuator. We characterize the thermal response of the conductive composite for Joule heating the actuator and the blocked force of the actuator when implemented as a McKibben-like muscle. From this, we show that the conductive composite performs as well as the original wire heater, with improved material compatibility. Finally, we demonstrate a 20 g silicone actuator embedded with the conductive composite lifting its 4.3 kg DC power source.**

Keywords: all-soft system; soft artificial muscle; soft electrically conductive heater; thermally responsive actuator;

I. INTRODUCTION

Soft-material robotics aims to provide robots with the compliance and large strains necessary for performing natural and delicate tasks [1], [2]. Rigid robotic systems have consistently had the advantage of high-speed, high-precision, and high-output force actuation that allows them to carry both their own power supplies and control circuits while performing autonomous (untethered) tasks. Developing all-soft actuators for replication and amplification of natural muscle functionality so that soft robots can compete with their rigid counterparts is an ongoing challenge for the soft robotics research community [3].

Recently Miriyev et al. reported a self-contained, stimulus-responsive composite material by simply mixing silicone rubber and ethanol [4]. This new soft, robust composite can be used as a high-stress actuator at very low voltages (as low as 8 V), with output linear strains of up to 140%. However, lacking a soft, robust Joule heater, actuation of this material was demonstrated using an embedded, nickel-chromium (Ni-Cr) spiral-shaped wire. Using a wire limited the ability to geometrically design an internal heater and the ability to simultaneously 3D-print the entire heater/actuator system [4]. A recent development of an electrically-conductive elastomer composite for stretchable sensors [5] possesses a promising opportunity to address the need for a soft, bulk-material Joule heater. The low-cost conductive composite, a silicone elastomer matrix with an expanded intercalated graphite (EIG) conductive additive, retains its performance even at large strains of up to 250%.

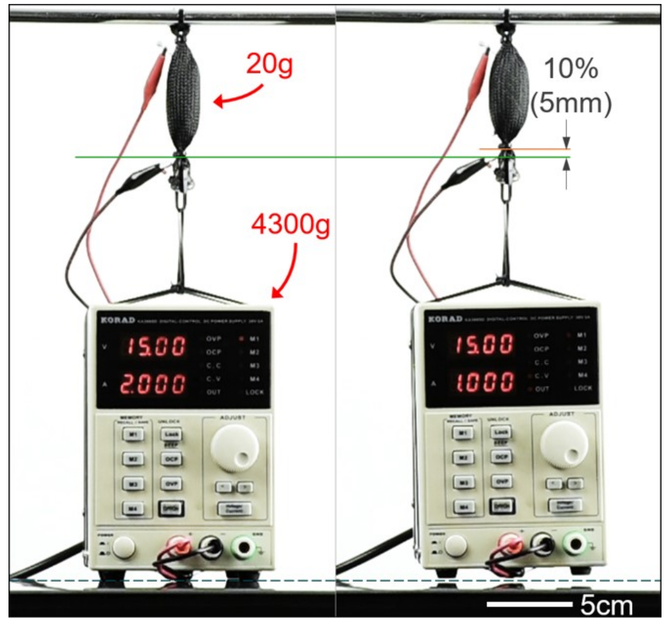

Fig. 1. All-soft heater/actuator being used as a McKibben-like muscle. The actuator is lifting its DC power supply, whose mass is greater than 200x that of the actuator.

In this work, we fabricate an EIG-silicone conductive composite for use as a Joule heater and encase it within the thermally responsive ethanol-silicone composite to form an all-soft actuator. We demonstrate that at 15 wt% conductive filler, the heater core is capable of stretching with the encasing actuator and has the low resistances required for Joule heating at low voltages. We characterize the heater core's capabilities with various geometries and demonstrate its application as a Joule heater in a fully-soft artificial McKibben-like muscle that compares in force output to the original variant with a Ni-Cr wire heater. Finally, as demonstrated in Figure 1, we show that this all-soft actuator can lift its own power supply (200x heavier than the actuator itself).

II. BACKGROUND

Many forms of soft actuators have emerged in recent years as partial solutions to the need for high-force, high-deflection actuators, using a wide range of activation methods. These include fluidic elastomer actuators (FEA) [6]–

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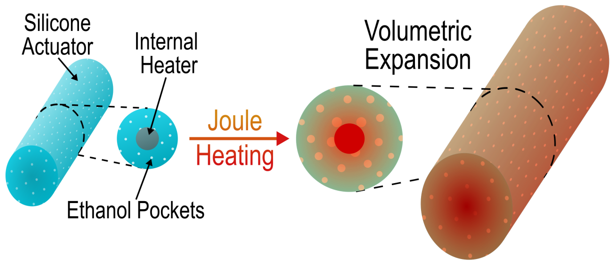

Fig. 2. All-soft actuator operation. Heating the core causes the external silicone to expand as the ethanol droplets trapped inside boil.

[11] and pneumatic artificial muscles (PAM) [12]–[14] which operate off of pressurized fluids, as well as electrically active (and Joule-heated) solutions such as electroactive polymers (EAP) (including dielectric elastomer actuators (DEA)) [15]–[19], ionic polymer-metal composites (IPMC) [20], [21], and shape-memory alloys (SMA) [22], [23]. Each of these actuator techniques has an advantage-disadvantage trade-off, making them only partial solutions to the development of autonomous soft robotic systems.

Actuation methods combining high actuation stress along with high actuation strain include FEAs, PAMs and DEAs [4]. FEAs and PAMs require compressors and pressure regulating equipment to inflate and deflate elastomer bladders or chambers. The required external equipment accompanying these types of soft actuators is usually rigid, bulky and heavy, negating their high force output [1]. DEAs operate at >1 kV to create electromechanical response of an elastomeric membrane between two electrodes, requiring a high voltage converter and complicating the safety of human-interaction with these devices [24]. Though SMA actuators can achieve high strains through Joule heating at low voltages when properly programmed, even small amounts of overheating causes a rapid degradation of the SMA programming [25]. Alternatively, monopropellant decomposition (and even combustion-based actuation) has been reported as a light-weight fluid pressure source for completely soft pneumatic robots [1], [26]. Designing a soft robot with fuel-decomposition-based actuators has resulted in moderate output forces and complex design challenges, since noise, high temperature and toxic by-products need to be taken into account [27]. Furthermore, despite the high actuation impact of a combustion-propelled robot, controlling such actuators has been a challenge. Finally, actuation methods which show limited strain but sufficient actuation stress include paraffin-based solid-liquid phase transition actuators (only 3% strain) [28] and piezo-polymers (less than 1% actuation strain). These strain values are insufficient for most soft robotic applications, and therefore do not meet current needs.

The silicone-ethanol actuator reproduced in this work has been shown to function on a basic principle: By mixing the two materials together, the ethanol is distributed throughout the silicone matrix in micron-scale pockets that are suspended in place after curing. Upon heating to 78.4°C, ethanol boils inside the micro-pockets, leading to tremendous increase in volume of the entire composite (see Figure 2). Ethanol was chosen for its low toxicity, its good ability to mix with silicone, and its moderate boiling temperature [4]. Previous work has succeeded in producing volumetric strains of up to 900% and exerting a force sufficient to lift a weight over 1000 times larger than the composite material.

Prior work with the EIG material has shown that it is possible to increase the amount of additive in a silicone matrix, without loosing stretchability [5]. The EIG material has also already been demonstrated as a conductive filler enabling internal heating in a rigid epoxy composite [29]. It enabled the Joule heating of the epoxy, causing the composite to soften and change its basic shape. This previous success motivated us to increase the concentration of EIG in the silicone composite and use it as a soft heater.

III. Manufacturing

We note that, for clarity, the silicone-ethanol actuator mixture will be referred to as the actuator composite, and the EIG-silicone mixture will be referred to as the heater composite. The manufactured silicone composite with a heater core will be referred to as the silicone actuator. Finally, when referencing the whole system (the silicone actuator in a mesh sleeve like a McKibben actuator), the system is referred to as a muscle.

A. Silicone Actuator Manufacturing

We used Ecoflex 00-50 (Smooth-On) for both the actuator composite and the heater composite. It is received from the manufacturer in two parts (part A and B) and we used it a 1:1 ratio. To create the actuator composite, we cast the silicone ethanol mixture into a 20 mm dia. cylindrical mold, 50 mm tall with a central shaft (see Figure 3a and 5a). We mixed both part A and B with ethanol (20 vol% ethanol) by hand for 1 min and then in a planetary centrifugal mixer machine (Thinky Mixer, Thinky USA) for 1 min. Once the silicone cured, the 3-part mold was removed, leaving an internal hollow core for later insertion of the heater composite.

For the heater composite, expandable graphite was purchased in a pre-prepared, dry state from Sigma-Aldrich. It was expanded and sonicated into EIG through a high-temperature oven roasting process (800°C) previously detailed by White et al. [5], with one key difference being the use of ethanol as the sonication solvent. We made this change (from cyclohexane used previously) to improve compatibility with the actuator, with no noticeable degradation of the conductivity of the final silicone composite. After preparation of the EIG-ethanol mixture (through sonication and drying), the mixture is still mostly ethanol (only ∼4 wt% graphite). Part B of the silicone was mixed with the EIG composite, and then air was blown across the composite to force the evaporation of the ethanol (see Figure 3b). This dries the mixture down while still enabling dispersion of the EIG in the silicone. Once the composite was dried to only 50 wt% ethanol, Part A was added and the entire composite was mixed thoroughly to create a ratio of 15 wt% EIG-silicone. The heater composite was then injected into the hollow core

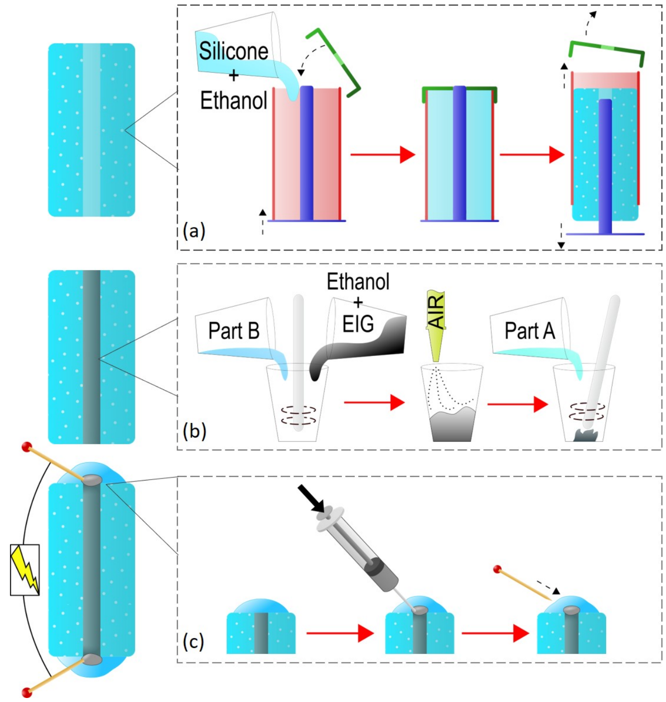

Fig. 3. Manufacturing the all-soft silicone based actuator. (a) A silicone-ethanol mixture is poured into a mold to cure, creating a cylindrical actuator with a hollow core. (b) To make the heater core, part B is mixed with an EIG-ethanol mixture, set under an airflow until nearly dry, and then part A is mixed in. Before it cures, the silicone-EIG composite is injected into the hollow core of the actuator. (c) The ends of the actuator are sealed with silicone and liquid metal is injected into the joint at the end of the heater composite. Finally, a pin (or copper wire) is inserted into the liquid metal bead to create an electrical connection to the heater core.

of the actuator composite using a syringe, and allowed to cure.

B. Muscle Assembly and Electrode Contacts

We used eutectic gallium-indium-tin (galinstan, Sigma Aldrich), a room-temperature liquid metal, to create a simple interface connecting the soft core heating composite with rigid wires and electrical components (Figure 3c). We sealed each end of the silicone actuator with additional (stronger) silicone (Dragonskin Fast, Smooth-on) and then injected galinstan into the ends of the actuator using a 25 gauge syringe needle. On removing the syringe, we sealed the hole with additional silicone and assembled the muscle by placing the silicone actuator into a mesh sleeve (Polyurethane terephtatalate mono-filament yarn, Techflex) and tying it off.

In order to electrically connect to the core, we punctured a needle through the mesh and into the liquid metal bead, allowing us to connect the heater to a power source. In the case of experiments where free-expansion (or heating) was required, the mesh sleeve was omitted. We note here that while these electrodes provided an ideal electrical interface, they were susceptible to leakage under high pressures, which manifested as electrical noise.

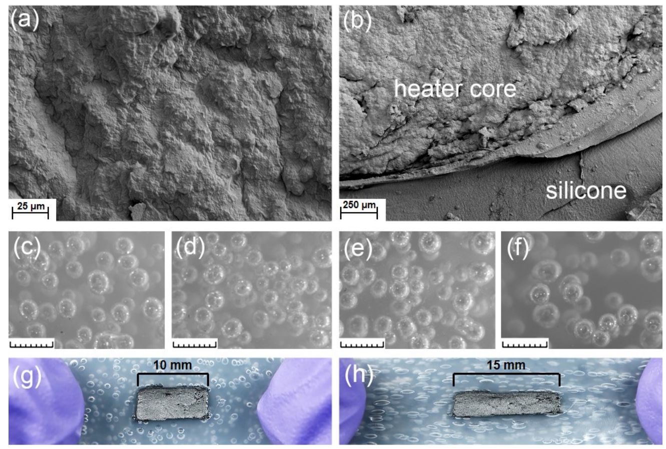

Fig. 4. Macro- and microstructure images of the all-soft material system for actuators. (a) SEM image of the soft heater composite. (b) SEM image of a silicone/heater interface cross-section. (c)-(f) macrostructure of actuator composites after preparation with different mixing modes and rates: (c) hand mixing for 4 min, (d) mixer machine mixing for 0.5 min, (e) mixer machine mixing for 1 min, (f) mixer machine mixing for 3 min (scale bars are 500 µm). All-soft actuator composite before (g) and during (h) hand-stretching, showing 50% linear strain extension in the core.

IV. Characterization

A. Manufacturing Implementation

1) Heating Core Resistance: The resistance in the heater silicone cores varied between 15-65 Ω, comparable to the 15 Ω in the original Ni-Cr wires [4]. Two key factors in our design and manufacturing allowed for such a low, uniform resistance in the composite material: the use of the liquid metal electrodes and prevention of the ethanol from drying out of the composite material during preparation. The liquid metal contacts decrease the contact resistance between copper wire electrodes and the soft heater composite. Without the liquid metal, the resistance in the heater core increases by 20-40 Ω, often doubling the sample resistance and causing uneven Joule heating due to the additional resistance concentrated at ends of the actuator. This is why the liquid metal was used even though it leaked during actuation.

Preventing the ethanol from fully drying out of the heater composite before it cures is the second key to maintaining low resistance. If the heater composite dries completely before mixing in Part A (during the manufacturing, as previously explained) the resultant resistance of the core jumps 1-2 orders of magnitude (from 25-65 Ω to 800-2500 Ω, measured on cores with a diameter of 5 mm and 7 mm). It is still possible to mix in Part A and inject the material, but the high resistance makes the core unusable as a heater. We suspect that when the composite dries prematurely the EIG flakes clump, resulting in poor dispersion throughout the composite. If the silicone cures in the 50% ethanol mixture, the EIG flakes remain suspended in the unmoving polymer after the ethanol dries off.

2) Heater Microstructure: We placed a silicone actuator into a scanning electron microscope (SEM) in order determine the quality of the heater composite mixture and to visually observe the joint between the actuator composite

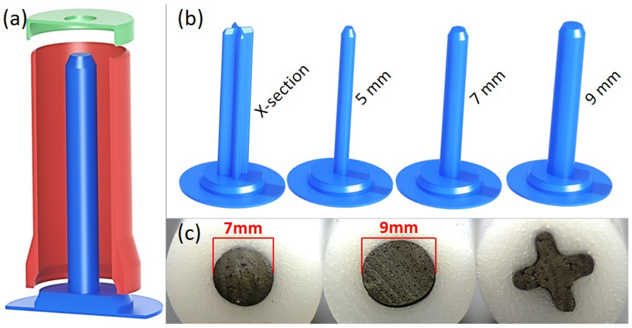

Fig. 5. CAD diagrams and photographs of the various heater core geometries. (a) A cut-away of the CAD rendering of the three-part mold. (b) Models of the four different cores used in the mold. (c) Cross-sectional photographs of three of the resultant heater core/actuator combinations.

and the heater composite. Figure 4a,b are images taken of both the pure heater composite and the heater composite interfacing with a pure silicone exterior. We also prepared a sample without ethanol in the actuator (to remove incompatibility with the high-vacuum SEM), and cut it with a knife to expose an inner cross-section for imaging. The heater composite has a textured microstructure topography on a scale from single microns to tens of microns, caused by the conductive EIG additive (Figure 4a). Although individual EIG flakes are too small to be seen at this scale, no EIG clumps are observable, indicating a good mixture of the EIG into the silicone. The interface between the heater composite and pure silicone rubber is characterized by multiple microcracks, and a noticeable difference in topography between the two materials (Figure 4b).

3) Actuator Macrostructure: To ensure that the ethanol was distributed evenly throughout the actuator composite when machine mixed, we tested the effect of mixing the actuator composite by hand or in a mixer machine on the bubble density of the composite. Four samples of silicone-ethanol composite were inspected under a microscope to observe the density of air-pockets (or ethanol droplets) in the mixed composite. Each sample was prepared with different mixing time/method. The first sample was mixed by hand for four minutes. The other three were mixed by hand for one minute (to fold the low-viscosity ethanol into the high-viscosity silicone) and then mixed in the mixer machine for 0.5 min, 1 min, and 3 min respectively. All samples were then cast into sheets 5 mm thick to allow the microscope to capture the images of the bubbles through the sample. Figure 4c-f shows that the largest amount of air bubbles was achieved after 30 s of mixing in the mixer machine, whereas mixing for three minutes resulted in the lowest density of air bubbles. This validates our mixing for 1 min, as the actuator composite has a comparable macrostructure to the hand-mixing method used in previous work [4].

4) Heater Stretchability and Interfacing: Although the interface in the all-soft material system was shown to have microcracks (Figure 4b), we still achieved a high bond between the heater composite and the actuator composite. To demonstrate this, we cast a large, flat sample of the actuator composite, with a small, 10 mm wide rectangular core, and filled the core with the heater silicone composite (Figure 4g). This enabled us to stretch the external silicone and observe the reactionary stretching of the internal heater. As Figure 4g-h demonstrates, we could achieve both good adhesion between the disparate composites and a 50% linear expansion of the heater composite. The ability to both adhere the bulk composites together and for both to have high strain capacities is vital for the success of these all-soft actuators.

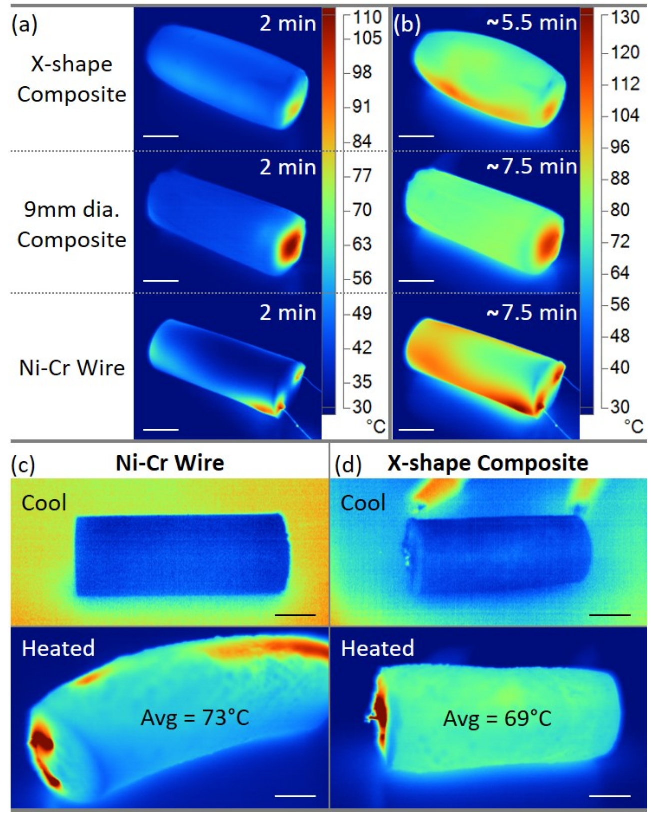

Fig. 6. IR images of several Joule heating experiments using 9 W of input power. (a)-(b) Two silicone heater composite cores are compared with a Ni-Cr wire heater via encapsulation in pure silicone. (a) At 2 min, the X-shaped core is distributing its heat better to the exterior of the silicone, when compared to the other two systems. (b) The same cross section achieves an external temperature of ∼78°C two minutes faster than the other systems. (c) The Ni-Cr wire heater compared with (d) the X-shape core, encapsulated in the actuator composite in their initial (cool) and final (heated) states. Scale bars are 1 cm.

B. Heating and Energy Distribution

1) Core Design: We used four different types of internal shafts in order to compare differences in heater performance based on the geometry of the core (Figure 5). Three actuators had circular cores with diameters varying between 5 mm, 7 mm and 9 mm. We also created a fourth core in the shape of an X, with the same cross-sectional area as the 7 mm circle (38.38 mm^2, see Figure 5c). This shape has the same volume of heater composite as the 7 mm core, but a larger contact area with the actuator composite. Ni-Cr wire (Remington Industries) heaters were coiled in a double-spiral and cast directly into the actuator composite in order to compare the current all-soft system to the original work employing this silicone-ethanol actuator technology [4].

2) Core Performance: We used a thermal camera (Fluke TiX580, Fluke) to characterize the ability of the heater composite to heat the surrounding actuator composite up to (78.4°C), the boiling temperature of ethanol. We started by heating a simple, pure elastomer sheath around the heater core (to remove the effects of the expanding ethanol). All four varieties of heater composite cores (5, 7, 9 mm, X-shape) and a Ni-Cr wire heater were encased in the silicone rubber and Joule heated with 9 W of power (only two of which are shown in Figure 6a,b).

After two minutes of heating, the X-shaped heater composite shows better heat distribution than any other composite (Figure 6a). The X-shaped heater also heated the entire outer surface to 78°C two minutes faster than the other setups, taking only 5.5 min. The X-shaped heater core proved to be the best Joule heater design when power was controlled as it can heat the required volume both quickly and evenly. Though it has a higher resistance than the 9 mm heater composite rod and Ni-Cr wire spiral (also shown in Figure 6a,b), those two suffered from localized overheating near the heaters and/or peripheral under-heating. The higher contact area of the X-shaped core with the actuator composite is more efficient as it nearly eliminates localized overheating. Note that the slight expansion of the specimen with the X-shaped heater composite core is caused by a small amount of ethanol trapped in the heater core during the filling process.

The spiral-shaped Ni-Cr wire has the smallest volume of the heating cores, and, though rigid, it causes significant expansion and shape deformation of the silicone actuator due to the high flexibility of the wire spiral and local overheating (Figure 6c). When heated, the X-shaped heater composite showed a smaller but more even expansion of the surrounding silicone actuator (Figure 6d). This difference, however, does not prevent the X-shaped heater from producing large output forces when constrained in a mesh (see next section).

C. Force Output

In Figure 7 and 8, we show the potential of our all-soft material system to be the actuator in a fully soft McKibben-like artificial muscle. When encased in a braided mesh sleeve (Figure 7a,b), the silicone actuator is capable of radial expansion in the net, leading to axial contraction of the entire muscle. The muscle is activated by supplying electrical power to the internal Joule heater. For comparison, the original work, which also demonstrated the actuator as a McKibben-like muscle [4], was also recreated (Figure 7).

To determine the maximum pulling force of these muscles, we performed a series of blocked force tests. We clamped a new artificial muscle in an Instron 3345 using pneumatic grips (Figure 7c) and Joule heated the actuator with 30 V and unregulated DC current. We measured the force output of the statically-held muscle until it either failed mechanically (Figure 7c) or electrically. As the current fluctuated while heating the actuators with heater composite cores, we were not able to record a steady value and were therefore unable to calculate power consumption.

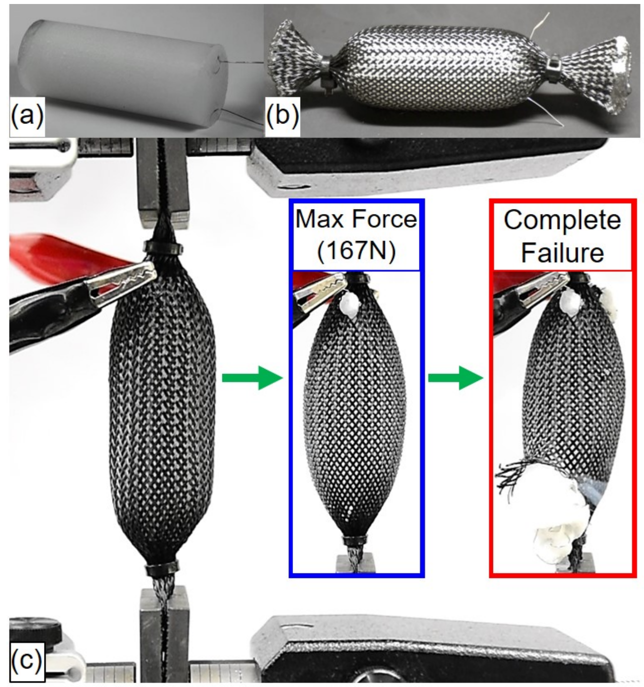

Fig. 7. Blocked force setup and test. (a) A Ni-Cr wire heated actuator. (b) The same actuator inside a mesh sleeve for use as a McKibben-like muscle. (c) The actuator installed in a blocked force test. Insets show the Joule heated actuator at its maximum force and then after complete failure (due to melting the external mesh).

We tested all four configurations of the all-soft muscles and the original Ni-Cr spiral-heated version in order to compare their maximum blocked force. The results, shown in Figure 8a, show that most variations of the all-soft muscles can consistently exert more than 200 N of force, corresponding to more than 1000x the weight of the entire artificial muscle (<0.2 N), as can the Ni-Cr heated version. On average, the 9 mm heater composite performed best, exerting a blocked force of nearly 300 N, significantly higher than that produced by the 5 mm cores (barely 60 N).

Both the 9 mm cores and Ni-Cr wire actuators failed mechanically. The pressure of the expanding silicone actuator exceeded the strength of the mesh, typically resulting in sudden and complete failure and force loss (see Figure 8c inset). Though the mesh failed for both types of actuators, the Ni-Cr averaged significantly less pulling force before failing (nearly 100 N less). The Ni-Cr wires would consistently draw 1.5 A of current, with the 9 mm cores drawing between 1-2 A during their testing. Although they both were drawing similar power, the 9 mm cores isolated the incoming energy as heat in the central core of the actuator, causing only an expansion of the ethanol. In contrast, the Ni-Cr wire created localized hot-spots at the exterior of the actuator (see Figure 6) weakening the mesh, and causing them to fail prematurely. This was especially true at the ends of the actuator, where the Ni-Cr wire leads entered the mesh and where the wire turns around. Input power regulation (and

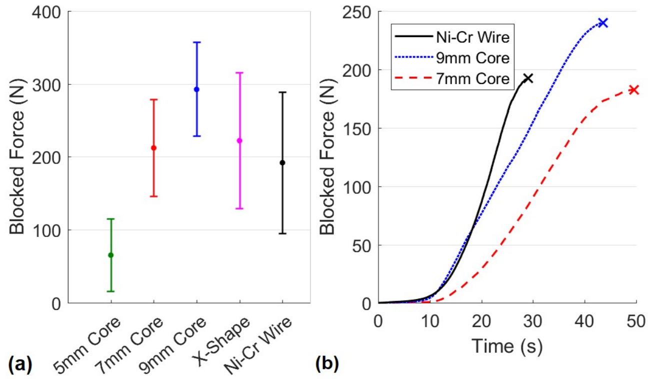

Fig. 8. Blocked force test results for the McKibben-like muscles. (a) The measured results of the force output of several all-soft muscle designs, compared with a Ni-Cr wire heater. Error bars represent 95% confidence. (b) Characteristic curves from the build up of force in the actuator muscle over time for three examples of different heater types. The 9 mm core and Ni-Cr wire, with nearly identical resistances, heat up at nearly the same rate, whereas the 7 mm core (with a higher resistance) takes longer to heat up.

therefore temperature regulation of the Ni-Cr wire) might enable the Ni-Cr wire actuators to produce higher forces by preventing overheating of these ends.

In contrast, the 5 mm dia., 7 mm dia., and X-section heater cores all failed electrically, losing connection between the two electrodes. This reduced the power input to near-zero, though only temporarily for the 7 mm dia. and X-section cores. After cooling briefly, both types would typically regain conductivity. For the 5 mm diameter cores, however, this loss-of connection was permanent, probably due to the small contact area in the thin cores and the heater material burning around the electrodes. Between their high initial resistance and the permanent heater-core death, muscles with these cores performed poorly.

Figure 8b shows three typical curves of blocked force as a function of time. The 9 mm heater composite and the Ni-Cr wire heat almost at the same rate, while the 7 mm core heats up slower. This may be attributed to the similar initial electrical resistance of the Ni-Cr wire and the 9 mm core used to gather these datasets (approximately 15 Ω each), compared to the higher resistance of the 7 mm core (at about 25 Ω).

V. Results and Discussion

To demonstrate the potential of these light-weight, all-soft actuator muscles, we used one to lift its own power supply (Figure 1). The actuator had a 7 mm dia. internal silicone heater core, and was strong enough to lift the power supply 5 mm (10% the length of the actuator) straight up, even though the supply is over 200x the mass of the actuator (see also Supplemental Video 1). Operating on a 15 V input, the actuator lifted the power supply to its maximum height in 22 s, and held it suspended for well over 1 min before being shut off.

The novel material combination of a silicone-EIG heater core with the silicone-ethanol actuator opens up many new design parameters for exploration. Apart from the entire system system being composed of elastomer composites (enabling bulk stretchability), a bulk heating material gives way to numerous possibilities in geometric design choices for the heater, beyond the few presented here. This can improve the way in which the heat from the heater core is distributed throughout the actuator (as demonstrated with the X-shaped core), potentially preventing over-heating of the ethanol and burning of the silicone immediately surrounding the actuator. By adding larger volumes of the bulk-heater, it is possible to both speed up the force generation (as demonstrated by the 9 mm cores), and increase the maximum blocked force produced by the muscles. With this bulk system, it will be possible to optimize both the size and shape of the heater core in order to improve the speed and efficiency of the all-soft muscles.

There are other advantages of this all-soft system when compared to its predecessor using the Ni-Cr wire. Although the Ni-Cr wire can have more coils looped through the actuator to facilitate heating, the system short-circuits and will not heat if any of the coils touch, a non-issue with a bulk silicone resistor. Furthermore, by limiting the heater core to a system exclusively internal to the actuator, it is less likely that an external mesh sleeve (or other materials) will heat up and weaken. Finally, because we successfully removed the Ni-Cr wire from the actuator, both the actuator and the heater are malleable in their uncured state, allowing for continued improvement to the design and manufacturing of the system.

VI. Conclusion and Future Work

In this paper, we have demonstrated that we can integrate a new, soft, stretchable, central core material that removes the need for a Joule heating wire used in the original system. We show that actuators powered with this soft composite heater are capable of producing comparable blocked forces, while also being able to improve the heat distribution by geometric design. Finally, we demonstrate that a single one of these light-weight, all-soft muscles is strong enough to lift over 200x its own weight. This is a big step forward for the soft robotics field, as the ability for a soft robotic actuator to carry weight (such as batteries and control units) is crucial towards the development of autonomous soft robotic systems.

This all-soft system is a significant advancement from the original work, as both the soft actuator material and the soft heater may potentially be patterned using 3D-printing. This would allow automated fabrication and endless varieties of actuator (and heater) shapes, while retaining the actuator expanding performance. 3D-printing of the silicone actuator material was shown in the original work [4], while 3D-printing of the heater composite will be explored as a part of a future work.

The accelerated Joule heating of the actuators came with a cost, reducing them to one-time use, though the muscles have been shown to be repeatably actuated at slower heating rates [4], [30]. We desire to improve both driving speed and durability by continuing to improve the mix ratios of the composite materials in the core, optimizing for stretchability, robustness, and printability. We will look to improve the interfacing of the material systems, focusing on both the interface between the heater composite and the actuator composite and the interface between the heater and any electrical leads used for power supply. Furthermore, with different bubble densities caused by different mixing times, and by using 3D printing technologies, it might be possible to combine actuator composites with different mixing times to create asymmetrically expanding actuators.

VII. Acknowledgments

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