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# Electrically Actuated Hydraulic Solids**

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*The authors introduce a new class of electrically-actuated soft materials. Electro-active hydraulic solids (EAHSs) are comprised of numerous microscale phase change capsules embedded inside a conductive elastomer matrix which replicate traditional wax actuators in a massively parallel fashion. EAHS can generate forces and stress densities that exceed traditional electroactive actuators. For example, a 14 mm diameter 50 mm long cylinder can generate 4 500 N force and have over 3% strain. The authors describe a simple method for fabricating EAHS and demonstrate their compatibility with a wide range of manufacturing processes including additive manufacturing, subtractive manufacturing, and forming.*

Electrically driven polymeric actuators are an important basis for modern microfluidics, soft electronics, and soft robotics, and are still one of the bottlenecks of many applications of robotic and automation.[1–6] Each one of the existing actuator technologies available today involves a difficult tradeoff between performance metrics. For example, dielectric actuators allow for high-frequency responses and high strains, but are unable to generate large forces.[5] Piezoelectric materials require high voltage and produce very small strains.[7,8] Shape memory alloys require high currents or small cross-sections to increase resistance.[9] Swelling polymer gels can be compliant and generate large volumetric changes by absorption compounds from the environment, which limits applicability.[10] While each has found their niche in the Pareto front of actuators, none can generate very high quasi-static loads, have a high stress density, and be driven by low voltages. In fact, very few material actuators can generate more than 100 N of force in a typical engineering or lab environment.

In order to address this challenge, we identified a new kind of bulk material actuator that offers a new performance tradeoff in stress density that is un-dominated by existing technologies. Whereas most compliant electroactive polymers attempt to induce a mechanical change by means of a charge migration, or charge separation, electro-active hydraulic sar (EAHS) actuators use a network of conductive materials suspended inside of an insulating elastomeric matrix to generate thermal energy (Figure 1A). This energy is then transferred into cells of thermally expansive materials embedded inside of the matrix. The heated cells expand when they transition from a solid to a liquid as they are heated, generating internal pressure. The elastomer matrix acts as a containment system for the embedded phase change material, preventing the liquid phase from leaching out of the system. Each entrapped paraffin globule acts as an independent "micro-piston" as a result. Motion is bidirectional: expansive on heating and shrinking on cooling. Large forces, however, are only generated during the expansion phase.

The approach we took replicates the functionality and components of a traditional paraffin piston into a scalable material framework. Paraffin motor actuators are well known for their high force stroke and stable actuation, making them ideal for large quasi-static force generation.[11] They operate at easily achievable voltages and currents, and have a slow cycle rate, making them robust against intermittent power disconnections. Paraffin motors have three distinct components: a chamber with an elastomeric membrane for containment of the wax, the wax itself, and a resistive heating source for converting current into thermal energy.[12–14] EAHS materials are a bulk material system where the functionality of these distinct components is replaced by the intrinsic behavior of

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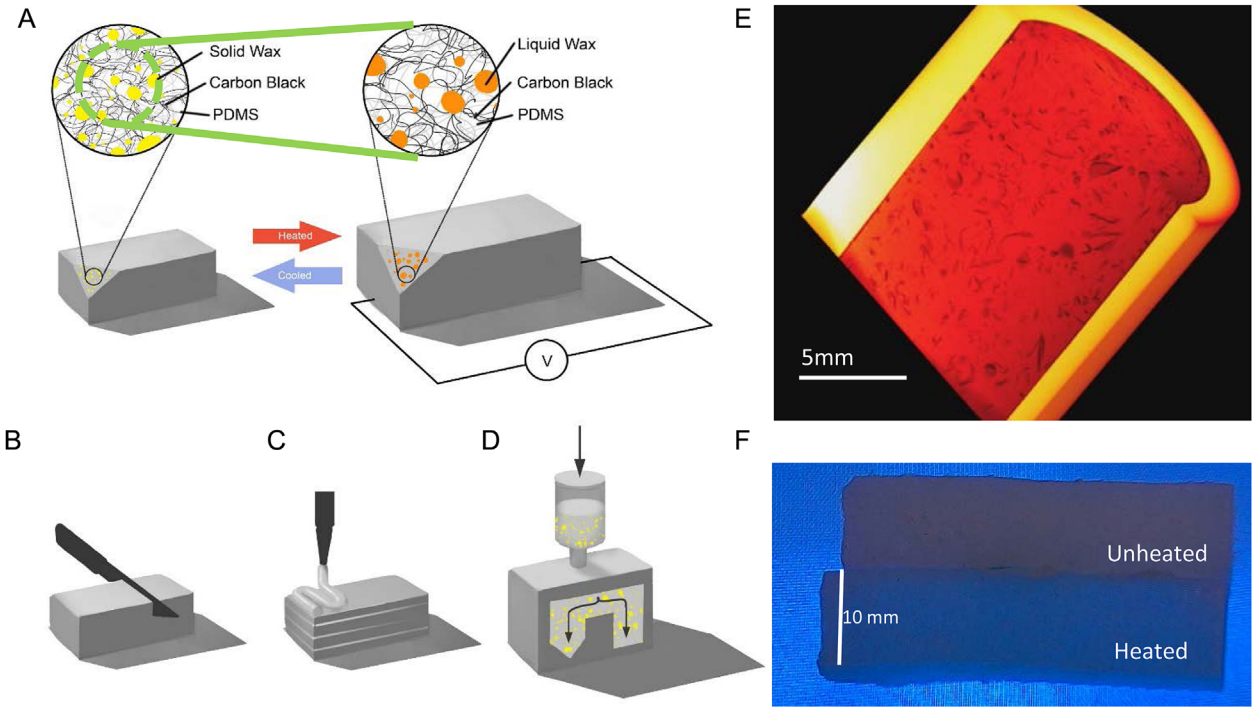



*Fig. 1. Basic structure and fabrication techniques for electrically actuated hydraulic solids. (A) A phase change material such as paraffin wax is dispersed in an elastomer matrix. The matrix contains a network of conductive material. This allows the elastomeric matrix to act as a heater and membrane for the phase changing cells. When a voltage is applied, the system heats, the PCM expands generating an internal pressure. This pressure causes the overall structure to expand. EAHS can be shaped by cutting (B), 3D printing (C), and molding (D). A cross-section of a micro-CT scan of a PDMS-wax sample (E) reveals that the solid wax forms wisps inside of the PDMS. This is likely formed by the turbulent mixing of the liquid wax in the PDMS as the wax cools. (F) A sample without carbon black becomes translucent when it is heated via an external source.*

three raw materials. This distributed cellular structure for the actuator makes it significantly more robust than its mono-cellular paraffin actuator counterpart. As seen in Figure 2A, it can be punctured repeatedly and severed into section and each cell not damaged remains operational.

Hydraulic solids can generate higher forces and stresses per unit density, than any previously reported actuator material. EAHS are operable at relatively low voltages and currents, allowing for easy integration into many environments where high voltages or currents can be detrimental. The actuators can be formed by casting, additive manufacturing, and mechanical operations allowing for the deployment of the actuators in small-scale rapid prototyped systems and large-scale commercial production. Their main drawback is actuation speed. Since EAHS are thermally actuated, cycle time depends on shape and insulation, and is approximately 1 000 s for a centimeter-cubed actuator.

## 1. Methods

We demonstrated this system using a two-part polydimethylsiloxane (PDMS) elastomer, embedded with a paraffin wax matrix. We used carbon black to form the conductive heating network. The paraffin wax had a melting temperature of 60 °C. In order to produce EAHSs, liquid paraffin wax was rapidly stirred into one of the PDMS precursors and allowed to cool. As seen in Figure 1E, the material phase separates entrapping the wax structures inside the PDMS. These structures are generated by the turbulent mixing and phase separation, randomly distributing them through the material. The carbon black can then be stirred into the other PDMS precursor. When we stirred both sets of doped precursor together, the material starts to cure and the EAHS is formed. Material without carbon black or a conducting matrix displays the same expansion properties (Figure 1F) but requires an external heat source.

To showcase the methods of integrating the material into manufacturing processes, actuators were formed using cutting (Figure 1B), casting (Figure 1D), and 3D printing (Figure 1C). We placed mixed material into a 3D printer based on syringe deposition, using the Fab@Home Model 3 platform.[15] The material could be extruded through an 18-gauge taper plastic tip form Nordson EFD during its pot-life.[16] Smaller tips lead to jamming of the head from the particles of wax. The material was self-supporting and bonded across layers. As an alternative to 3D Printing, the material could also be placed into rigid mold and cast into a variety of shapes. Alternatively, a piece of the cured material can be cut or carved into shapes using a blade.

By varying the relative ratio of the elastomeric matrix to the phase change material, we can control the internal pressure generated for a specified temperature. Lower internal pressure results in a smaller expansion and lower

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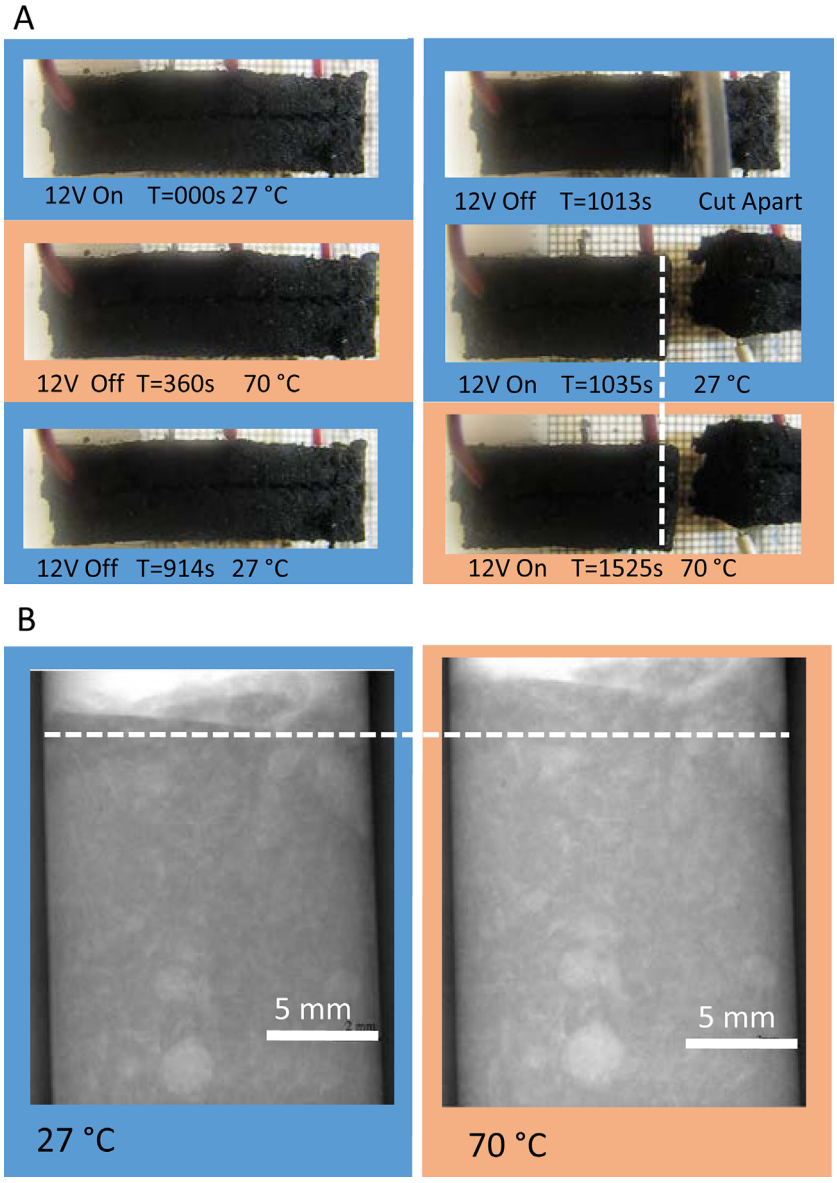



*Fig. 2. EAHS actuators are robust against puncture and tears. Electrodes can be placed directly into the material to form electrical contact (A). The EAHS can be cut into two parts using a conventional knife and still operate as long as electrical connections are maintained (A). When EAHS are constrained by an external housing, the volumetric expansion can be concentrated into a linear expansion (B). We see under micro CT imaging that the internal positioning of the paraffin cells changes to accommodate the changes in the cell size.*

forces generated for the same thermal condition. We were able to create successful EAHS with concentrations of phase change material between 0 and 60% of the bulk material by volume. When the concentration of phase change material exceeded 60%, the matrix became too sparse to encapsulate the cells, causing leakage between pistons that resulted in loss of pressure.

The patterning of placing electrodes into the system for the current delivery allows for the control of the effective resistance of the system. Inserting the electrodes as set of interwoven combs allows for minimal resistance and selective actuation of the material. The insulating nature of the elastomer matrix slows the rate of thermal conduction between sections with current flow and sections which are dormant.

### 2. Demonstrations

We demonstrated a purely linear actuator by confining a cylinder of the material inside of a rigid tube with a cap on one end. Since the internal pressure from the phase change material will expand in any direction, containing the materials expansion is necessary for generating high forces for linear displacement. As seen in Figure 2B, we heated a 50 mm long, 14 mm diameter cylindrical sample to 70 °C. The paraffin expanded and caused the cells to shift inside of the constrained space to generate a linear expansion. The blocked force, outward stroke, and return stroke were measured as the sample was heated. As seen in Figure 3, the system demonstrated a significant but small amount of hysteresis. Most likely, this is due to internal energy losses from straining the elastic matrix.

This actuator allowed for up to 4.5 kN of force and a displacement on the order of 2 mm from a 50 mm long sample. This is several orders of magnitude ($10^5$) more force than ionic polymer–metal composites (IPMCs) bending actuators can generate at their tip for similar voltages and several orders of magnitude ($10^2$) than dielectric elastomer actuators (DEA) can generate at 5 kV (Table 1).[17,18] The material is extremely light, having a density of 9.6 g cm$^{-3}$ at room temperature. The high force and low density results in a specific actuation of $3.0 \times 10^{-2}$ MPa (g cm$^{-3}$)$^{-1}$. In comparison, shape memory alloys have a specific actuation of $2.8 \times 10^{-2}$ MPa (g cm$^{-3}$)$^{-1}$ twisted polymer fibers have a specific actuation of only $6.52 \times 10^{-3}$ MPa (g cm$^{-3}$)$^{-1}$.[19] While shape-memory alloy (SMA) and twisted fiber actuators generate their forces by contracting, the EAHS actuators generate their forces by expanding. Additionally, unlike twisted fiber actuators, SMA and EAHS actuators contain an internal heating source, allowing for a completely integrated system.

Often actuators with high stresses have engineering limitations on their geometry which limit the total force they can generate. SMA actuators' high conductivity necessitates their production into thin forms, in order to increase the effective resistance.[20] Without such limitations, the current requirements to get a sample to self-heat would be impractical for most applications. As a result, SMA actuators are often used in flat sheets and thin wires. EAHS actuators have higher

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*Table 1. EAHS can generate orders of magnitude more force than other electroactive materials.*

| Actuator type | Voltage range [V] | Typical force [N] | Maximum stress [MPa] | Maximum strain [%] | Density [kg m$^{-3}$] | Specific actuation [MPa (kg m$^{-3}$)$^{-1}$] |
|---|---|---|---|---|---|---|
| **Hydraulic solids** | $1\times10^{0}$ – $3\times10^{2}$ | $2.1\times10^{3}$ – $4.5\times10^{3}$ | $1.3\times10^{1}$ – $2.9\times10^{1}$ | 1.0 – 4.2 | $9.7\times10^{2}$ | $3.0\times10^{-2}$ |
| Dielectric actuators | $5.5\times10^{3}$ – $1.8\times10^{4}$ | $5.0\times10^{0}$ – $2.9\times10^{1}$ | $1.3\times10^{-2}$ – $1.2\times10^{0}$ | 2.9 – 220 | $1.0\times10^{3}$ | $1.20\times10^{-3}$ |
| IPMC | $1\times10^{0}$ – $6.0\times10^{0}$ | $2.0\times10^{-3}$ – $1.6\times10^{-2}$ | $4\times10^{0}$ – $1.0\times10^{1}$ | 6.0 – 50 | $2.0\times10^{3}$ | $5\times10^{-3}$ |
| Piezoelectric | $2\times10^{1}$ – $2.5\times10^{2}$ | $5\times10^{-1}$ – $8.5\times10^{2}$ | $1.0\times10^{-3}$ – $2.0\times10^{1}$ | $5.0\times10^{-4}$ – $8.7x10^{-2}$ | $7.80\times10^{3}$ | $2.6\times10^{-3}$ |
| SMA | $1\times10^{0}$ – $3.6\times10^{1}$ | $8.9\times10^{-2}$ – $4\times10^{0}$ | $7.0\times10^{1}$ – $1.8\times10^{2}$ | $2.0\times10^{-1}$ – 9.0 | $6.4\times10^{3}$ | $2.8\times10^{-2}$ |
| Twisted nylon | NA | $1.0\times10^{1}$ – $5.0\times10^{2}$ | $1\times10^{0}$ – $7.5\times10^{0}$ | 20 – 49 | $1.2\times10^{3}$ | $6.5\times10^{-3}$ |

When compared with other electrically driven actuatable materials, EAHS generate these forces at lower voltages and for less mass. Several other actuators outperform EAHS on the strain metric, but those materials generate very small stresses. In the table, the top third of the performance range is colored green, the middle third yellow, and the lower third red. Typical force ratings are based upon standard applications of the technology. For citations, see Supplementary Materials.

resistances and therefore can be heated with less current than SMA actuators. This requires higher voltages (1 – 300 V) but such voltages are possible in most electrical actuation applications without specialized equipment. This allows the system to be produced in larger operable structures than SMA actuators and therefore generate more force. The limiting engineering principles of this material are not yet known, but it can already generate more force than comparable electrically driven material actuators.

The main electrical drawback to EAHS is their slow speed and high power consumption. In Figure 2A, the system required 12.4 V of power and 0.4 A of current and 12 min time, consuming $3.6\times10^{3}$ J to heat from 22 to 70 °C. The cylinders of 40% in Figure 3A performed 4.5 J of work while consuming up to 800 J of energy, making it 0.6% efficient.

## 3. Applications

To probe the utility of the material, we built a small robotic system seen in Figure 4. Each leg of the robot was powered by a single 14 mm diameter cylinder of the material. The center of the cylinder contained a copper wire for connection to power. The exterior of the casing was connected to ground. Activating the actuator caused it to expand from 50 to 52 mm. This small length changed was turned into a large angle change by allowing the actuator to pivot through the center of the leg. One end of the actuator was affixed 17 mm from the pivot of the leg. The other end was affixed 35 mm from the pivot point. This allowed the triangle formed from the three points to collapse to a line when the actuator expanded. This resulted in a rotation of 21 °. This motion allowed the robot to rise 14 mm, substantially more than the 2 mm length of expansion.

## 4. Discussion

Other application areas may benefit from EAHS actuators. Wax actuators are currently employed in temperature-dependent systems as passive controls. Green house, HVAC (heating, ventilating, and air conditioning), and home appliance industries use them to passively adjust valves, open vents, or activate locking mechanisms whenever a critical temperature is reached and can drive them into a state by actively heating them. Our system can be used in the same way with much less complexity in the actuator. EAHS can also be used to apply quasi-static loads for adjusting the loading on a truss structure or actively controlling the leveling of large concrete surfaces. Valves could potentially be made by surrounding a compressible tube with EAHS and a strain limiting layer to cause the EAHS expansion to reduce or stop flow without coming in contact with the liquid.

There are two foreseeable ways to improve the speed of EAHS systems: higher heat transfer rates, and phase change materials with lower latent heat of fusion. Faster heat transfer can be done by applying more current to cause the system to

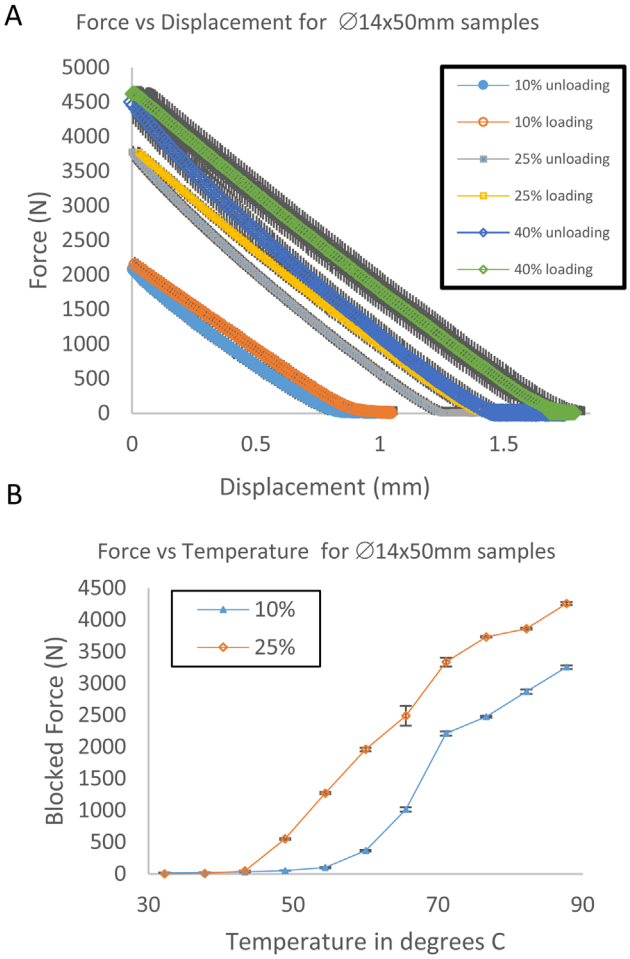



*Fig. 3. Performance of an EAHS sample. (A) A 14 mm diameter, 50 mm long sample is held at 71 °C in a metal container. The force and strain generated are dependent on the concentration of the phase change material. There is significant hysteresis in the actuation. (B) The blocked force is dependent on the temperature of the sample and concentration of phase change material. These data are based on n = 3.*

reach higher temperatures. At sufficiently high temperatures, one runs the risk of burning the carbon black or phase change material (PCM). Additionally, smaller PCM material cells would absorb energy more quickly and would melt faster. A PCM with a lower latent heat of fusion would require less energy to melt and would therefor actuate faster.

## 5. Conclusions

Electrically actuated hydraulic solids are an exciting new class of electroactive polymer actuators. The high forces which can be generated open up new application spaces for electroactive polymer actuators (EAP) actuators. The ability to replicate the complete systems of a traditional wax actuator is a new way to think about the design of material actuators. Rather than design a migration of charge, a chemical reaction, or a realignment of atomic structures, the bulk material replicates the functionality of different elements of a mechanical design using different functional sub-materials.

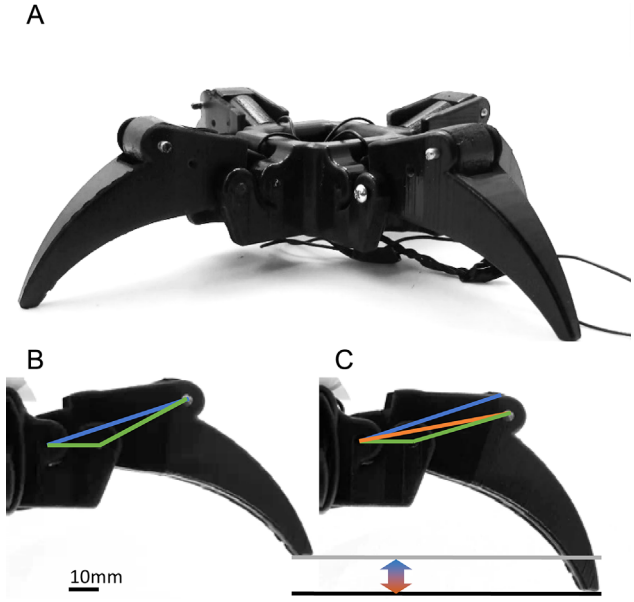



*Fig. 4. A robot made with EAHS actuators. The robot (A) uses four EAHS actuators, the outside of the actuator is grounded with a wire, and a wire runs down the length of the core of the expansion cylinder to deliver power. When the leg is in the cooled state, (B) the expansion cylinder is 50 mm long. When the leg is heated, (C) the cylinder expands and changes the angle of the joint. This causes the leg to rotate 21° from the 2 mm expansion. This rotation is then used to lift the structure between the gray and black lines.*

The result is a functional analog that is produced in a massively parallelized fashion. We propose that this method might be applied to other traditional mechanically manufactured actuators in the future to produce many other functionally mimetic analogs to traditional actuators.

## 6. Materials

Detailed fabrication information for EAHS actuators and the robot can be found in the Supplemental Information. Analysis of the actuator performance relative to theory is also found in the Supplemental Information. Movie S1 shows the continuous operation of Figure 2A. Movie S2 and S3 show the transition shown in Figure 2B. Movie S4 shows a fly-through of the microCT reconstruction seen in Figure 1E.

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