REPORT

MATERIALS SCIENCE

Hydraulically amplified self-healing electrostatic actuators with muscle-like performance

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Existing soft actuators have persistent challenges that restrain the potential of soft robotics, highlighting a need for soft transducers that are powerful, high-speed, efficient, and robust. We describe a class of soft actuators, termed hydraulically amplified self-healing electrostatic (HASEL) actuators, which harness a mechanism that couples electrostatic and hydraulic forces to achieve a variety of actuation modes. We introduce prototypical designs of HASEL actuators and demonstrate their robust, muscle-like performance as well as their ability to repeatedly self-heal after dielectric breakdown—all using widely available materials and common fabrication techniques. A soft gripper handling delicate objects and a self-sensing artificial muscle powering a robotic arm illustrate the wide potential of HASEL actuators for next-generation soft robotic devices.

Human-made machines rely on rigid components and excel at repetitive tasks in a structured environment, whereas nature predominantly uses soft materials for creating versatile systems that conform to their environment. This discrepancy in mechanics has inspired the field of soft robotics (*1*–*4*), which promises to transform the way we interact with machines and to enable new technologies for biomedical devices, industrial automation, and other applications (*2*, *5*, *6*). For soft robotics to proliferate, there is a need for an artificial muscle technology that replicates the versatility, performance, and reliability of biological muscle (*2*).

Currently, soft robots predominantly rely on fluidic actuators (*7*), which can be designed to suit a variety of applications (*8*–*10*). However, fluidic actuators require a supply of pressurized gas or liquid, and fluid transport must occur through systems of channels and tubes, limiting speed and efficiency. Thermally activated artificial muscle actuators made from inexpensive polymer fibers can provide large actuation forces and work density, but these are difficult to control and have low efficiency (1.32%) (*11*). Electrically powered muscle-mimetic actuators, such as dielectric elastomer (DE) actuators, offer high actuation strain (>100%) and potentially high efficiency (80%) and are self-sensing (*12*–*14*). However, DE actuators are driven by high electric fields, making them prone to failure from dielectric breakdown and electrical aging (*15*). Fault-tolerant DE actuators have been demonstrated that rely on localized destruction of the electrodes or dielectric to isolate the location of breakdown (*16*, *17*). Dielectric materials made of silicone sponges swollen with silicone oil (*18*) continued operating after dielectric failure but demonstrated actuation strains only below 5%. More important, DE actuators are difficult to scale up to deliver high forces, as large areas of dielectric are required [e.g., in stacked actuators (*13*)], which are much more likely to experience premature electrical failure, following the Weibull distribution for dielectric breakdown (*19*).

Here, we develop a class of high-performance, versatile, muscle-mimetic soft transducers, termed HASEL (hydraulically amplified self-healing electrostatic) actuators. HASEL actuators harness an electrohydraulic mechanism to activate all–soft-matter hydraulic architectures, combining the versatility of soft fluidic actuators with the muscle-like performance and self-sensing abilities of DE actuators. In contrast to soft fluidic actuators, where inefficiencies and losses arise from fluid transport through systems of channels, HASEL actuators generate hydraulic pressure locally via electrostatic forces acting on liquid dielectrics distributed throughout a soft structure. The use of liquid dielectrics in HASEL actuators enables self-healing with immediate recovery of functionality after numerous dielectric breakdown events.

To discuss fundamental physical principles, we describe one design for HASEL actuators, where an elastomeric shell is partially covered by a pair of opposing electrodes and filled with a liquid dielectric (Fig. 1A). Applying voltage induces an electric field through the liquid and elastomeric dielectric. The resulting electrostatic Maxwell stress (*20*) pressurizes and displaces the liquid dielectric from between the electrodes to the surrounding volume. As voltage increases from V_1 to V_2, there is a small increase in actuation strain s. When voltage surpasses a threshold V_2, the increase in electrostatic force starts to exceed the increase in mechanical restoring force, causing the electrodes to abruptly pull together (Fig. 1B)—a characteristic feature of a so-called pull-in or snap-through transition. Pull-in transitions and other nonlinear behaviors are features of soft active systems that offer opportunities to improve actuation response or functionality (*21*) and have been used to amplify response of fluidic (*22*) and DE actuators (*23*). After the pull-in transition (Fig. 1A), actuation strain further increases with voltage (Fig. 1B). For this design, hydraulic pressure causes the soft structure to deform into a toroidal or donut shape (Fig. 1C).

Hydraulic pressure within the elastomeric shell is coupled to Maxwell pressure, $p \propto \varepsilon E^2$, where ε is the dielectric permittivity of the material system and E is the applied electric field (*20*). Because Maxwell pressure is independent of the electrode area, actuation force and strain can be scaled by adjusting the ratio of electrode area to total area of the elastomeric shell. We fabricated two donut HASEL actuators (fig. S1) (*24*) that were identical except for their respective electrode diameters. The donut HASEL actuators were made from polydimethylsiloxane (PDMS; Sylgard 184, Dow Corning) as the elastomeric shell, a vegetable-based transformer oil (Envirotemp FR3, Cargill) as the liquid dielectric, and ionically conductive polyacrylamide (PAM) hydrogels as the electrodes. The actuator with larger electrodes displaced more liquid dielectric, generating a larger strain but a smaller force, because the resulting hydraulic pressure acts over a smaller area (Fig. 1D and fig. S2). Conversely, the actuator with smaller electrodes displaced less liquid dielectric, generating less strain but more force, because the resulting hydraulic pressure acts across a larger area (Fig. 1E). We tested the cycle life of a donut HASEL actuator used in Fig. 1E for more than 1 million cycles while lifting 150 g (actuation stress ~0.75 kPa) at 15% strain and noticed no perceivable loss of performance (fig. S3). We performed a full-cycle analysis of actuator efficiency using force displacement and voltage charge work-conjugate planes (fig. S4) (*24*). Conversion efficiency was 21%, which is comparable to typical experimental values for DE actuators; whereas DE actuators have potentially high efficiencies (80%) (*12*), experimentally measured efficiency ranges from 10 to 30% (*25*–*27*).

The use of liquid dielectrics enables HASEL actuators to self-heal from dielectric breakdown. In contrast to solid dielectrics, which are permanently damaged from breakdown, liquid dielectrics immediately return to an insulating state (fig. S5 and movie S1). This characteristic allowed donut HASEL actuators to self-heal from 50 dielectric breakdown events (Fig. 1F and movie S2). Although breakdown through the liquid produced gas bubbles, which have low breakdown strength, the bubbles had a limited impact on self-healing performance because they were forced away from the region of highest electric field between the

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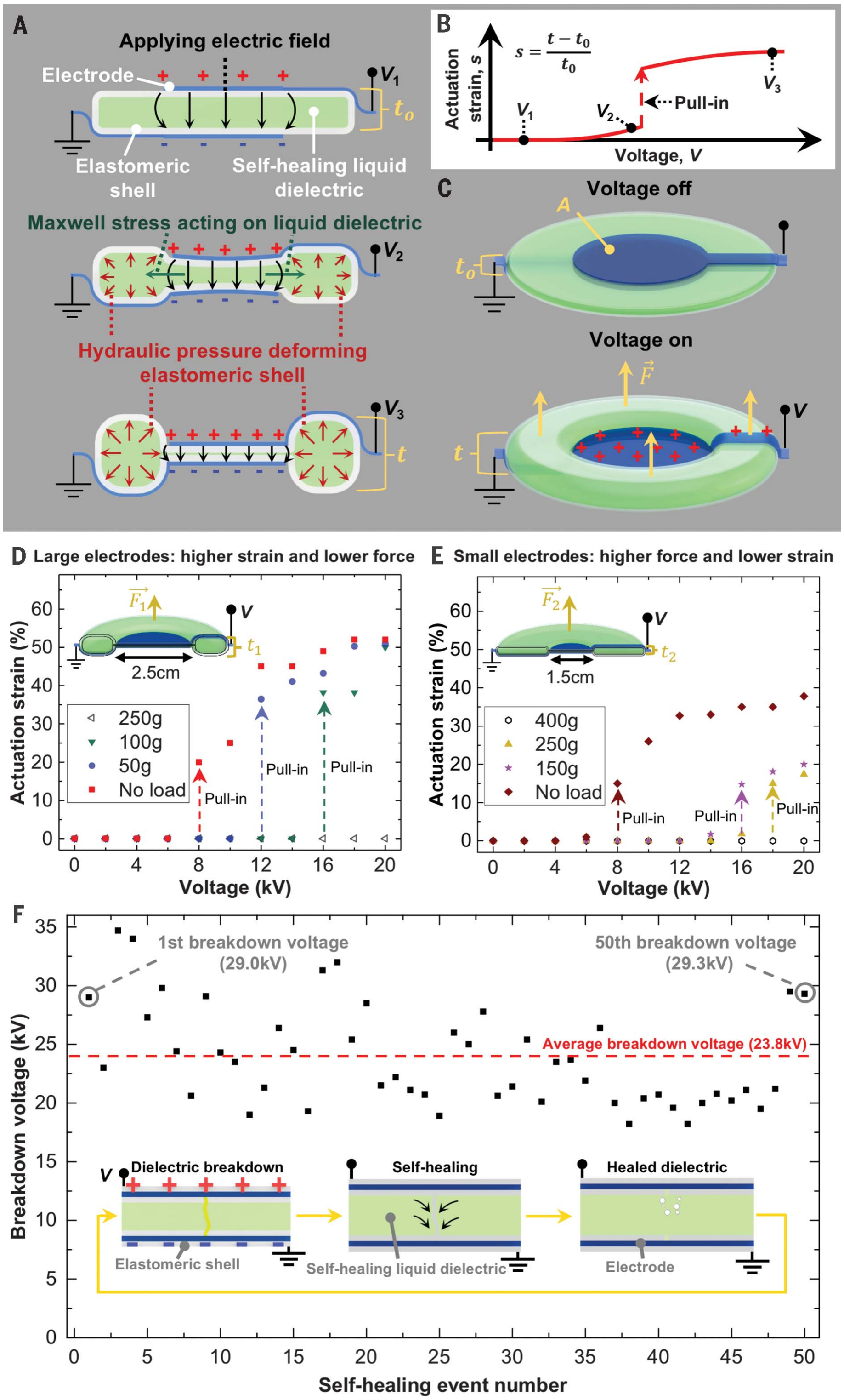

Fig. 1. Basic components and fundamental physical principles of HASEL actuators. (**A**) Schematic of a HASEL actuator shown at three different applied voltages, where $V_1 < V_2 < V_3$. (**B**) Typical actuation response of a HASEL actuator with geometry shown in (A). (**C**) The actuator deforms into a donut shape with application of voltage. This voltage-controlled deformation can be used to apply force F onto an external load. (**D** and **E**) Strain and force of actuation can be tuned by modifying the area of the electrode. The minimum electric field to trigger the pull-in transition was ~2.7 kV/mm; the maximum field applied was ~33 kV/mm. (**F**) The use of a liquid dielectric confers self-healing capabilities to HASEL actuators.

electrodes (movie S2). Dielectric breakdown is a statistical process (*19*), and voltage varied over 50 cycles, with several breakdown voltages exceeding the initial breakdown voltage (including the last one shown; Fig. 1F).

The ability of HASEL actuators to self-heal from electrical damage provides the means to scale up devices to produce a large actuation stroke by stacking multiple actuators (Fig. 2A). A stack of five donut HASEL actuators achieved 37% linear strain, which is comparable to linear strain achieved by biological muscle (*26*) and corresponds to an actuation stroke of 7 mm (Fig. 2B). Hydraulic pressure is generated locally in HASEL actuators, and liquid dielectrics are displaced over short distances, allowing for high-speed actuation. The stacked actuators readily showed large actuation response up to a frequency of 20 Hz (movie S3).

We modified two stacks of donut HASEL actuators to operate as a soft gripper, a common application for soft robotics (*8*, *28*). Actuators within the stacks were constrained on one side to produce a tilting motion (Fig. 2, C to G, and fig. S6). When a DC voltage was applied to the stacked HASEL actuators, the device grasped delicate objects such as a raspberry (Fig. 2, C to E, and movie S4) and a raw egg (Fig. 2, F and G, and movie S4).

The geometry of HASEL actuators, like that of soft fluidic actuators, can be adapted to react with a variety of different actuation modes. For planar HASEL actuators, the electric field is applied over almost the entire region of the actuator containing liquid dielectric. Planar HASEL actuators react to application of voltage with in-plane expansion, resembling a commonly used mode of operation for DE actuators, where an elastomeric dielectric contracts in thickness and expands in area under an applied electric field. To compare the actuation response of HASEL and DE actuators, we measured area strain as a function of voltage for two circular actuators with the same total dielectric thickness, t (Fig. 3A). Both were fabricated from Ecoflex 00-30 (Smooth-on); however, one-third of the thickness of the HASEL actuator was liquid dielectric, t_{liq} (*24*). At 11 kV, the area strain of the HASEL actuator exceeded the area strain of the DE actuator by a factor of ~4 (Fig. 3A and fig. S7). The higher actuation strain is attributed to the layer of liquid dielectric, which effectively reduces the modulus of the HASEL actuator while maintaining the high dielectric strength of the layered dielectric structure.

Linear actuation can be achieved with planar HASEL actuators by implementing a fixed prestretch in one planar direction and applying a load in the perpendicular planar direction (*29*). This lateral prestretch causes a preferential expansion in the direction of the load when voltage is applied (Fig. 3B). We fabricated single- and two-unit planar HASEL actuators, where a unit is defined as a discrete region of liquid dielectric (figs. S8 and S9) (*24*). Linear actuators were oriented vertically with the load applied in the direction of gravity, but they can be operated in any orientation as long as the liquid dielectric regions are sufficiently small to limit uneven distribution of liquid dielectric (fig. S10). A single-unit planar HASEL actuator (Fig. 3C) was activated by increasing DC voltage in discrete steps and achieved a maximum of 79% linear actuation strain under a load of 250 g (actuation stress ~32 kPa), exceeding typical values of strain observed for biological muscle (*26*). Soft active devices such as HASEL actuators are elastic systems that can be used near resonances to improve performance and efficiency (*30*)—a characteristic that could find use in legged robots that move over long distances. We found that for planar HASEL actuators, linear actuation is amplified near a resonant frequency; a single-unit actuator achieved 107% linear strain under a load of 250 g (actuation stress ~32 kPa) and a two-unit actuator achieved 124% linear strain under a load of 700 g (actuation stress ~114 kPa) (fig. S11 and movie S5). Peak specific power during contraction of the two-unit actuator was 614 W/kg; specific work during contraction was 70 J/kg (fig. S12) (*24*). The measured peak specific power is double that of natural muscle and comparable to values for silicone DE actuators (*26*). Thermally activated coiled polymer fiber actuators (49.9 kW/kg) (*11*) and shape-memory alloys (50 kW/kg) (*11*, *26*) have higher peak specific power; however, their efficiency is low (<2%) (*11*, *26*) and thermomechanical actuators are more difficult to control than electromechanical actuators. Cycle life at high mechanical output power was demonstrated with a single-unit HASEL actuator, which provided 358 W/kg average (586 W/kg peak) specific power during contraction until mechanical rupture occurred at 158,061 cycles (fig. S12D). A single unit actuator was able to operate under a large applied load of 1.5 kg [corresponding to a stress of 0.3 MPa, near the maximum value for mammalian skeletal muscle (*26*)] and still achieved 16% strain (fig. S13).

Planar HASEL actuators were also able to self-heal from dielectric breakdown for at least 50 cycles, although, relative to donut HASEL actuators, gas bubbles were more easily trapped between the electrodes (fig. S14). Nonetheless, the ability of planar HASEL actuators to tolerate high electric fields applied over large areas enabled us to scale up actuation force by combining six planar HASEL actuators in parallel to lift a gallon of water (~4 kg, which corresponds to ~120 kPa) at 69% linear actuation strain (Fig. 3D and movie S6). The combination of high actuation strain and the ability to scale up for large actuation force is critical for developing high-performance soft robotic actuators for human scale devices.

Soft robotic actuators require feedback to sense and regulate position. The electrodes of a HASEL actuator form a hyperelastic capacitor with capacitance C, which is directly linked to geometry and actuation strain via $C \propto A/d$, where A is electrode area and d is the distance between electrodes. Consequently, HASEL actuators are able to self-sense deformation attributable to external forces or applied voltage. Because HASEL actuators are equivalent resistor-capacitor circuits, capacitance can be measured transiently by applying a low-amplitude AC voltage (*14*), then analyzing the phase and amplitude of voltage and current signals (fig. S15) (*24*). The low-amplitude AC signal can be superimposed onto a high-amplitude actuation voltage signal, so only one set of electrical connections is required for both actuation and sensing. To demonstrate self-sensing actuation, we powered a robotic arm with two planar HASEL actuators combined in parallel and simultaneously measured capacitance (Fig. 4, fig. S16, and movies S7 and S8). Here, we only measured capacitance and did not attempt to control position of the robotic arm; however, capacitive self-sensing has been used for closed-loop control of DE actuators (*31*).

HASEL actuators rely on all–soft-matter hydraulic architectures and local generation of hydraulic pressure via electrostatic forces acting on self-healing liquid dielectrics—a recipe that combines the strengths of soft fluidic and electrostatic actuators while addressing important problems of each. The use of hydraulic principles in HASEL actuators results in the capability to scale actuation force and strain—a feature also used in other device classes such as microhydraulic systems, which are constructed from thin films and rigid substrates (*32*), and in hydrostatically coupled DE actuators (*33*), where electric fields are applied across elastomeric layers, which do not self-heal after dielectric breakdown. We have demonstrated versatile, robust, muscle-like performance of HASEL actuators made from one set of inexpensive, widely available materials and using only basic fabrication techniques. However, the thick elastomer shells (>1 mm) used in this work required high voltages to reach electric fields large enough for actuation. This need for high voltage is an existing limitation that may be addressed by using dielectric layers with higher permittivity and by using advanced fabrication techniques to produce high-resolution dielectric structures with feature sizes on the order of 10 μm. With a plethora of geometries, materials, and advanced

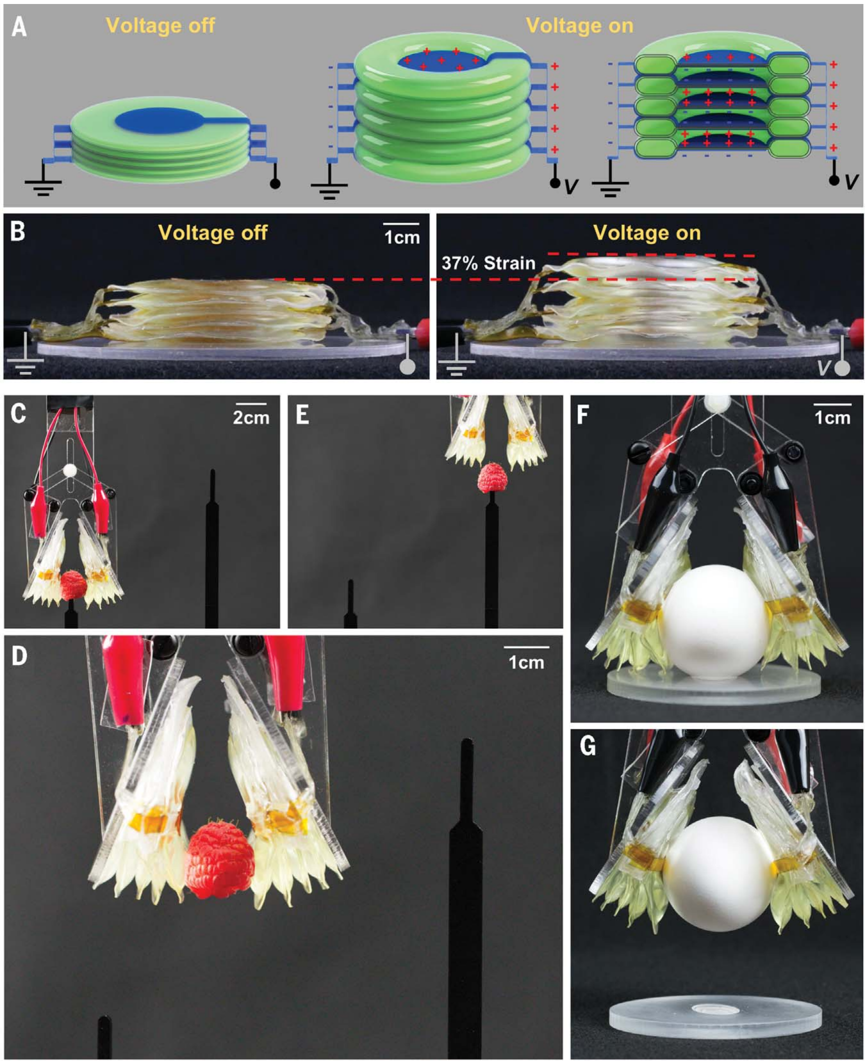

Fig. 2. Stacks of donut HASEL actuators operating as linear actuators and soft grippers. (**A**) Schematic depicting a stack of five donut HASEL actuators oriented such that adjacent electrodes are at the same electrical potential (cross-section view). (**B**) Demonstration of linear actuation with stacked-donut HASEL actuators. (**C** to **G**) A soft gripper fabricated from two modified stacks of donut HASEL actuators handled fragile objects such as a raspberry [(C) to (E)] and a raw egg [(F) and (G)].

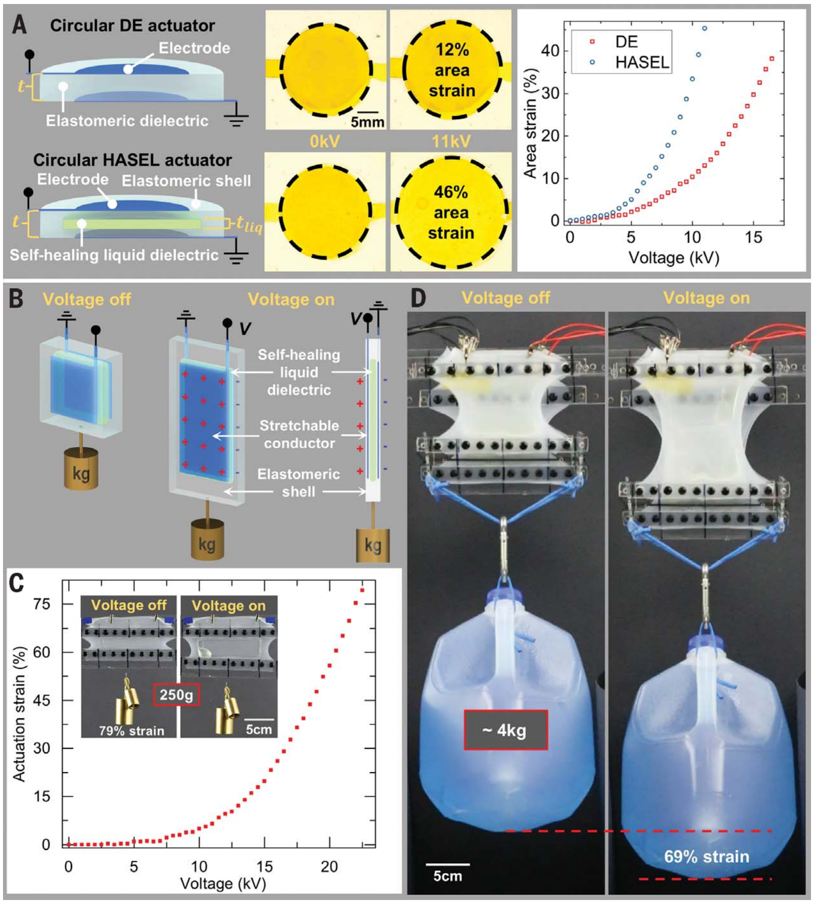

Fig. 3. Design and performance of planar HASEL actuators. (**A**) For a given voltage, a circular planar HASEL actuator achieves larger area strain in comparison to a circular DE actuator. (**B**) Schematic of a planar HASEL actuator that functions as a linear actuator. The actuator is prestretched laterally and a load is applied in the direction perpendicular to the prestretch. (**C**) Demonstration of linear actuation with a single-unit planar HASEL actuator. (**D**) HASEL actuators can be readily scaled up to exert large forces.

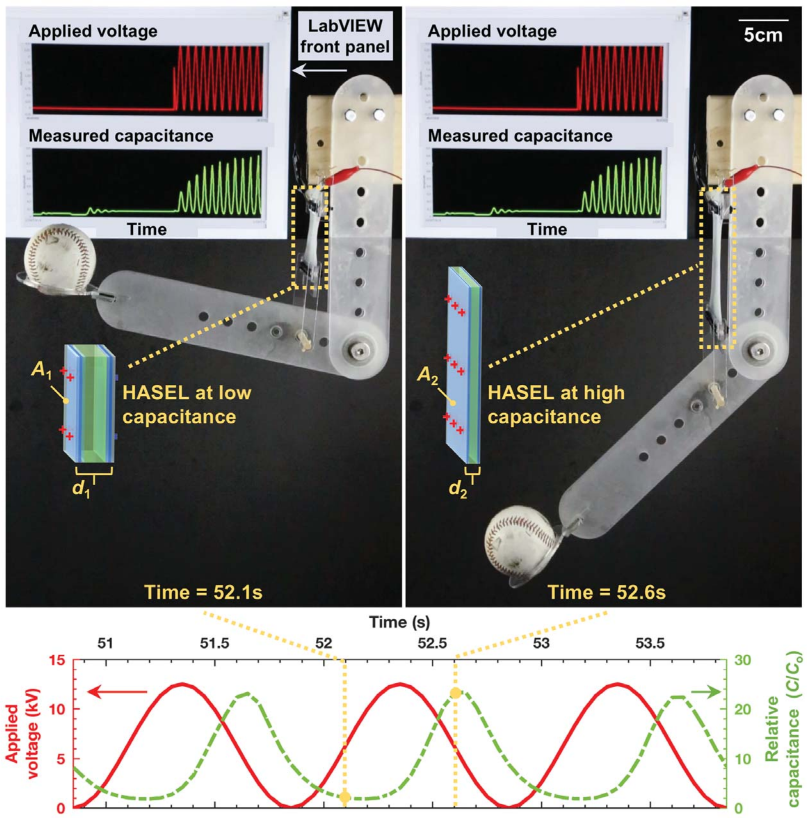

Fig. 4. A self-sensing planar HASEL actuator powering a robotic arm. HASEL actuators simultaneously serve as strain sensors; measured capacitance is low when the arm is fully flexed (left; screenshot of movie S7 at 52.1 s) and capacitance is high when the arm is extended (right; at 52.6 s). The bottom plot shows details of the applied voltage signal (red) and measured relative capacitance (green, dashed), C/C_o, where C is measured capacitance and C_o is the minimum value for capacitance. Voltage and capacitance are ~90° out of phase, which is typical for a driven damped oscillator.

fabrication strategies still unexplored, HASEL actuators offer a new platform for research and development of muscle-mimetic actuators with wide-ranging applications.

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ACKNOWLEDGMENTS

This work was supported by startup funds from the University of Colorado, Boulder. M.B.E, M.K., and M.R. received financial support from the Undergraduate Research Opportunities Program at the University of Colorado, Boulder. E.A., S.K.M., M.B.E., and C.K. are listed as inventors on a provisional patent application (U.S. 62/474,814) submitted by the University of Colorado, Boulder, that covers fundamental principles and various designs of HASEL transducers.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/359/6371/61/suppl/DC1
Materials and Methods
Figs. S1 to S16
References (*34*, *35*)
Movies S1 to S8

8 August 2017; resubmitted 28 September 2017
Accepted 4 December 2017
10.1126/science.aao6139

Science

Hydraulically amplified self-healing electrostatic actuators with muscle-like performance

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Science **359** (6371), 61-65.
DOI: 10.1126/science.aao6139

Liquids show their strength

Dielectric elastomer actuators are electrically powered muscle mimetics that offer high actuation strain and high efficiency but are limited by failure caused by high electric fields and aging. Acome *et al.* used a liquid dielectric, rather than an elastomeric polymer, to solve a problem of catastrophic failure in dielectric elastomer actuators. The dielectric's liquid nature allowed it to self-heal––something that would not be possible with a solid dielectric. The approach allowed the authors to exploit electrostatic and hydraulic forces to achieve muscle-like contractions in a powerful but delicate gripper.

Science, this issue p. 61