Keplinger Research Group

University of Colorado **Boulder**

Stacked HASEL actuators as artificial muscles in next-generation soft robotic devices

Shane K. Mitchell [1], Xingrui Wang [1], Khoi Ly [1], Trent Martin [2], Eric Acome [1], Timothy G. Morrissey [1], Nicholas Kellaris [1,3], Vidyacharan Gopaluni Venkata [1], Christoph Keplinger [1,3]

[1] Department of Mechanical Engineering, University of Colorado, Boulder, CO 80309, USA.
[2] Department of Electrical, Computer & Energy Engineering, University of Colorado, Boulder, CO 80309, USA.
[3] Materials Science and Engineering Program, University of Colorado, Boulder, CO 80309, USA.

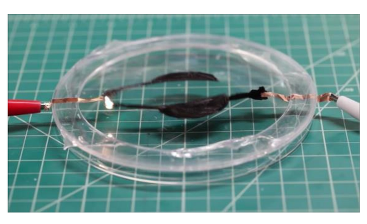
Abstract

Robots are becoming more life-like; a product of our desire to seamlessly integrate multifunctional machines into our everyday lives. The field of soft robotics promises to create such machines, which can safely and effectively operate within unstructured environments. A new soft robotic technology, HASEL artificial muscles, is robust, self-sensing, fast, and self-healing from electrical damage, which enables the creation of practical soft robots. Here, we focus on scaling up HASEL actuators to create muscles which mimic those found in nature. We demonstrate high performance stacks of donut HASEL actuators which simulate the adaptability of muscular hydrostats found in nature such as the octopus arm or elephant truck. Additionally, we stack Peano-HASEL actuators to increase force production of the linearly contracting muscle analogous to the human bicep.

Problem

Soft fluidic actuators are difficult to implement due to the need for bulky and complex systems of compressors, pumps, valves, and tubes. Additionally, electrically powered muscle-mimetic actuators, such as dielectric elastomer actuators (DEAs), are difficult to scale up since they are prone to failure by dielectric breakdown and electrical ageing. For soft robots to become ubiquitous, there is a need for a soft actuator which mimics the scalability and performance of natural muscle.

Bulky and complex control of pneumatic actuators



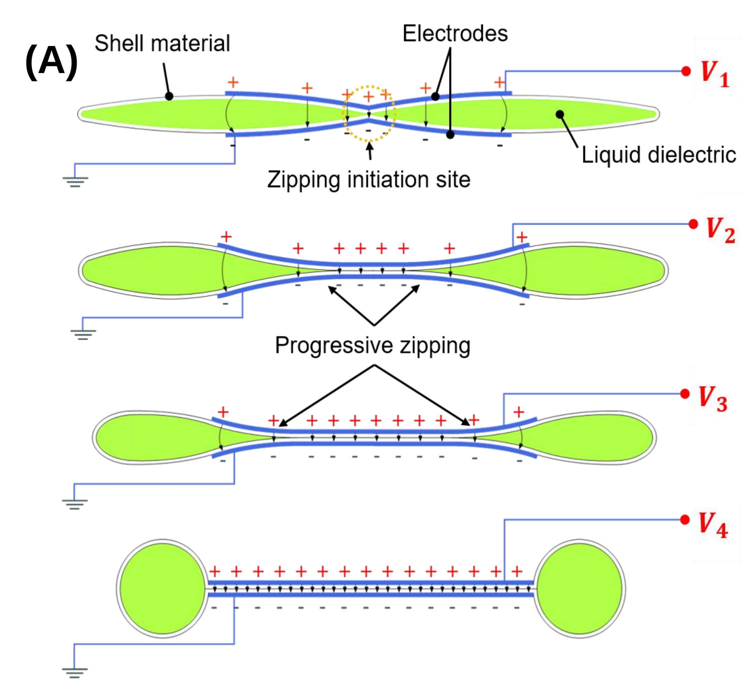
Dielectric breakdown of a DE actuator

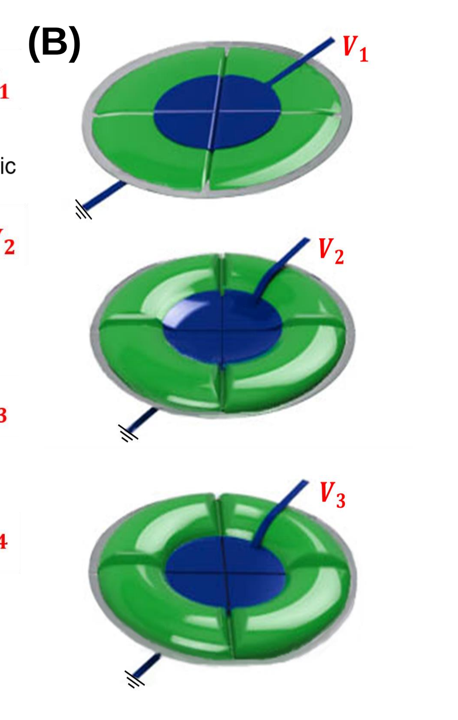
Approach

Donut HASEL actuators were created using 18 µm thick biaxially oriented polypropylene (BOPP) as the shell material. This thermoplastic was heat sealed and the electrodes were placed near the weld lines to create actuators which harness an electrostatic zipping mechanism promoting actuation at lower voltages and mitigating pull-in instabilities. Additionally, the shells were heat sealed into four discrete chambers which were filled with equal amounts of liquid dielectric. This segmentation ensures an even distribution of the liquid dielectric when the actuators are stacked.

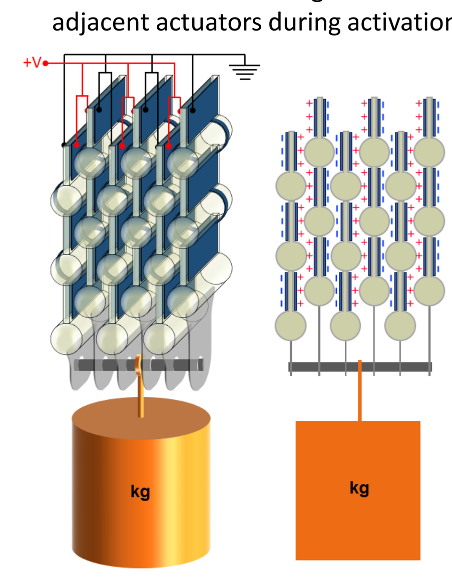
Peano HASEL actuators were also constructed from 18 µm thick BOPP and were stacked by combining individual actuators in parallel. They also incorporated an electrostatic zipping mechanism.

Donut HASEL actuators which harness an electrostatic zipping mechanism. (A) A depiction of the electrostatic zipping mechanism which enables lower voltage operation. The electrodes progressively close together as voltage is increased from for V_1 to V_4. **(B)** A 3D view of donut HASEL actuators with shells that are segmented into four discrete sections. This segmentation allows the electrodes to zip together as voltage is increased from V_1 to V_3, and ensures homogenous distribution of the hydraulic fluid.

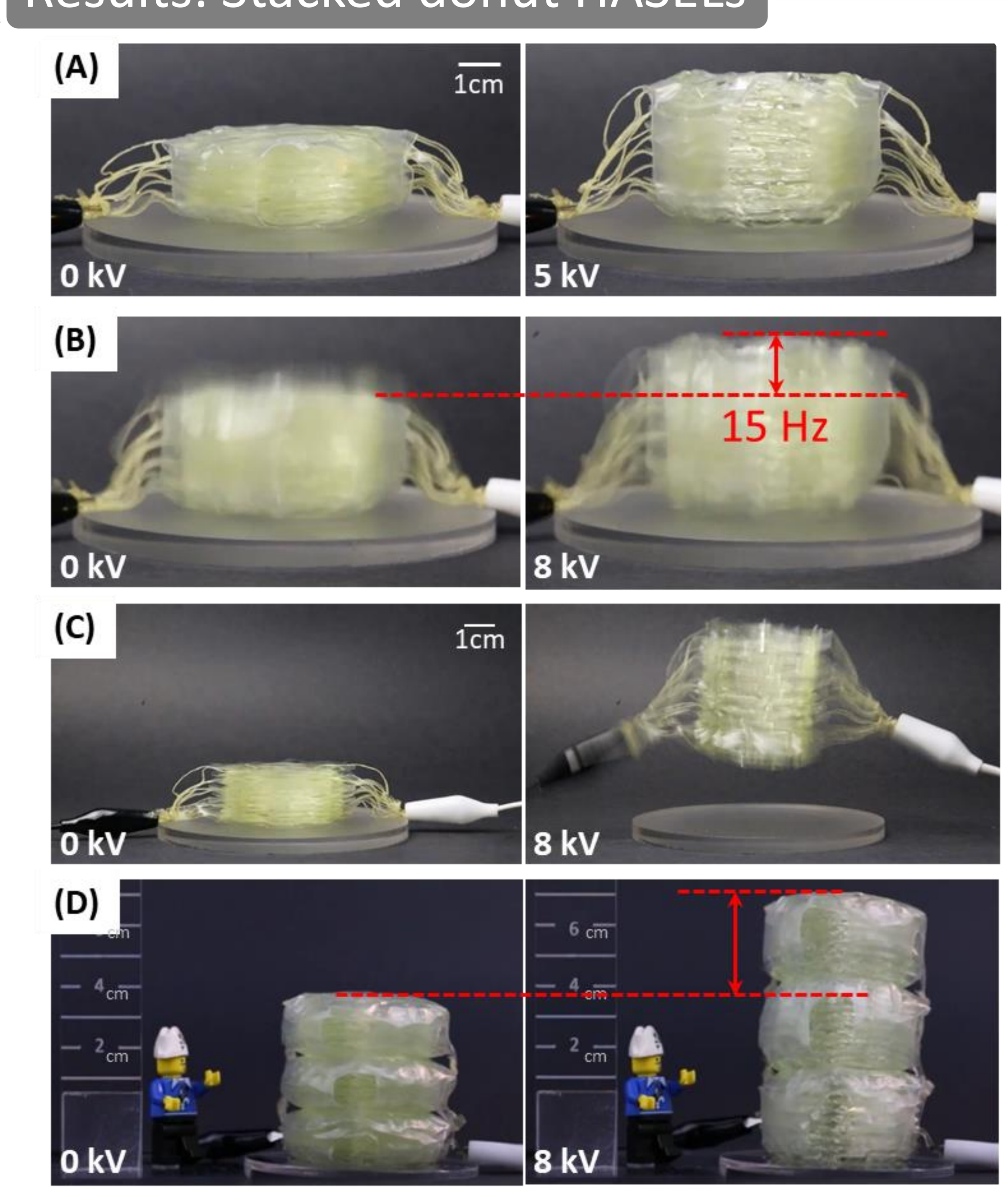




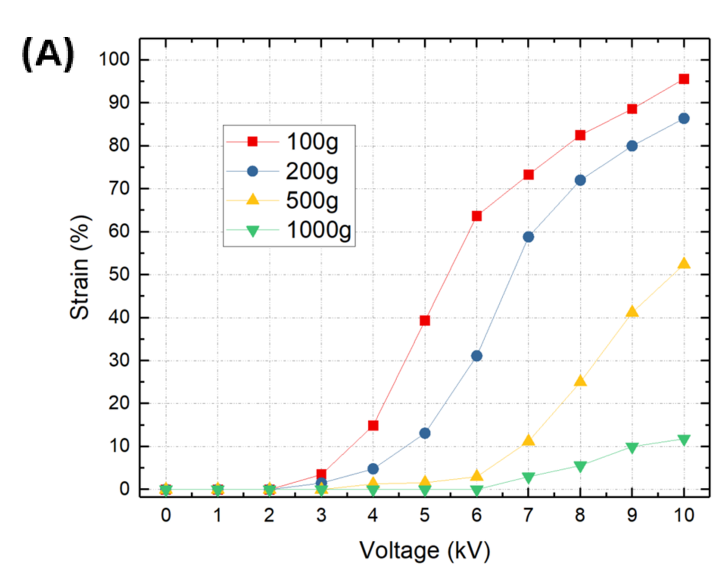
A schematic of a stack of Peano-HASEL actuators. The actuators are oriented in such a way that the bulged sections of each pouch nest within the electrode regions of the adjacent actuators during activation.

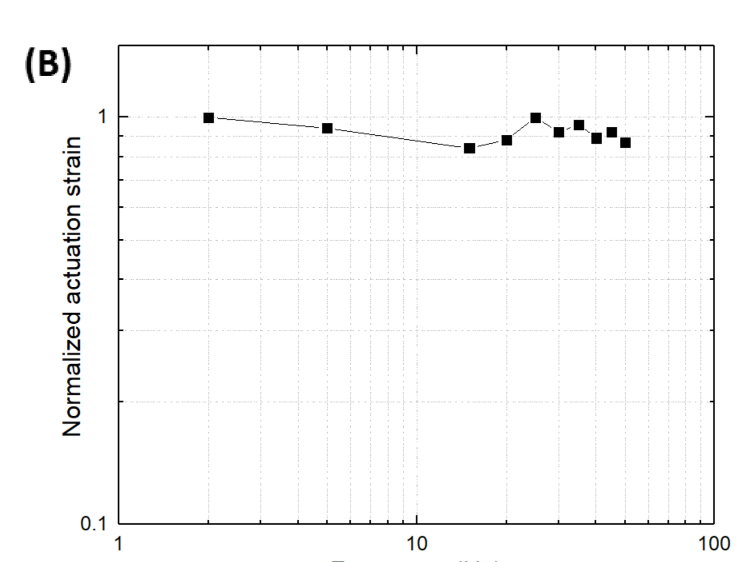


Results: Stacked donut HASELs

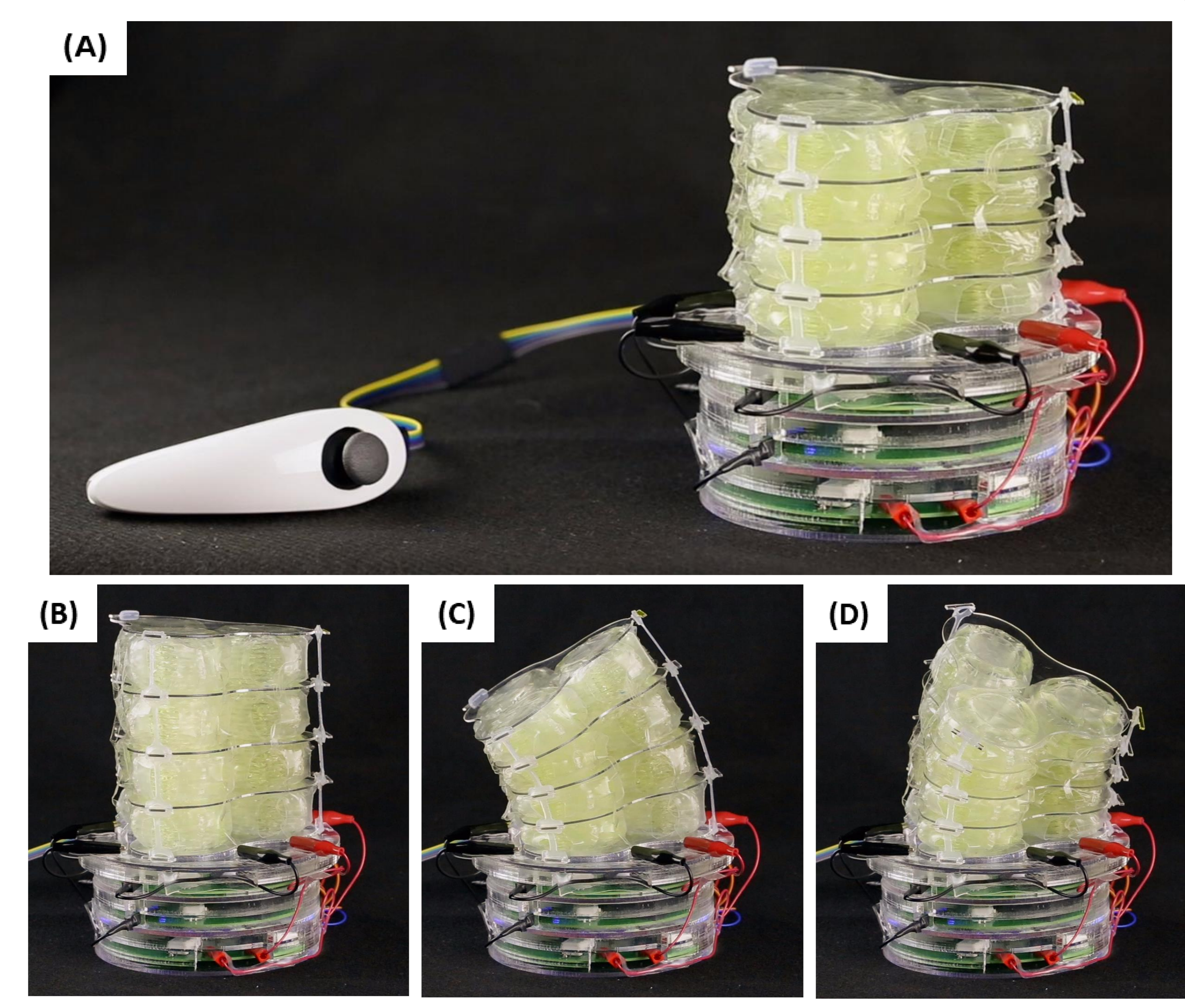


Actuation of stacked donut HASELs. (A) A stack of ten donut HASELs was encapsulated in a thin silicone elastomer to provide an elastic restoring force. This stack achieved large actuation strain at 5 kV. **(B)** Large actuation strain at high frequencies (15Hz). **(C)** The high power density of donut HASEL actuators enabled jumping modes at 8kV and 4Hz. **(D)** A stack of 30 donut HASELs achieved an actuation stroke of 3cm.



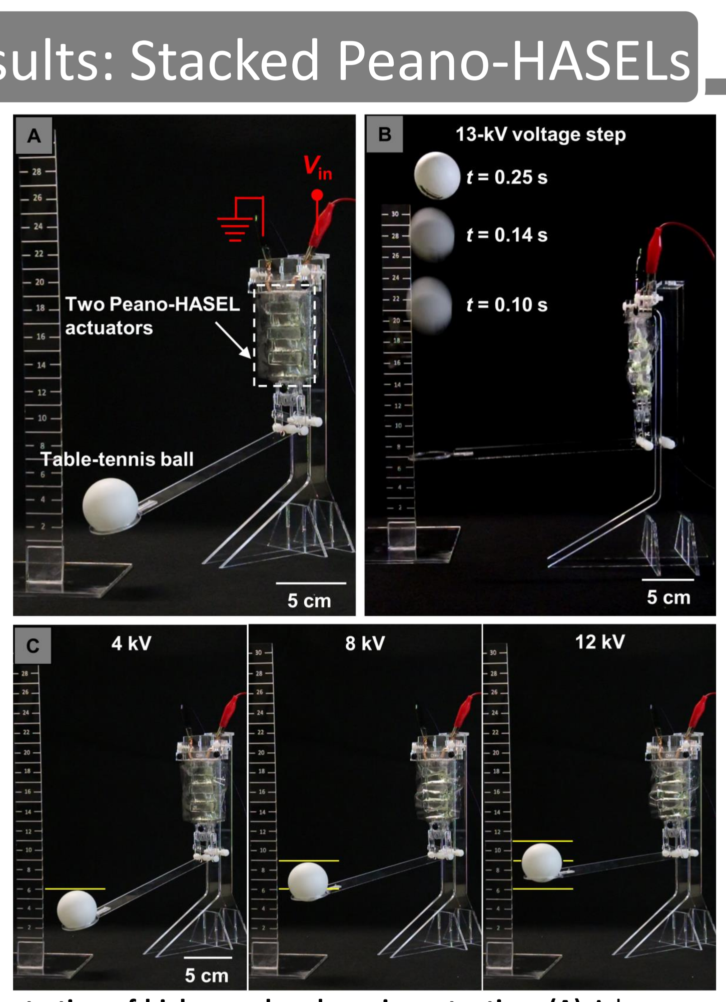


Performance characteristics of a stack of three donut HASEL actuators. (A) Actuation strain as a function of voltage for the stack under various loads. **(B)** Preliminary data shows a nearly flat frequency response up to 50Hz.

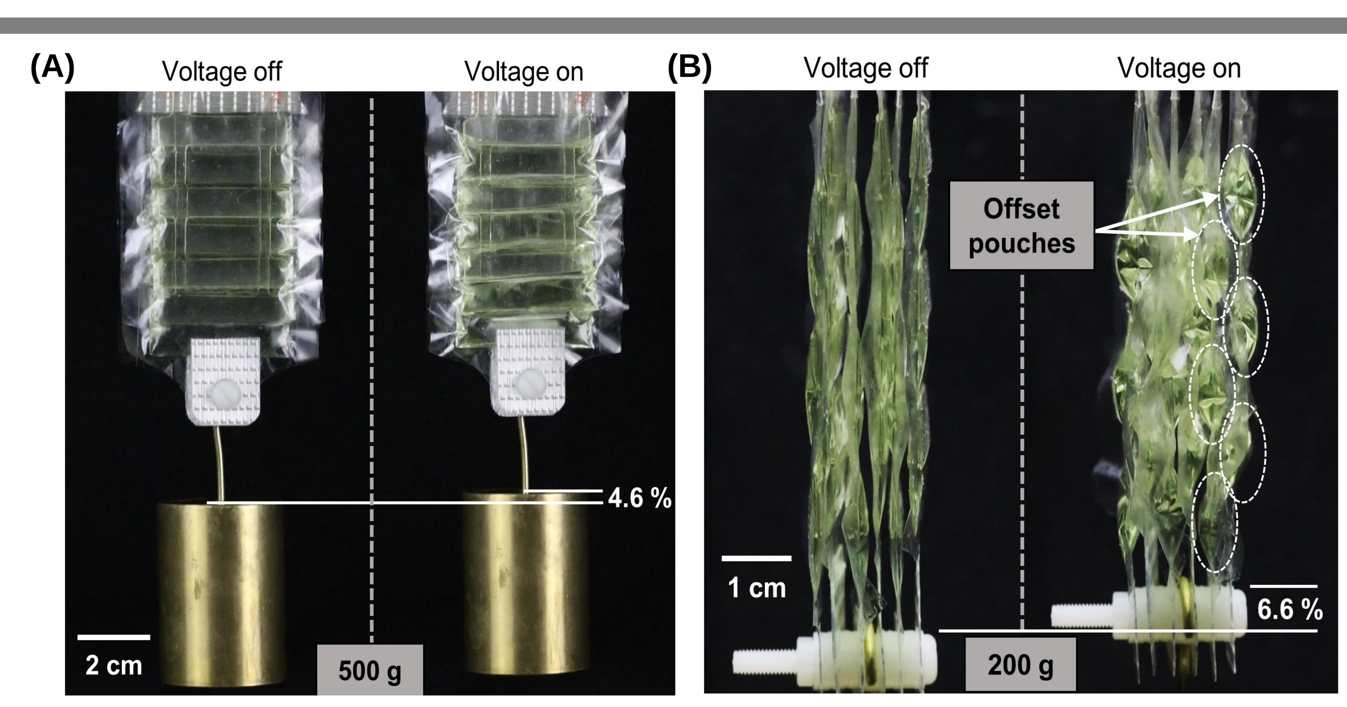


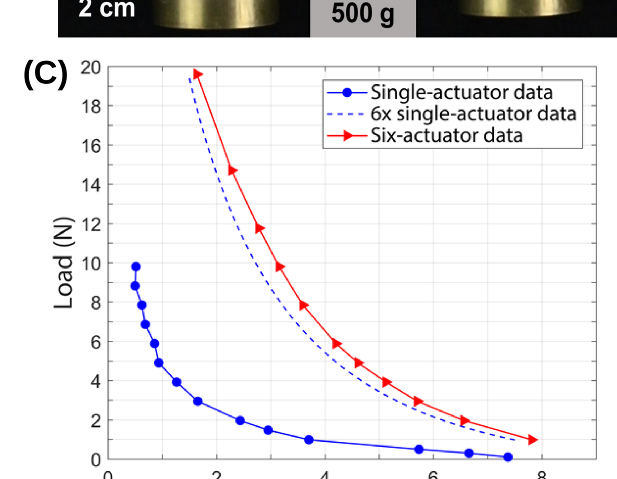
Towards a synthetic muscular hydrostat: ***Terry the Tentacle*** **(A)** Three stacks each with 44 donut HASEL actuators were oriented in a triad configuration, with each stack controlled independently by a miniature high voltage amplifier. Cell phone batteries were used to power each amplifier, as well as a microcontroller. A modified video game controller provided user interface with the tentacle, allowing precise control of position with the movement of a joystick. **(B)** An embedded switch within the joystick allowed activation of all stacks simultaneously. **(C)** Activation of the right-most stack caused the structure to bend to the left. **(D)** Activation of the left-most stack caused the structure to bend to the right.

Results: Stacked Peano-HASELs



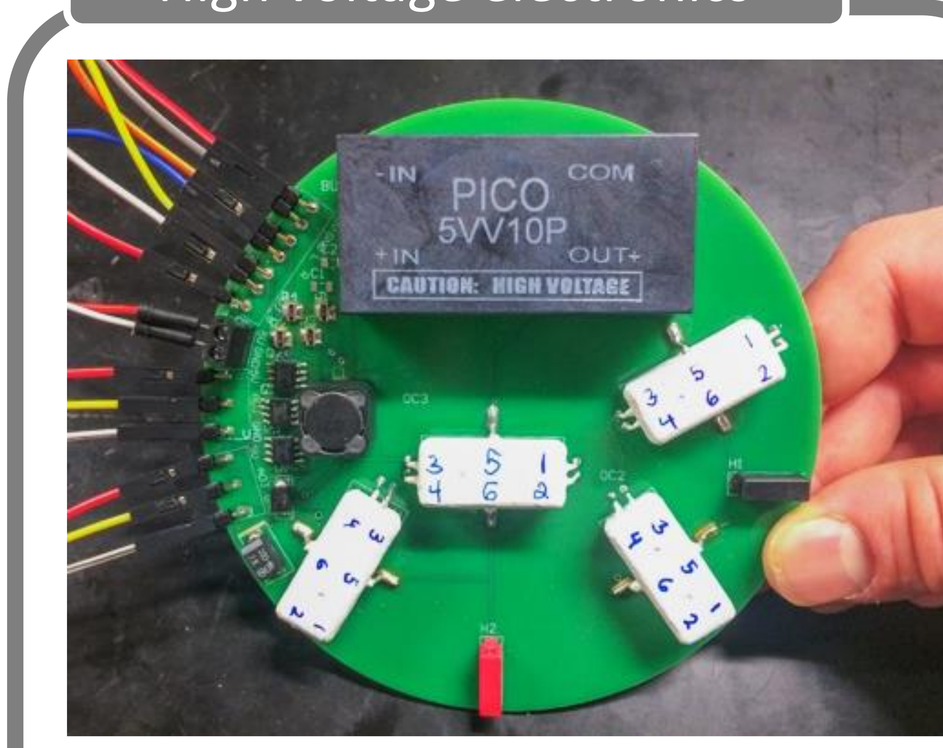
Demonstration of high-speed and precise actuation. (A) A lever-arm setup was connected to a stack of two Peano-HASEL actuators for demonstrating fast and controllable actuation. **(B)** By applying a 13-kV voltage step, these actuators contracted fast enough to throw a table tennis ball 24 cm into the air. Labeled times are measured from the start of contraction. **(C)** Incrementing voltage allowed controllable actuation of the arm, as shown in the progression of images with increasing voltage left-to-right. The yellow lines mark the position of the top of the ball for comparison.





Scaling up forces with arrays of Peano-HASEL actuators. (A) A compact array of six Peano-HASEL actuators in parallel lifting 500 g at 8 kV. **(B)** Side view of the array, lifting 200 g at 8 kV. Adjacent actuators are offset to allow efficient nesting during contraction. **(C)** Comparison of the force-strain characteristics for one actuator to an array of six. Single-actuator data were projected upward by multiplying the load by six (dashed line) to estimate expected performance for an array of six actuators. The array of six actuators slightly outperforms expected results, demonstrating the ability to effectively scale up actuation force.

High voltage electronics



Miniature high voltage electronics for untethered actuation of HASELs. A 5W high voltage amplifier was purchased from Pico Electronics and used to power stacks of HASEL actuators. Optocouplers from Voltage Multipliers Inc. were configured in an H-bridge in order to reverse polarity of the voltage supplied to the actuators. Reversing polarity was shown to improve the performance of the actuators by mitigating the build up of static charge on the BOPP shell. Future designs will focus on encapsulating the electronic components to further reduce the amount of dead space on the board.

Significance

Comparison of HASEL actuator performance with natural muscle and other artificial muscle technologies:

		Stress (MPa)	Linear Strain (%)	Specific Power (W/kg)	Efficiency (%)	Lifetime	Frequency	Energy source	Additional comments
HASEL		>> 0.3	> 100	> 350 (average); > 600 (peak)	> 30	>> 10^6 @ 15% strain	>> 50 Hz	*Electrical*	Self-healing from dielectric breakdown; enables versatile fluidic actuation modes; compatible with a wide range of materials; self-sensing
Natural Muscle		0.35 (*1*)	20 (typ); 40 (max) (*1*)	50 (sustained); 300 (peak) (*1*)	35 (*1*)	10^9 (*1*)	Moderate (2)	*Chemical*	Versatile; scalable; efficient; closely integrated with sensing
Dielectric Elastomer Actuator (DEA)	Silicone	3 (2)	63 (2)	500 (continuous); 5,000 (peak) (*1*)	25 (typical); 80 (max) (*1*)	> 10^7 @ 5% strain; 10^6 @ 10% strain (*1*)	Fast (2)	*Electrical*	Permanent failure from dielectric breakdown; self-sensing; muscle-like performance
	Acrylic elastomer (VHB)	1.6 (typ) (*1*); 7.2 (max) (2)	380 (2)	400 (continuous); 3,600 (peak) (*1*)	30 (typ) (*1*); 60-80 (max) (2)	> 10^7 @ 5% strain; 10^6 @ 50% strain (*1*)	50% strain at 1 Hz; 1% strain at 100 Hz; produce sound at 20 kHz (3)		
Pneumatic	McKibben	0.35 (*4*)	15 (typ); 30 (max) (*5*)	3,000 (*5*)	20 (*6*)	10^7 (*7*)	> 1 Hz; max 150 Hz for vibration (*7*)	*Pressurized gas*	Readily designed for different modes of actuation – bending, twisting, extension/compression; requires supply of high pressure fluid and bulky system of valves and tubing
	VAMPs	0.1 (*8*)	45 (*8*)	18.5 (*8*)	27 @ 20% strain (*8*)	> 10^6 @ 5 Hz (*8*)	> 1 Hz (*8*)		
Hydraulic	McKibben	1.8 (*9*)	30 (*6*)	30 (*9*)	60 (*6*)	10^7 (*7*)	7 Hz (*10*)	*Pressurized liquid*	
Shape Memory	Alloy (Nitinol)	200 (*11*)	10 (*11*)	46,000 (*12*)	3 (*11*)	10^6 (3-4% strain) (*11*)	3 Hz (*11*)	*Thermal*	Low speed; low efficiency; difficult to sense and control
	Polymer	4 (*13*)	400 (*13*)	-	< 10 (*13*)	> 1,000 (*14*)	< 1 Hz (*15*)		
Ferroelectric		43 (2)	4 (*16*)	-	~ 80 (2)	-	100 Hz; 0.1% strain > 10 kHz (*1*)	*Electrical*	High stress; low actuation strain; high theoretical efficiency
Conductive Polymer Actuators (Polypyrrole, PANI)		450 (2)	10 (2)	150 (*1*)	5 (2)	28 x 10^3 (typical); 800 x 10^3 (max) (*1*)	<< 1 Hz (2)	*Electrical*	Critically low speed; low efficiency; low lifetime
Thermally Activated Coiled Polymer Fibers (Artificial Muscles from Fishing Line)		140 (*17*)	49 (*17*)	27,100 (average); 49,900 (peak) (*17*)	1.32 (*17*)	10^6 (*17*)	8 Hz (with cooling fluid) (*17*)	*Thermal*	High actuation stress; high power; low efficiency; difficult to control

HASEL actuators are based on coupling between electrostatic and hydraulic forces.

- Enables wide range of actuation modes
- Compatible with versatile range of materials and fabrication techniques
- Leads to actuators that self-heal electrically and mechanically (coming soon).

HASEL is a new platform for research and development of muscle-mimetic actuators with wide-ranging applications.

References

1. J. D. W. Madden *et al.*, Artificial Muscle Technology: Physical Principles and Naval Prospects. *IEEE J. Ocean. Eng.* **29**, 706–728 (2004).
2. P. Brochu, Q. Pei, Advances in Dielectric Elastomers for Actuators and Artificial Muscles. *Macromol. Rapid Commun.* **31**, 10–36 (2010).
3. C. Keplinger *et al.*, Stretchable, Transparent, Ionic Conductors. *Science* **341**, 984–987 (2013).
4. Ching-Ping Chou, B. Hannaford, Measurement and modeling of McKibben pneumatic artificial muscles. *IEEE Trans. Robot. Autom.* **12**, 90–102 (1996).
5. F. Daerden, D. Lefeber, Pneumatic Artificial Muscles: actuators for robotics and automation. *Eur. J. Mech. Environ. Eng.* **47**, 11–21 (2002).
6. M. A. Meller, M. Bryant, E. Garcia, Reconsidering the McKibben muscle: Energetics, operating fluid, and bladder material. *J. Intell. Mater. Syst. Struct.* **25**, 2276–2293 (2014).
7. Festo, Fluidic Muscle DMSP/MAS (2008), (available at https://www.festo.com/cat/en-gb_gb/data/doc_ENUS/PDF/US/DMSP-MAS_ENUS.PDF).
8. D. Yang *et al.*, Buckling Pneumatic Linear Actuators Inspired by Muscle. *Adv. Mater. Technol.* **1**, 1600055 (2016).
9. B. Sangian, Danial, Naficy, Sina, Spinks, Geoffrey M., and Tondu, The effect of geometry and material properties on the performance of a small hydraulic McKibben muscle system. *Sensors Actuators A Phys.* **234**, 150–157 (2015).
10. M. Focchi *et al.*, in *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems* (IEEE, 2010; http://ieeexplore.ieee.org/document/5650432/), pp. 2194–2199.
11. M. A. Jani, Jaronie Mohd, Leary, Martin, Subic, Aleksander, and Gibson, A review of shape memory alloy research, applications and opportunities. *Mater. Des.* **56**, 1078–1113 (2014).
12. I. W. Hunter, S. Lafontaine, J. M. Hollerbach, P. J. Hunter, in *[1991] Proceedings. IEEE Micro Electro Mechanical Systems* (IEEE; http://ieeexplore.ieee.org/document/114789/), pp. 166–170.
13. New materials for micro-scale sensors and actuators: An engineering review. *Mater. Sci. Eng. R Reports*. **56**, 1–129 (2007).
14. D. Kong, X. Xiao, High Cycle-life Shape Memory Polymer at High Temperature. *Nat. Publ. Gr.* (2016), doi:10.1038/srep33610.
15. C. Liu *et al.*, Review of progress in shape-memory polymers. *J. Mater. Chem.* **17**, 1543 (2007).
16. Q. M. Zhang, V. Bharti, X. Zhao, Giant Electrostriction and Relaxor Ferroelectric Behavior in Electron-Irradiated Poly(vinylidene fluoride-trifluoroethylene) Copolymer. *Science* **280**, 2101–2104 (1998).
17. C. S. Haines *et al.*, Artificial Muscles from Fishing Line and Sewing Thread. *Science* **343**, 868–872 (2014).

Acknowledgements and notes

For more details on HASEL actuators, see:

Hydraulically amplified self-healing electrostatic actuators with muscle-like performance
E. Acome, S. K. Mitchell, T. G. Morrissey, M. B. Emmett, C. Benjamin, M. King, M. Radakovitz, C. Keplinger
Science 359 (6371), 61-65 (2018)
DOI: 10.1126/science.aao6139

Peano-HASEL actuators: Muscle-mimetic, electrohydraulic transducers that linearly contract on activation.
N. Kellaris, V. Gopaluni Venakata, G.M. Smith, S. K. Mitchell, C. Keplinger
Science Robotics 3 (14), eaar3276 (2018)
DOI: 10.1126/scirobotics.aar3276

This work was supported by startup funds from the University of Colorado, Boulder and by a 2017 Packard Fellowship for Science and Engineering. E.A., S.K.M., N.K., M.B.E., T.G.M. and C.K. are listed as inventors on provisional patent applications submitted by the University of Colorado, Boulder, that cover fundamental principles and various designs of HASEL transducers.