

PROCEEDINGS OF SPIE

[SPIDigitalLibrary.org/conference-proceedings-of-spie](https://spiedigitallibrary.org/conference-proceedings-of-spie)

Synthetic Muscle electroactive polymer (EAP) shape-morphing and pressure sensing for robotic grippers

Rasmussen, Lenore, Vicars, Peter, Briggs, Calum, Cheng, Tianyu, Clancy, Edward, et al.

Lenore Rasmussen, Peter N. Vicars, Calum Briggs, Tianyu Cheng, Edward A. Clancy, Shannon Carey, Benjamin Secino, "Synthetic Muscle electroactive polymer (EAP) shape-morphing and pressure sensing for robotic grippers," Proc. SPIE 11375, Electroactive Polymer Actuators and Devices (EAPAD) XXII, 1137505 (21 May 2020); doi: 10.1117/12.2558965

SPIE.

Event: SPIE Smart Structures + Nondestructive Evaluation, 2020, Online Only, California, United States

Synthetic Muscle™ Electroactive Polymer (EAP) Shape-Morphing and Pressure Sensing for Robotic Grippers

Lenore Rasmussen,¹ Peter N. Vicars,¹ Calum Briggs,¹ Tianyu Cheng,^{1,3} Edward A. Clancy,² Shannon Carey,³ and Ben Secino³

¹Ras Labs, Inc., 12 Channel Street, Suite 202, Boston, MA 02210, ²Electrical Engineering and Computer Science, Worcester Polytechnic Institute, 100 Institute Rd, Worcester, MA, 01609, ³Robotics Engineering, Worcester Polytechnic Institute, 85 Prescott Street, Worcester, MA, 01609.

ABSTRACT

Ras Labs makes Synthetic Muscle™, which is a class of electroactive polymer (EAP) based materials and actuators that controllably contract and expand at low voltage (1.5 V to 50 V, including use of batteries), potentially sense pressure (gentle touch to high impact), and attenuate force. This offers biomimetic movement by contracting similar to human muscles, but also exceeds natural biological capabilities by expanding under reversed electric polarity. These EAPs are affordable and robust. They have been tested in many harsh environments, including extreme temperatures, high pressure underwater environments, and in space on the International Space Station. Potential load bearing applications are feasible, with significant mechanical strength when tested in compression. Selected EAP samples were tested and survived 3,000,000 cycles at 4 Hz from 5 psi to 30 psi, followed by a 50-psi compression. Human grasp is gentle yet firm, with tactile touch feedback. In conjunction with shape-morphing abilities, these EAPs also are being explored to intrinsically sense pressure due to the correlation between mechanical force applied to the EAP and its electronic signature. We are continuing to advance EAP technology and apply this technology towards robotic grippers. The robotic field is experiencing phenomenal growth in this fourth phase of the industrial revolution, the robotics era. The combination of Ras Labs' EAP shape-morphing and sensing features promises the potential for robotic grippers with human hand-like control and tactile sensing. This work is expected to advance both robotics and prosthetics, particularly for collaborative robotics to allow humans and robots to intuitively work safely and effectively together.

1. INTRODUCTION

The EAPAD community will play a role in helping combat the SARS-CoV-2 pandemic that is affecting us worldwide. Technology pushes humanity forward and saves lives. Synthetic Muscle™ is a class of EAP based materials and actuators that contract and expand at low voltage (battery levels), sense pressure from gentle touch to high impact, and attenuate force.^{1,3} These EAPs can withstand environments unsafe to humans due to extreme temperatures, radiation, and pressures, summarized in Chart 1,¹ as well as environments with biological agents such as infectious contagions. Noteworthy is significant mechanical strength when tested in compression (Chart 1). For shape-morphing, the dual motion of contraction and expansion is achieved by easily switching the electric polarity of the voltage applied to the EAP back-and-forth to produce contraction-expansion cycles. The amount of movement can be controlled by adjusting the voltage level, which lends these materials to biofeedback.² In addition, these EAPs serve dual use as mechanical pressure sensors, from gentle touch to high impact.^{1,3} Ras Labs' EAPs, synthesized to mimic the unique gentle-yet-firm nature of human tissue, is a potential asset to both robotic and prosthetic applications. These EAPs, both the shape-morphing aspects and the sensing aspects as soft sensors, were applied to robotic grippers.

Chart 1. Synthetic Muscle™ properties from specialized testing including extreme environments.¹

Property	Value
Strength	Able to withstand ~ 2000 N, 1200 impacts at 908 N (tested in collaboration with Children's Hospital of Philadelphia) and over 10 G (tested by US Army) Able to withstand 3,000,000 compression cycles (5 - 30 psi, ambulation mimicry, tested by O&P B2B partner)
Durometer	Shore O: 5 to 34
Power Requirement	Linear range between 0 and 50 V
Force output	0.01 mN (with less than 2 g actuator, US Army project)
Work Output ratio	Move objects 1:18 actuator weight: total load weight, ~2X human work output (US Army project)
Temperature Tolerance	4 to 408 K (-269 to 135°C, tested at US DOE's Princeton Plasma Physics Lab & Cava Lab, Princeton University)
Radiation Resistance	Over 305 kRad gamma radiation (tested at PPPL); broad spectrum exposure on International Space Station 65 mGy (76X exposure on Earth)
Vacuum Tolerance	1.5 x10 ⁻⁵ Torr
Onset of electro-actuation at nano-level	Within 48 milliseconds (tested at CHSLT Lab, Worcester Polytechnic Institute)
High Pressure Tolerance	2200 psi (over ~1500 meters of ocean depth, tested by New England based AUV robotics company)
Axis of Expansion & Contraction	3-axes simultaneously; can be controlled to desired direction

When one considers motion, how a train moves comes to mind; or when one opens a watch, how the inner workings mesh. Alternatively, when one thinks about motion, how a bird flies comes to mind, or how a fish swims through the water, or how we walk, run, and manipulate tools – and never the twain shall meet. Even in Ben Franklin's time, electricity was applied to frog legs to cause movement, but as biological tissue, the frog legs decomposed within days. Synthetic Muscle™ based EAPs are man-made materials. These EAPs can withstand and work for long periods of time and in environments where living organisms cannot survive. Now the twain can meet. This blending of mechanical and biological concepts within the EAPAD community is leading to truly innovative biomimetic motion.

The Synthetic Muscle™ based EAP actuators are a system: the EAPs, the wiring, the coatings, and the attachments. The relationships for electroactivity in these EAPs are shown in Equation 1. Electroactivity is directly proportional to the amount of voltage. If slower or less pronounced movement is needed, the voltage level can be reduced. If faster or more pronounced movement is needed, then the voltage can be increased. Electroactivity is directly proportional to time. The longer the voltage is applied, the greater the change in size, up to a plateau point. In these EAPs, the ionic content of the polymer directly influences the electroactivity, as well as the concentration of the electrolytes. Electroactivity is inversely proportional to the EAP volume (in terms of percentage change, vs. absolute change) and to the EAP's hardness. In other words, the harder or firmer the EAP, the more inflexible it is, and the less it changes in size. The softer the EAP is, the more flexible it is, and the more it can shape-morph and change in size.

$$E_a \propto (V)(T)(IC)[X] / (Vol)(H)$$

Equation 1

where

E_a = electroactivity

V = voltage

T = time

IC = ionic content of EAP

$[X]$ = molar electrolyte concentration

Vol = EAP volume (time dependence)

H = EAP hardness

This is the fourth era of the industrial revolution, the robotics era, which has its challenges. Most robotic automation is fast and strong, so needs to be partitioned away from humans for safety reasons. For many repetitive tasks that humans do with delicate or fragile objects, it would be beneficial to use robotics; whether it is for agriculture, medical surgery, therapeutic or personal care, or in environments where it isn't safe for humans to be. The other challenge with robots is sensing. Currently, robotic sensing is mainly visual. This is only useful up until the point of contact with the object. After that, to understand how an object is being gripped, tactile feedback is needed. For handling fragile objects, if the grip is too tight, breakage occurs, and if the grip is too loose, the object will slip out of the grasp, also leading to breakage. Rigid robotic grippers using a visual feedback loop can struggle to determine the exact point and quality of contact. Robotic grippers can also get a stuttering effect in the visual feedback loop. By using soft Synthetic Muscle™ based EAP pads as the sensors, immediate feedback was generated at the first point of contact. Because these pads provided a soft, compliant interface, the first point of contact did not apply excessive force, allowing the force applied to the object to be finely controlled. The EAP sensor could also detect a change in pressure location on its surface, making it possible to detect and prevent slippage by then adjusting the grip strength. In other words, directional glide provided feedback for the presence of possible slippage to then be able to control a slightly tighter grip, without stutter, due to both the feedback and the soft gentleness of the fingertip-like EAP pads themselves. The soft nature of the EAP fingertip pad also naturally held the gripped object, improving the gripping quality over rigid grippers without an increase in applied force.

2. EXPERIMENTAL

The EAP cross-linked networks were produced by ultraviolet (UV) photo-polymerization of ion-containing monomers with specialized cross-linking agents using a photo-initiator. The UV source was a UVitron® SunRay 600 W 175 mW/cm² UVA (320-390 nm) array operated at the lower setting.

For the EAP sensors, the 3D printed molds were used for creating the silicone molds. The EAPs were UV photo-polymerized in the silicone molds. Extensive design experiments were performed to select the most suitable system for integration of electrodes within the EAP pads. Various strategies were investigated for the wiring to produce good adhesion, which helped with reliability and predictability for modeling sensing output.

The first step in designing pressure sensors was to address how the electrical sensing circuitry should be connected to the EAP. There are two primary factors that were considered: flexibility and contact resistance. Contact resistance is the electrical resistance which is present due to the imperfect electrical connection at an electrical contact, which can be affected by pressure, temperature, or a chemical change at the point of contact, such as metal corrosion. Minimizing the magnitude and variance of contact resistance was vital to creating a robust pressure sensor. Contact design focused on two major areas, using metal and carbon-based electrodes. Selections for the two types of electrodes were based on their flexibility and relatively low contact resistance.

For mechanical pressure sensing testing, the basic test setup is shown in Figure 1. First, electrode filaments were placed through the holes on the cylinder and the piston. Flat head steel pins were inserted into the holes along with the electrode filament, and the metal head was contacting the EAPs. Then an EAP sample was placed in the center of the cylinder. The piston was placed at the top of the EAP and used to press the EAP sample to deform it to a desired geometry. There were two EAP sample shapes investigated, both with cylindrical shape but with different dimensions:

Sample 1: $\varnothing 10.2 \times 17.3 \text{ mm}$. Volume = $449.97\pi \text{ mm}^3$

Sample 2: $\varnothing 13.0 \times 10.7 \text{ mm}$. Volume = $452.08\pi \text{ mm}^3$

The dimension of the cylinders:

Cylinder: $\varnothing 16 \times 7 \text{ mm}$. Volume = $448\pi \text{ mm}^3$

After the piston was pressed all the way down to the stop inside the cylinder, both samples were then compressed to the same geometry as the inside of cylinder, i.e., under compression they had the same length, L , and same section area, A . However, since the two samples had different initial lengths, they had different stresses under compression, which was assumed to lead to differences of the change of conductivity, ρ , and therefore the two samples had different resistances, R . Sample 1 and 2 consisted of one sample pair. Four pairs were prepared and labelled from A to D. Each pair were charged for more than 5 minutes until their resistance plateaued as they were pressed simultaneously. Each sample pair was tested 8 times, during which their cylinders were exchanged, and each sample was then flipped upside down. The final result took the average of 8 trials.

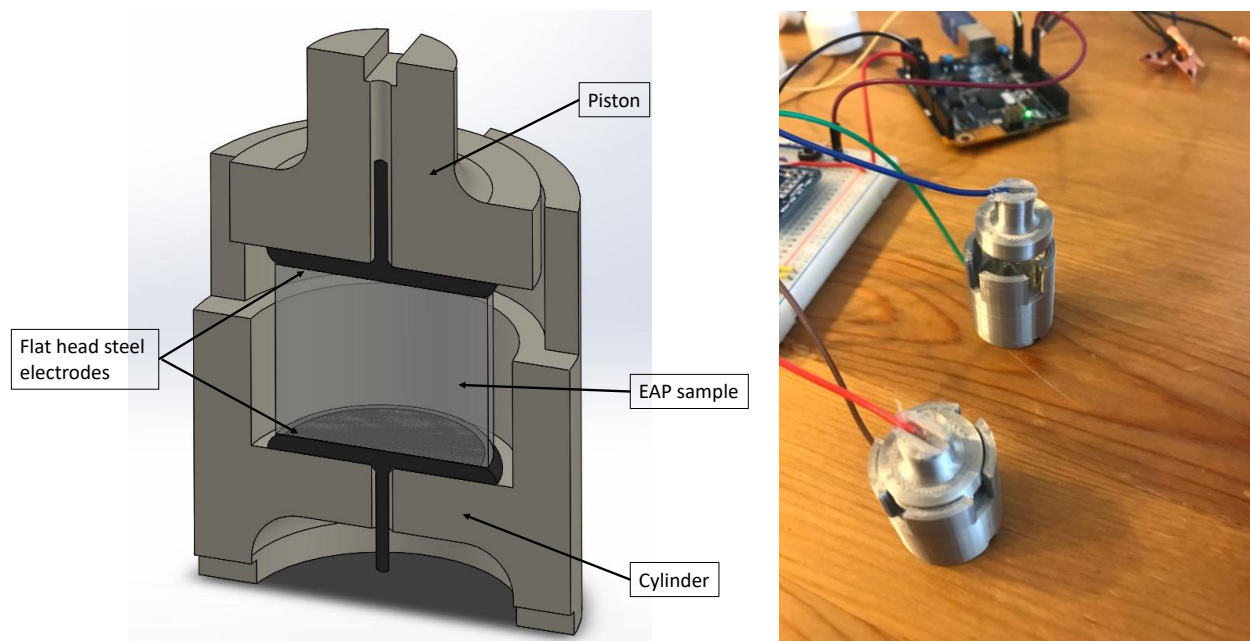


Fig. 1. Test setup for mechanical pressure sensing of EAPs.

Sensor development focused on two major designs: the dome shaped Synthetic Fingertip™ Sensor and the flat rectangular Synthetic Fingerpad™ Sensor. The Synthetic Fingertip™ Sensor was constructed with a hemispheric shape, while the Synthetic Fingerpad™ Sensor was an approximate rectangular prism shape. Pressure sensing information was gathered by measuring the electrical properties between electrodes. This information was then coalited to create a 3D understanding of the pressure profile of the EAP.

3. RESULTS AND DISCUSSION

The focus of this research and development was on the sensing capabilities of Synthetic Muscle™. Synthetic Muscle™ based EAPs have variable resistance when subjected to mechanical pressure, even light pressure. These EAPs are neither pure conductors nor pure insulators, but are something in between, and so are semi-conductive, with unique electronic signatures. Their variable resistive nature combined with their soft and compliant physical nature can be extremely useful. The method of sensing using the EAP can be compared to a strain gauge. Pressure applied to the surface of the compliant EAP caused a change in the geometry and properties of the substance. By placing electrodes in strategic locations, changes in the EAPs' electronic signature(s) caused by mechanical strain were measured and a sophisticated understanding of the distribution of could be determined.

From the results of the mechanical pressure sensing testing (Figures 1 and 2), it was observed that for every sample pair, V1 (V_{out} of sample 1) was lower than V2 (V_{out} of sample 2), which meant that $R1 > R2$, and therefore $\rho1 > \rho2$. Since sample 2 experienced more pressure, the conclusion was that the conductivity decreased when the EAP experienced more pressure. These were preliminary results.

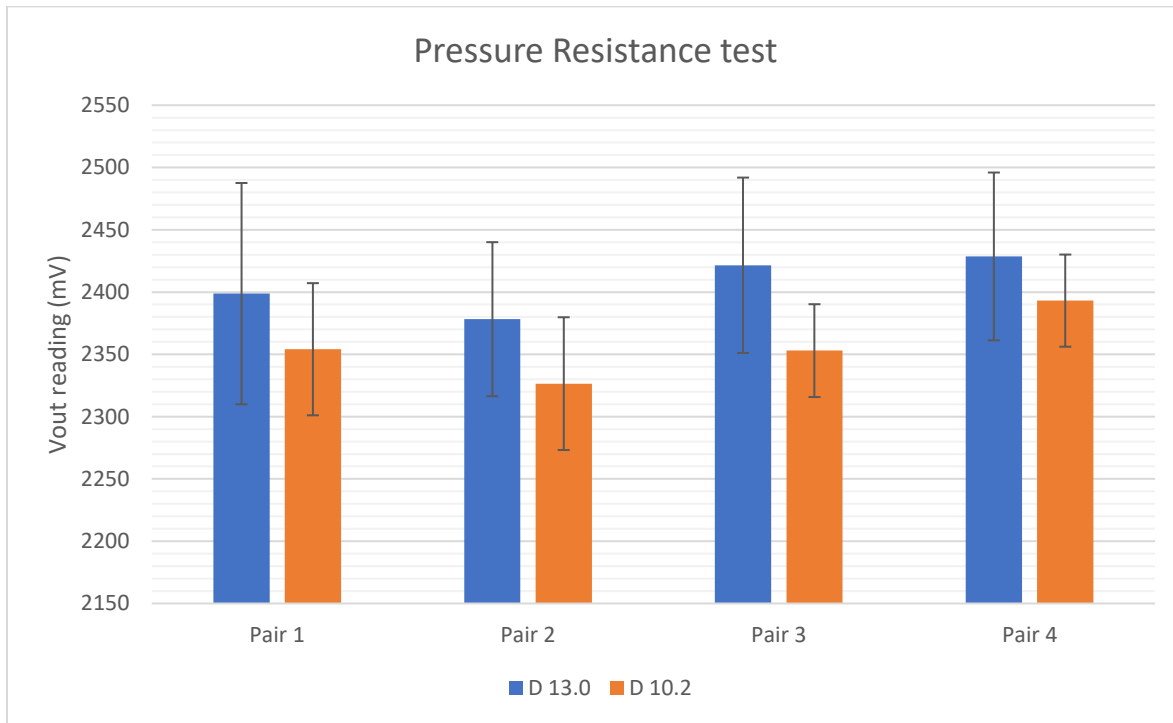


Fig. 2. Pressure resistance for EAPs with same dimension under different compression.

The development of using Synthetic Muscle™ based EAPs as soft sensors provided for sensors that felt much like the pads of human fingertips. Both the dome shaped Synthetic Fingertip™ Sensor and the flat rectangular Synthetic Fingerpad™ Sensor provided feedback for point of contact, what we know as tactile touch, as well as for glide to detect slippage (Figures 1 and 2).

Figure 3 depicts the dome-shaped soft sensor. This soft sensor has a hemispheric shape. The goal of the Synthetic Fingertip™ sensor was to mimic the form and function of the human finger in terms of tactile touch of mechanical pressure. Human sensitivity is around 0.1 Newtons (N) of force over a fingertip.⁴ While individual cells on the human fingertip can react to structural features of a few nanometers in size and mechanical differences in the Pascal (Pa) range, the tactile sensitivity of the human finger is only capable of detecting structural features above 10 nm and local mechanics (the gentlest touch) around 1 kPa.^{4,5} Pressure sensing information of the Synthetic Fingertip™ was gathered by measuring the electrical properties between its electrodes. This information was then coalited to create a three-dimensional understanding of the pressure profile. Initial results have been promising. Basic pressure position and magnitude tests have been successful, with pressure sensitivity down to 0.2 N.

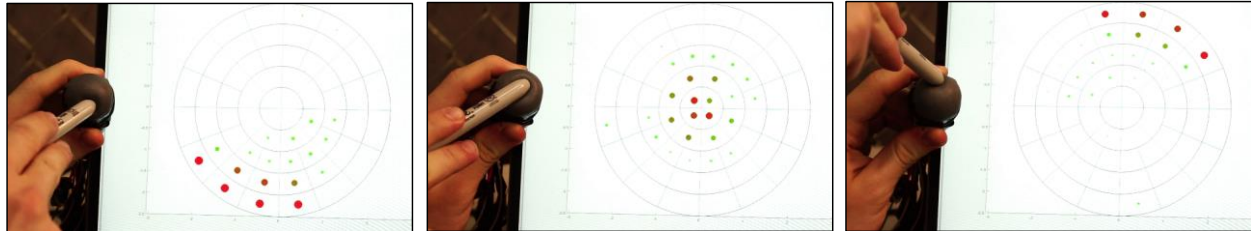


Fig. 3. Dome-shaped EAP based fingertip-like sensor with real time output display, which provides point of contact detection and glide feedback to prevent slippage.

Figure 4 shows the flat Synthetic Fingerpad™, where the gripper pad using the EAP based soft sensor is circled in yellow. On the computer, the different touch points of the gripper were again observed in real time. An open source robotic hand, OpenHand,⁶ was 3D printed to demonstrate the longer and flatter finger-like pad on the robotic gripper and its ability to sense different areas along the length of that soft sensor. This would be beneficial to show glide and thus provide feedback to prevent slippage.

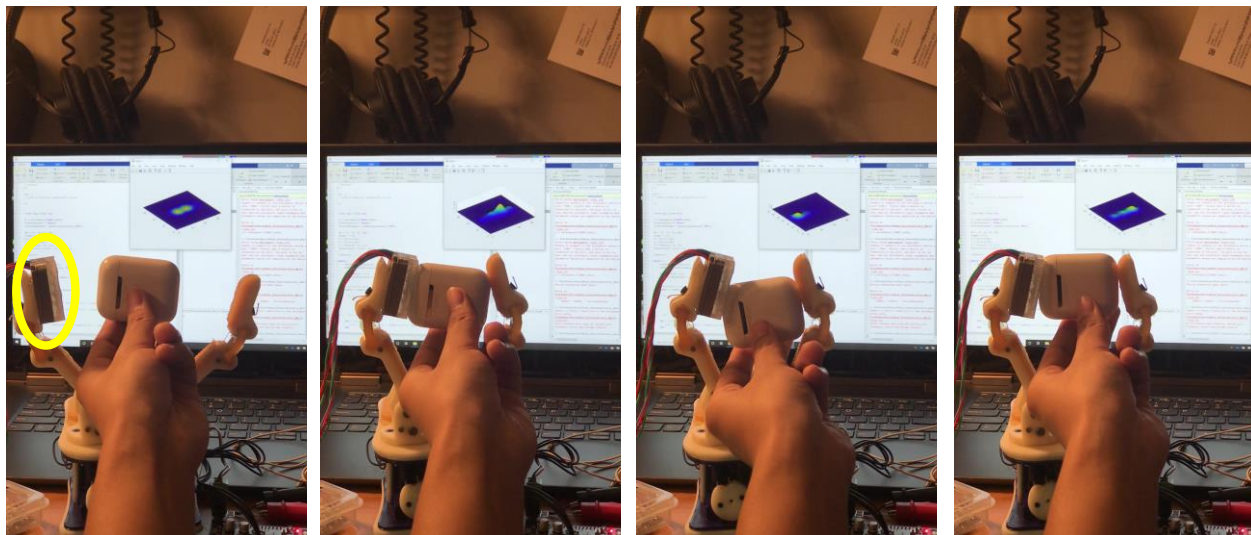


Fig. 4. Flat fingerpad-like sensor retrofit to robotic gripper with real time output display to provide point of contact detection and glide feedback to prevent slippage.

Synthetic Muscle™ also shape-morphs. These EAPs contract and expand in a controllable fashion by simply adjusting the voltage.¹⁻³ An off-the-shelf sprue gripper was retrofitted with a Synthetic Muscle™ based EAP system. Its actuation was compared to standard pneumatic pressure to handle soft fruit such as a blueberry (Figure 5). This EAP system weighed 9 grams, which included the EAP, the wiring, and the coating. First 20 V was applied to actuate to point of contact, then reduced to 5 V to hold the blueberry, with no droppage, no slippage, and no damage to the fruit.

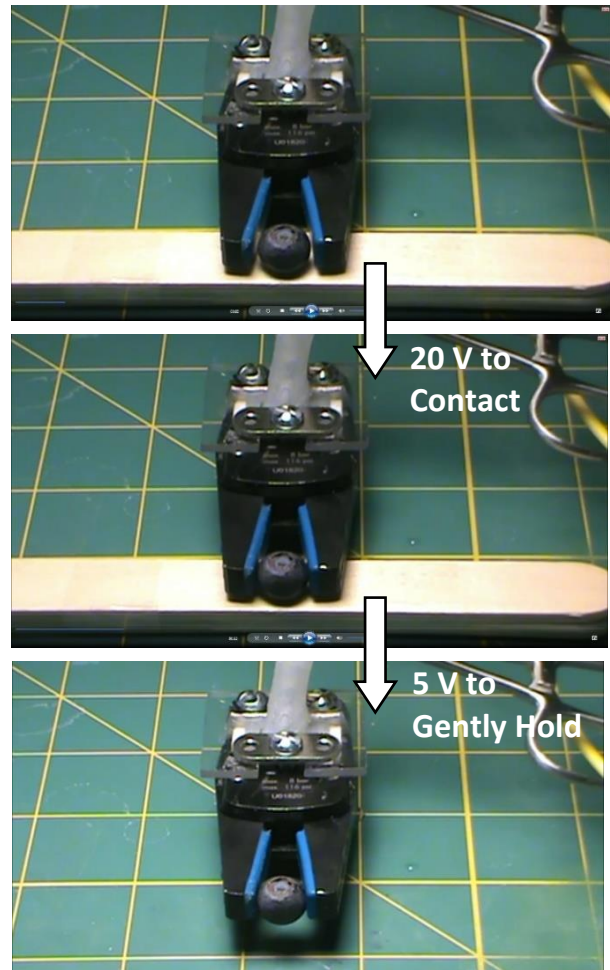
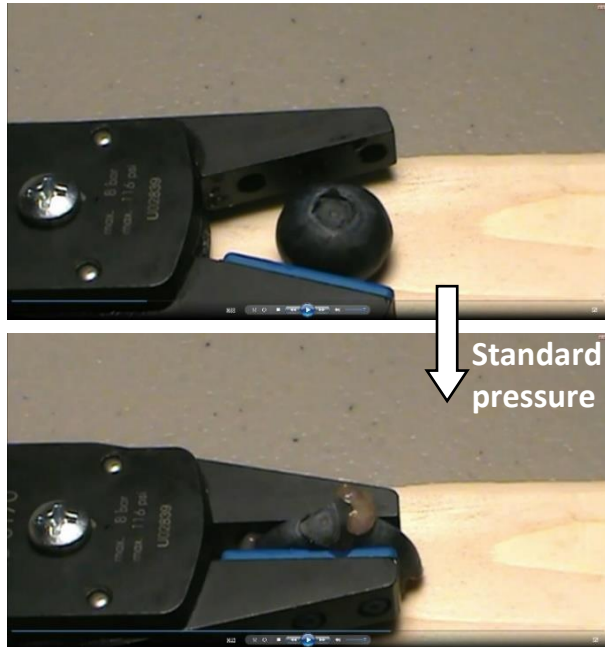
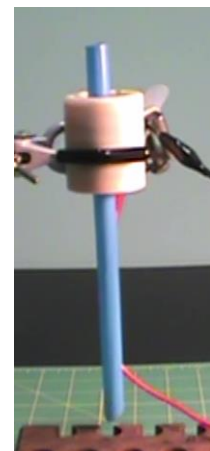


Fig. 5. EMI® Gripper handling a blueberry using standard pneumatic pressure (left); and retrofitted with a Synthetic Muscle™ based EAP actuator (right) with 0 V (top right), 20 V to quickly make contact (middle right), and then 5 V to handle blueberry with no droppage, no slippage, and no damage to fruit (bottom right).

More recently, another Synthetic Muscle™ based EAP system was retrofitted into what is known in the robotics trade as an air hand. This provided for pick-and-place of fragile thin walled cylinders (Figure 5).

Fig. 6. Pick-and-place of a thin walled cylinder using an off-the-shelf air hand retrofitted with a Synthetic Muscle™ based EAP actuator.



4. CONCLUSIONS AND FUTURE WORK

Replicating human grasp has implications in robotics, particularly for collaborative robots, also known as cobots, for humanoid robots, also known as hubots, and for safe human and work assist robotics. Synthetic Muscle™ can survive and work in environments where humans cannot safely enter, due to extreme environments or due to contagions that have no cure. In addition to shape-morphing abilities, these EAPs were also used to intrinsically sense pressure due to the correlation between mechanical force applied to the EAP and its electronic signature. Two sensor designs were investigated: a dome-shape fingertip-like soft sensor and a flat rectangular prism fingerpad-like soft sensor. Both designs gave good point of contact detection and were able to provide glide information, which is useful for slippage detection when robotic grippers are handling objects, particularly fragile items. This work is ongoing. For the mechanical pressure sensing testing, this was only a preliminary comparison test. The standard deviations were too large when comparing the differences between the sample pairs. In future tests, an Instron® universal testing machine can be used to measure the exact pressure value before and after the compression of the samples. Signal consistency is currently being worked on to reduce any drift and to achieve good baseline signaling when there is no mechanical pressure. Machine learning (ML) and artificial intelligence (AI) can be layered into the sensor systems, however, even with these add-ons for more intuitive feedback, it is highly desirable to have these EAP sensor systems as consistent, reliable, and simple as possible to maintain low latency, i.e., to keep the feedback speed near instantaneous in real time without delays. Concerning glide feedback, to prevent slippage, there could be a fast feedback loop without much ML and AI, while for more sophisticated tasks and motion, ML and AI could be more fully employed. The analogy is when our hand feels pain, we immediately jerk our hand back because of the faster response from the spinal cord feedback loop, while the more delayed interpretation of pain and analysis comes from the brain's feedback loop. The immediate feedback loop helps prevent injury, while for more sophisticated tasks like fine craftsmanship, most of the feedback to our hands is cerebral. The combination of Ras Labs' EAP shape-morphing and sensing features promises the potential for robotic grippers with human hand-like control and tactile sensing.

ACKNOWLEDGEMENTS

We gratefully acknowledge high school interns Curran Dillis and Alex Zhong of the Hingham High School Robotics Club for their work on this project. We gratefully acknowledge the National Science Foundation, the Kalenian Award, Breakout Labs, Children's Hospital of Philadelphia/Philadelphia Pediatric Medical Device Consortium, CASIS, US DOE, and US DOD for funding of the synthetic muscle projects. The MLSC Internship Challenge graciously provided internship support.

REFERENCES

- ¹ L. Rasmussen, S. Rodriguez, M. Bowers, D. Smith, G. Martino, L. Moy, P.S. Mark, D. Prillaman, R. Nodarse, R. Carpenter, D. Martin, C. Scheiber, J. d'Almeida, *Proc. SPIE 10966, Electroactive Polymer Actuators and Devices (EAPAD) XXI*, Vol. 10966, 1096626; doi: 10.1117/12.2514429, 2019.
- ² L. Rasmussen, Editor, "Electroactivity in Polymeric Materials," Springer-Verlag, GmbH & Co. KG © 2012.
- ³ L. Rasmussen, S. Rodriguez, M. Bowers, G. Franzini, C. A. Gentile, G. Ascione, R. Hitchner, J. Taylor, D. Hoffman, L. Moy, P. S. Mark, D. L. Prillaman, R. Nodarse, M. J. Menegus, R. Carpenter, D. Martin, M. Maltese, T. Seacrist, C. Furlong, P. Razavi, G. Martino, *Proc. SPIE 2018, Electroactive Polymer Actuators and Devices (EAPAD) XX*, Vol. 10594, 105942C; doi: 10.1117/12.2297660, 2018.
- ⁴ B. Patel, Synthetic Skin Sensitive to the Lightest Touch, <https://spectrum.ieee.org/biomedical/bionics/synthetic-skin-sensitive-to-the-lightest-touch> © 2010.
- ⁵ Y. Jiang, U. Mansfield, K. Kratz, A. Lendlein, "Programmable microscale stiffness pattern of flat polymeric substrates by temperature-memory technology," *MRS Communications* 9(01):181-188, 2019.
- ⁶ W.G. Bircher, A.M. Dollar, A. Morgan, OpenHand: <https://www.eng.yale.edu/grablab/openhand/> © 2020.