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

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ABSTRACT

Ras Labs makes Synthetic Muscle™, which is a class of electroactive polymer (EAP) based materials and actuators that sense pressure (gentle touch to high impact), controllably contract and expand at low voltage (1.5 V to 50 V, including use of batteries), and attenuate force. We are in the robotics era, but robots do have their challenges. Currently, robotic sensing is mainly visual, which is useful up until the point of contact. 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 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. Analogous to finger-like tactile touch, the EAPs with appropriate coatings and electronics were positioned as pressure sensors in the fingertip or end effector regions of robotic grippers. This development of using Synthetic Muscle™ based EAPs as soft sensors provided for sensors that feel like the pads of human fingertips. Basic pressure position and magnitude tests have been successful, with pressure sensitivity down to 0.05 N. Most automation and robots are very strong, very fast, and usually need 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 extreme environments where humans cannot enter, including with contagions that have no cure. Synthetic Muscle™ was also retrofitted as actuator systems into off-the-shelf robotic grippers and is being considered in novel biomimetic gripper designs, operating at low voltages (less than 50 V). This offers biomimetic movement by contracting like human muscles, but also exceeds natural biological capabilities by expanding under reversed electric polarity. 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. 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.

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1. INTRODUCTION

The smart material community will play a role in assisting humanity. 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] These EAPs can withstand environments unsafe to humans due to extreme temperatures, radiation, and pressures (Chart 1), as well as environments with biological agents such as infectious contagions with no cure. Ras Labs EAP technology is scalable (Figure 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.[1] In addition, these EAPs serve dual use as mechanical pressure sensors, from gentle touch to high impact.[2] Ras Labs' EAPs, synthetized to mimic the unique gentle-yet-firm nature of human tissue, is a potential asset to both robotic and prosthetic applications. Both the shape-morphing aspects and the sensing aspects as soft sensors of these EAPS were applied to robotic grippers.

Fig. 1. Scale-up batch of Synthetic Muscle™.

Synthetic Fingertip™ Sensors provided feedback for point of contact, analogous to tactile touch, as well as for glide to detect slippage. Human sensitivity is around 0.1 Newtons (N) of force over a fingertip. 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. 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. Basic pressure position and magnitude tests have been successful, with pressure sensitivity down to 0.05 N. In fact, while we were holding one of our sensors during some testing, we noticed what we thought at first was an electronic artifact, but was actually the sensor picking up the heartbeat pulse in our fingers. By placing the sensors on our wrist, we can readily pick up our heartbeat pulse. Thus far in our testing and characterization, the range is from very sensitive (0.05 N and probably quite lower) to over 45 N with the same sensor. Most automation and robots are very strong, very fast, and usually need 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 extreme environments where humans cannot enter, including with contagions that have no cure. Synthetic Muscle™ was also retrofitted as actuator systems into off-the-shelf robotic grippers and is being considered in novel biomimetic gripper designs, operating at low voltages (less than 50 V). This offers biomimetic movement by contracting like human muscles, but also exceeds natural biological capabilities by expanding under reversed electric polarity. 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. 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.

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, i.e. 34 – 207 kPa, ambulation mimicry, tested by O&P B2B partner) Fatigue Testing: 1,500,000 cycles of compressive force at 1.3 Hz, 300,000 cycles at 5 N, 700,000 cycles at 10 N, 500,000 more cycles at 5 N.
Durometer	Shore O: 5 to 34
Power Requirement	Linear range between O 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
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

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.

$$Ea \propto (V)(T)(IC)[X] / (Vol)(H) \qquad \textbf{Equation 1}$$

where
Ea = 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 FingerTip™ 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.

A TestResources™ single column universal testing machine (UTM) Model 2100024-01C was used to characterize the materials in compression and tension, and the entire sensor system in compression.

Mechanical Fatigue Testing was performed to 1,500,000 cycles of compressive force at 1.3 Hz for 300,000 cycles at 5 N, 700,000 cycles at 10 N, and then 500,000 more cycles at 5 N. For determining algorithms and performing machine learning (ML), a variety of different shapes (spherical, cylindrical, and rectangular heads) with different forces and angles were pressed against the fingertip sensor using test rigs constructed to spec. Robotiq® and Sake Robotic® grippers were used to handle a variety of objects, with integrated feedback for gentle grasp. A Robotiq® gripper was used for ML data acquisition.

3. RESULTS AND DISCUSSION

The focus of this research and development was on the sensing capabilities of the Synthetic Muscle™ EAP technology. These materials 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 complaint 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.

The FingerTip™ soft sensors are extremely sensitive, with a broad pressure range from at least 0.05 N up to over 45 N, with 1 mm resolution (Figures 2 and 3). These FingerTip™ sensors were validated and verified down to 0.05 N, with ongoing testing to capture the limits of the extreme sensitivity and linearity above 50 N (Figure 2B). Human touch is around 0.1 N pressure sensitivity [3]. In Figure 3, each pixel corresponds to 1 square millimeter. The 1mm^2 white pixel showing the highest contact pressure, surrounded by shades of red depicting surrounding pressure intensities. The FingerTip™ sensors were also able to pick up heartbeat pulses, including components of the pulse, at the wrist and other locations. From fatigue testing, these sensors were also robust, surviving 1,500,000+ cycles of compression force at ~ 1.3 Hz, with 300,000 cycles of 500 g weight (5N), 700,000 cycles with 1 kg weight (10 N), and 500,000 cycles at 5 N, with full functionality and no visible breakdown. These soft compliant FingerTip™ sensors are robust, extremely sensitive, and have a wide pressure range.

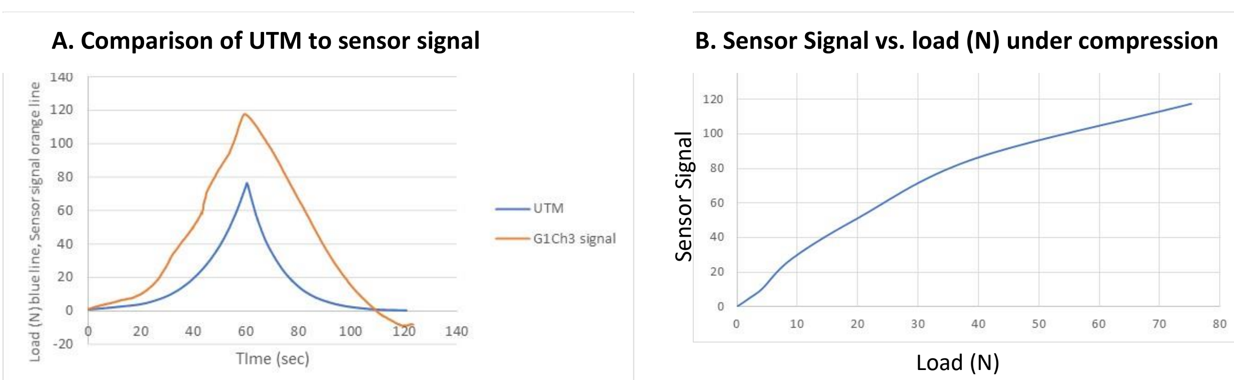
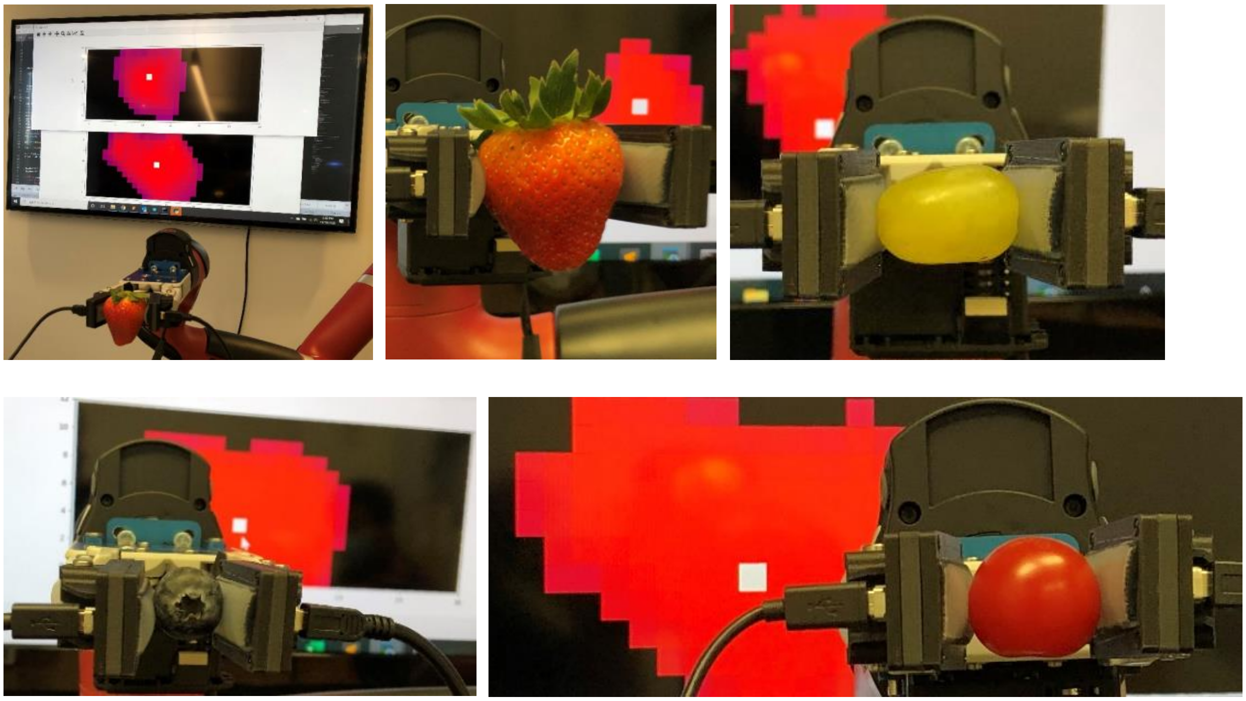
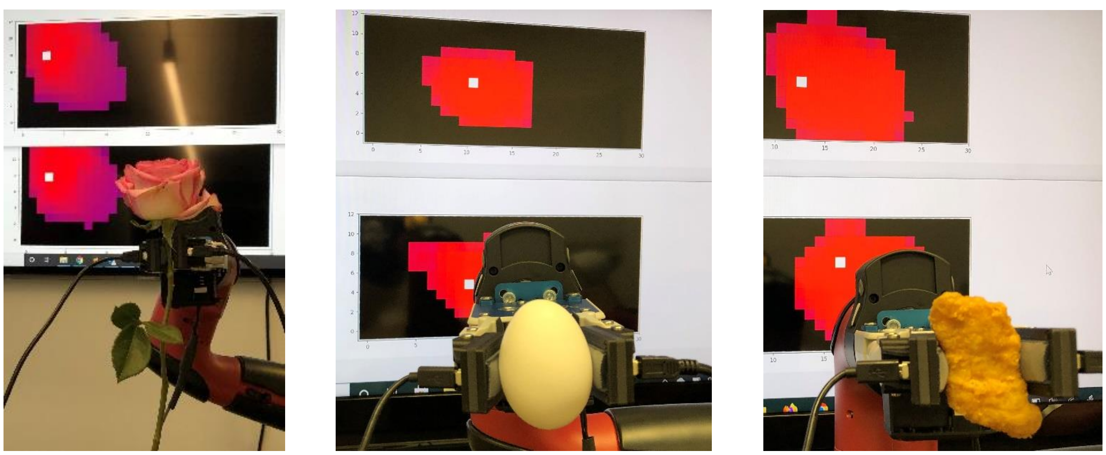


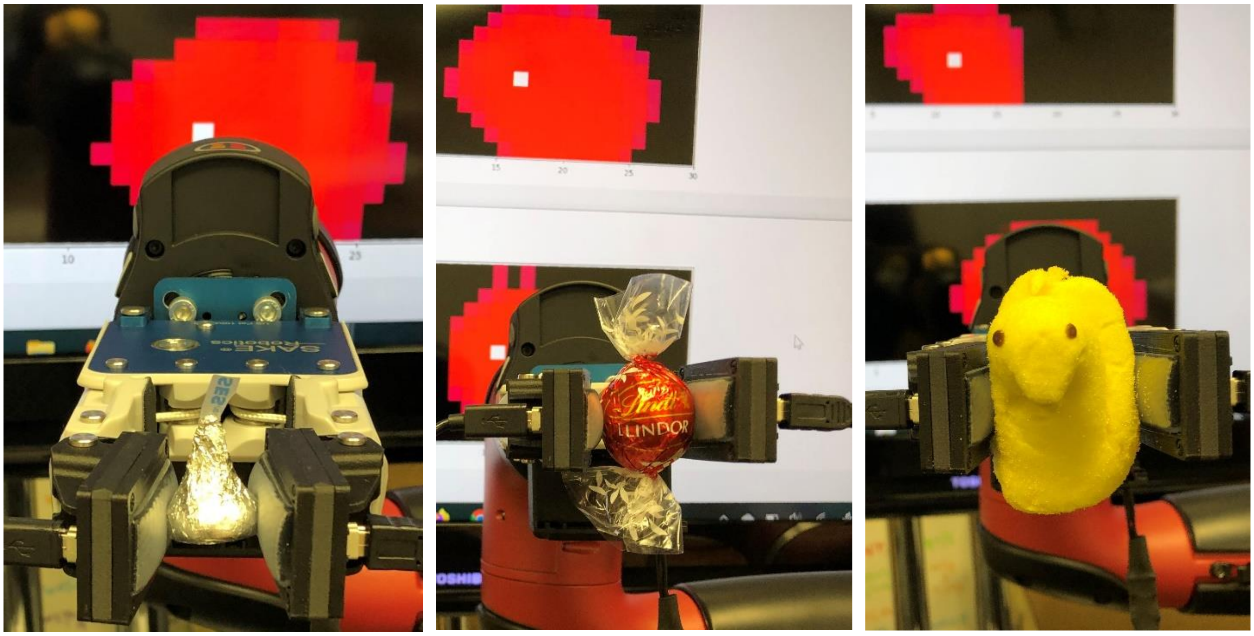
Fig. 1. A. UTM compression data and the sensor's electronic signal B. The sensor's electronic signal as a function of load from 0 to 75 N.



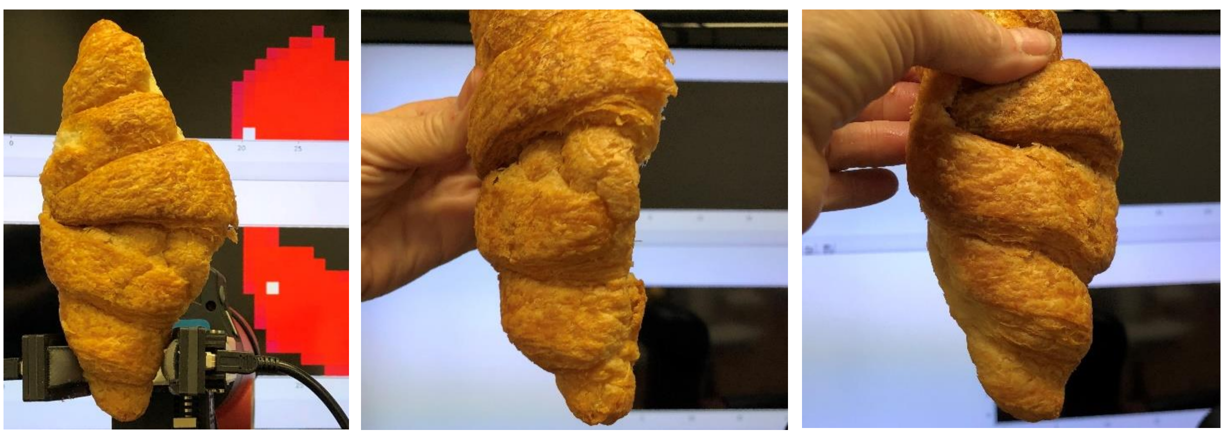
FingerTip™ Sensors retrofitted to a robotic arm and EOAT gripper, handling a variety of fruit with real time point of contact detection, with no droppage, no slippage, and no damage.



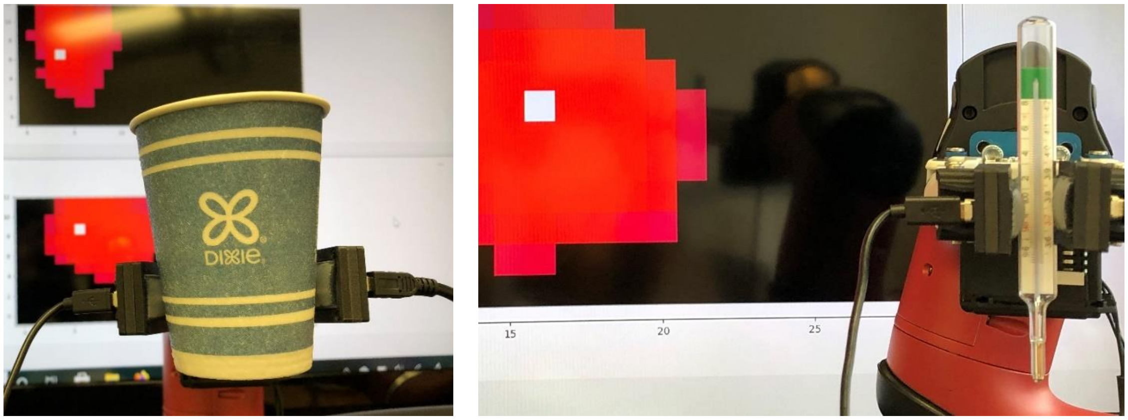
FingerTip™ Sensors handling a rose stem, a raw egg, and a McDonald's® chicken McNugget® with real time point of contact detection and with no droppage, no slippage, and no damage.



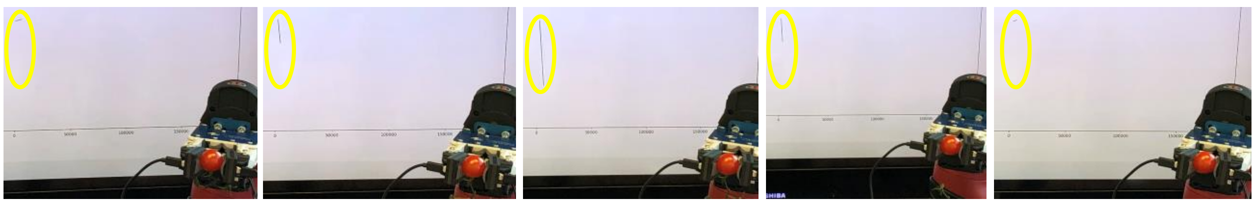
FingerTip™ Sensors handling a milk chocolate Hershey Kiss®, a soft centered Lindt Lindor® milk chocolate truffle, and a Just Born marshmallow Peep® with real time point of contact detection and with no droppage, no slippage, and no damage.



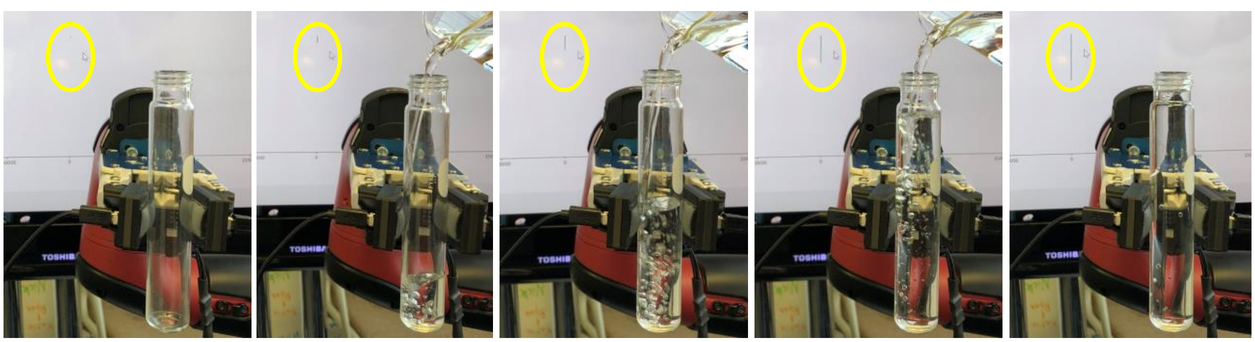
FingerTip™ Sensors handling a croissant with real time point of contact detection and with no droppage, no slippage, and no damage.



FingerTip™ Sensors handling a paper Georgia-Pacific Dixie® cup and a thermometer with real time point of contact detection and with no droppage, no slippage, and no damage.



FingerTip™ Sensors, retrofitted to a robotic gripper and arm, showing a ripe cherry tomato being picked off the vine, with no droppage, no slippage, and no damage. Circled in yellow shows the predominantly downward z-direction in near instantaneous real time: at ~0 N force before picking (far left), maximum force prior to tomato and vine cleanly separating (middle), and return to ~0 N force after the tomato was picked from the vine(far right).



FingerTip™ Sensors handling a Pyrex® glass test tube as it was filled with 50 mL of water. Circled in yellow shows the force in the downward z-direction in near instantaneous real time, from ~0 N (far left) to 0.5 N (far right).

Fig. 2. EAP technology based FingerTip™ sensors, retrofitted on a Sake Robotics® EOAT gripper with a Rethink Robotics® Sawyer robotic arm, handling a variety of fruit, a rose, a raw egg, a chicken nugget, a variety of candy, a croissant, a paper cup, a thermometer, business cards, and a test tube, with real time contact points displayed for both sensors, and with no droppage, no slippage, and no damage. The white pixel shows the highest contact pressure, surrounded by shades of red depicting surrounding pressure intensities, with 1 mm^2 resolution for each pixel. For the tomato, point of contact and release from the vine were easily detected. For the test tube, water was added and easily detected in real time.

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. Machine learning (ML) and artificial intelligence (AI) are being layered into these 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 quick 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 and prosthetic hands with human hand-like dexterous control and tactile touch sensing. Iterate sensitivity and range.

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