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Sensitive and robust electroactive polymer tactile pressure sensors and shape-morphing actuation for robotic grippers

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ABSTRACT

Current 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. Human grasp is gentle yet firm, with integrated tactile touch feedback. Ras Labs makes Synthetic Muscle™, which is a class of electroactive polymer (EAP) based materials and actuators that sense pressure from gentle touch to high impact, controllably contract and expand at low voltage (battery levels), and attenuate force. The development of this technology towards sensing has provided for fingertip-like sensors that were able to detect very light pressures down to 0.01 N and even 0.005 N, with a wide pressure range to 25 N and more and with high linearity. By using these soft yet robust Tactile Fingertip™ sensors, immediate feedback was generated at the first point of contact. Because these elastomeric pads provided a soft compliant interface, the first point of contact did not apply excessive force, allowing for gentle object handling and control of the force applied to the object. The Tactile Fingertip could also detect a change in pressure location on its surface, i.e., directional glide provided real time feedback, making it possible to detect and prevent slippage by then adjusting the grip strength. Machine learning (ML) and artificial intelligence (AI) were integrated into these sensors for object identification along with the determination of good grip (position, grip force, no slip, no wobble) for pick-and-place and other applications. Synthetic Muscle™ is also being retrofitted as actuators into a human hand-like biomimetic gripper. The combination of EAP shape-morphing and sensing promises the potential for robotic grippers with human hand-like control and tactile sensing. This is expected to advance 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, as well as for collaborative robotics to allow humans and robots to intuitively work safely and effectively together.

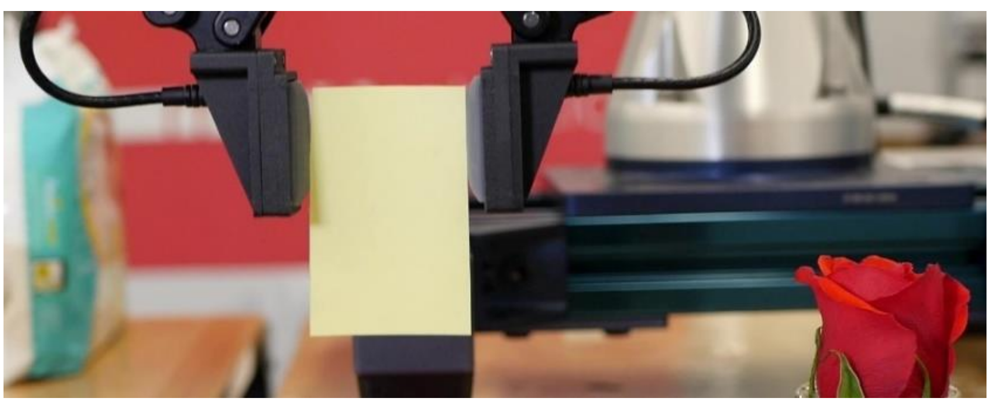

Figure 1. Extremely sensitive Tactile Fingertips™ retrofitted and with integrated feedback to a Robotiq® gripper, gently handling a Post-it® Note piece of paper.

Keywords: robotic gripper, robotic manipulation, pick-and-place, robot, electroactive polymer, EAP, smart material, tactile fingertip, soft pressure sensor, machine learning, artificial intelligence, neural network

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1. INTRODUCTION

Most automation and robots are very strong, very fast, and typically 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 for E-commerce, consumer products, agriculture, medical surgery, therapeutic or personal care, or in extreme environments where humans cannot enter, including environments with contagions that have no cure. Robotic sensing is mainly visual, which is useful up until the point of contact. 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, which can also lead to a stuttering effect in the visual feedback loop. To fully understand how an object is being gripped, tactile feedback is needed.

The human grip is gentle yet firm with integrated tactile touch feedback. Humans easily and intuitively adjust grip force to maintain good grasp without crushing the object being handled. Human sensitivity is around 0.1 Newtons (N) of force over a fingertip with resolution of 2 mm [1]. 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 with local mechanics (the gentlest touch) around 1 kPa [1]. The glabrous grasping surfaces (non-hairy skin) of the human hand has about 17,0000 mechanoreceptors, with the highest density in the fingertip pad [2]. The skin of the human fingertip is viscoelastic, with many layers and a nonlinear stress-strain relationship [3,4,5]. Fingerprint ridges also play a role in the elegance of human grasp.

Ras Labs makes Synthetic Muscle™, which is a class of electroactive polymer (EAP) based materials and actuators that sense pressure, from gentle touch to high impact; controllably contract and expand at low voltage, typically 1.5 V to 50 V, including use of batteries; and attenuate force. The sensor development used EAP technology [6,7,8,9,10,11] towards tactile fingertips, where the padded areas served dual use as a soft compliant interface while also sensing mechanical pressure, positional information, and other features. These Tactile Fingertips™ were retrofitted into standard off-the-shelf robotic grippers and end of arm tooling (EOAT) (Figure 1).

A variety of shape-morphing EAPs developed for a biomimetic human hand-like robotic gripper was produced. The design has actuators around joints for biomimetic linked actuation, and tactile fingertips at the "fingertips" of the gripper for closed loop real time tactile feedback (Figure 2). Above 1.23 V operation, any electrophoresis effects can be captured by a fuel cell to provide electricity back to the EAP system [6,7] (Figure 3). An EAP based push-pull actuator design was also designed with tactile sensing. In collaborative robotics, a robot must intuitively and safely perform its tasks and deal with humans, who are prone to error, through the control of its motion. Real time tactile feedback is crucial.

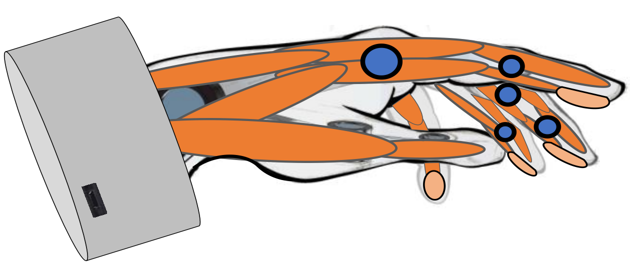


Figure 2. Biomimetic antagonistic linked actuation for a human hand-like robotic gripper.

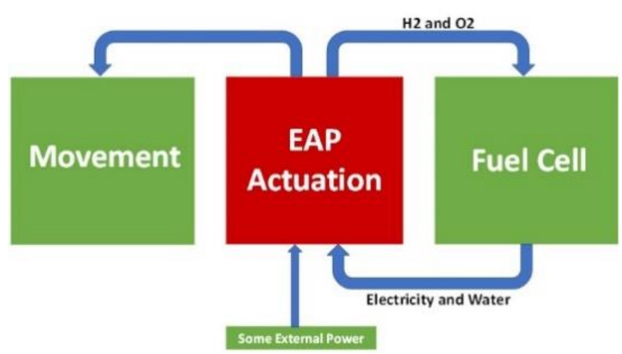


Figure 3. Fuel cell tie-in for extremely energy efficient motion [6,7].

2. EXPERIMENTAL

The Tactile Fingertips™ were produced using standard polymerization techniques followed by attachment(s) of a conductive layer(s). These were coated with a thin silicone outer layer, which were cast in molds. These sensor materials were scaled up (Figure 4) and analyzed for consistent physical properties within spec. Extensive design experiments were performed to select the most suitable system for integration of electrodes within the soft Tactile Fingertips. Various strategies were investigated for the wiring to produce good adhesion, which helped with reliability and predictability for modeling output. After breadboarding, printed circuit boards (PCBs) were constructed.

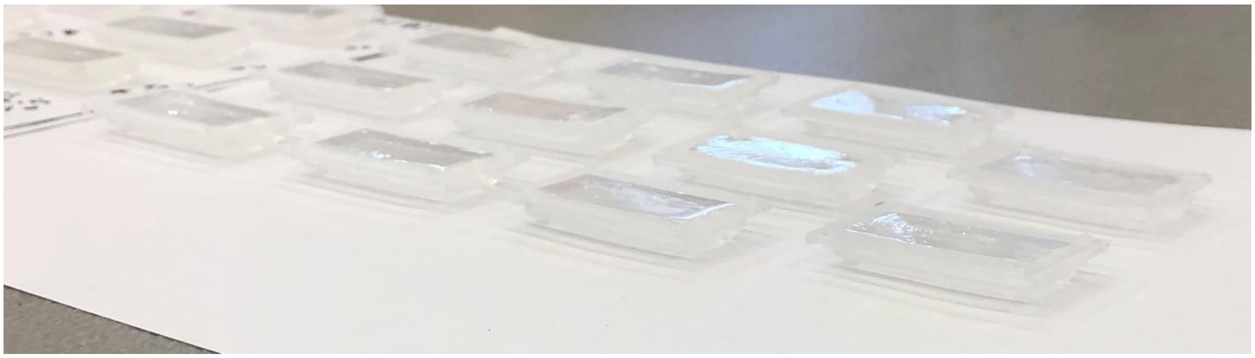


Figure 4. Scaled-up syntheses of the sensor materials for Tactile Fingertips™.

A TestResources™ single column universal testing machine (UTM) Model 2100024-01C was used to characterize the materials in compression and tension, and the entire tactile fingertip system in compression. Load cells used were a calibrated TestResources™ 250-lbf load cell Model SM-250-294 and a 10-lbf load cell Model SM-10-294. Durometer was determined using a DLTeren Model HT-6510 digital Shore OO harness tester. Tensile testing was performed at 25 mm/min to break with samples prepared to DIN 53504 mini-dogbone shape dimensions (Figure 5). This work is ongoing. Mechanical fatigue testing was performed on a test rig to 1,500,000 cycles of variable compressive forces at 1.3 Hz. Fatigue testing is ongoing.

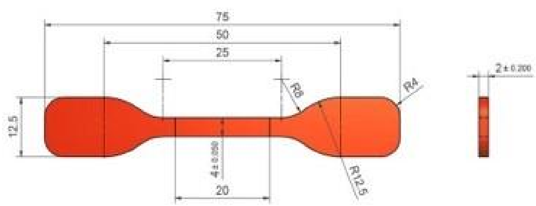


Figure 5. Mini-dogbone shaped DIN 53504 with dimensions in mm for tensile testing.

Robotiq® and Sake Robotic® end of arm tooling (EOAT) grippers were also used to handle a variety of objects, with integrated feedback for gentle grasp. For determining algorithms and performing ML, objects with a variety of different shapes (spherical, cylindrical, and rectangular heads) with different forces and angles were pressed against the Tactile Fingertip using test rigs constructed to spec. Software was developed to provide real time feedback for first point of contact, positional information including three-dimensional force gradients at contact point(s), and incipient slip detection. The test reg and a Robotiq® gripper was used for ML data acquisition. To provide correct data to the machine learning algorithm, a geometric analysis program was created to determine the point of contact between each object and the tactile fingertip. Algorithm modeling and shallow learning were first explored, and neural networks were started: Several ML tooling methods were investigated, including k-nearest neighbor and random forests, and convolutional neural networks were investigated to extract position, force, and shape data from the tactile fingertip.

For the human hand-like robotic gripper, a variety of different contractile EAPs were produced using standard polymerization techniques, attached to appropriate wiring, and encased. The design involved actuators placed in antagonistic pairing around joints, where one side contracts while the other side, with reversed polarity electric input, expands. Switching the electric polarity provides motion in the opposite direction around the joints. The components of the scaffolding were 3D printed and constructed. The joints were low friction glass bearing for simple hinge-like joints, except for the joint at the base of the thumb, which was a low friction modified ball-and-socket joint, also known as a universal joint, to allow for multiple degrees of freedom. Scaled up contractile EAP based Synthetic

Muscle™ was synthetized, with *in situ* wiring in place and with wiring connected later. Further design iterations are anticipated.

For the push-pull actuation, contractile EAP-based Synthetic Muscle™ was produced using standard polymerization techniques, connected to appropriate wiring, and encased. The design has the entire push-pull system further encased in 1-inch inner diameter (ID) reinforced tubing.

3. RESULTS AND DISCUSSION

3.1 Sensing The focus of this research and development was on the sensing capabilities of the Synthetic Muscle™ EAP based technology. These materials have variable resistance when subjected to mechanical pressure, even very light pressure. The materials 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. This can be compared to a strain gauge. Pressure applied to the surface of the compliant material caused a change in the geometry and properties of the substance. By placing electrodes in strategic locations, changes in the electronic signature(s) caused by mechanical strain were measured and a sophisticated understanding of the distribution could be determined.

Sensing information of the Tactile FingerTip was determined by measuring the electrical properties between its electrodes. This information was then coalited to create a three-dimensional understanding of the pressure profile (Figures 6 and 7). Pressure position and magnitude of force tests were successful, with excellent pressure sensitivity. In fact, while holding one of our Tactile Fingertip™ during testing, what we thought at first was an electronic artifact, was the tactile fingertip picking up the heartbeat pulse in our fingers. The human fingertip can detect down to about 2 mm spatial resolution using the two-point discrimination test [1, 12]. Software was developed to follow and display touch in real time with the Tactile Fingertips, with a resolution of 1 mm^2.

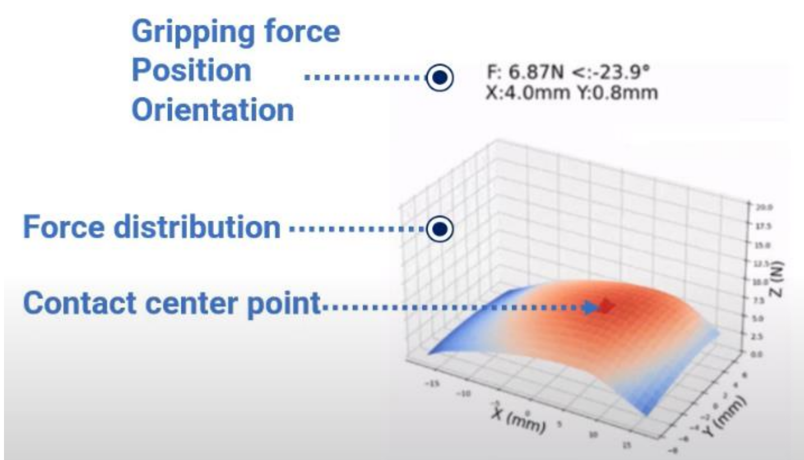


Figure 6. Three-dimensional display of the Tactile Fingertip™ showing grip force, angle, positional orientation, overall force distribution, and highest contact point with 1 mm^2 resolution.

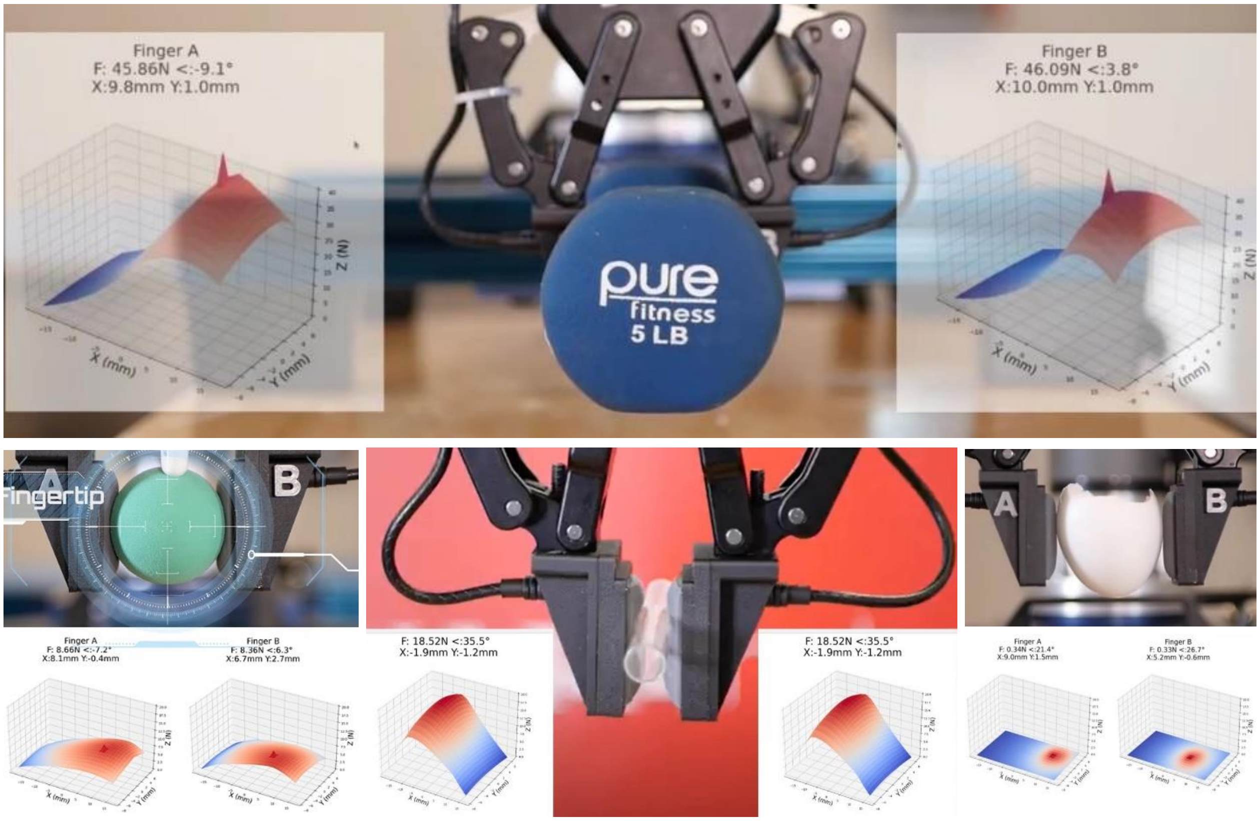


Figure 7. Tactile Fingertips™ retrofitted on a Robotiq™ robotic gripper and a robotic arm handling a soft green ball, slippery glassware, a fragile (empty) eggshell, and at the other extreme, a 5-lb (2.3 kg) weight, with information of real time contact points provided for both Tactile Fingertips, and with no droppage, no slippage, and no damage. The red triangle in the 3-dimensional display shows the highest contact pressure, surrounded by lighter shades of red depicting surrounding pressure intensities, with 1 mm^2 resolution for each pixel. Force, angle, and positional information are also displayed. Easily observable in the ball and the glassware is how the compliant fingertips conform around the objects, providing gentle yet firm grasp.

Human touch has a pressure sensitivity around 0.1 N [1]. The Tactile Fingertips were validated and verified down to 0.05 N, with additional testing capturing the limits of the extreme sensitivity to 0.005 N, and with high linearity to 25 N using a variety of shaped objects and above 75 N using a flat surface (Figures 8 and 9). In compression, small changes in pressure could be picked up by the Tactile Fingertip as well (good signal to noise, much better than the load cell). Further optimization in terms of shape and thickness of the polymeric sensing material and experimentation with the electrodes and electronics could potentially drive the sensitivity of these tactile fingertips to even greater extreme sensitivity. Overall, the Tactile Fingertips are extremely sensitive, with a broad pressure range from at least 0.05 N, and even 0.005 N in its maximum sensitivity mode, to 25 N, with 1 mm resolution (Figures 6, 7, 8, and 9). Various shapes of an object pressing into the Tactile Fingertip were also investigated. As expected, a flat surface (flat platens) reached a high force at less depth into the soft Tactile Fingertip than a small object (26 mm diameter hemisphere) (Figure 10). The polymeric sensing material was able to conform to the smaller objects being pressed against the Tactile Fingertip as well, which helped to provide not only a gentle grip, but also a firm grip.

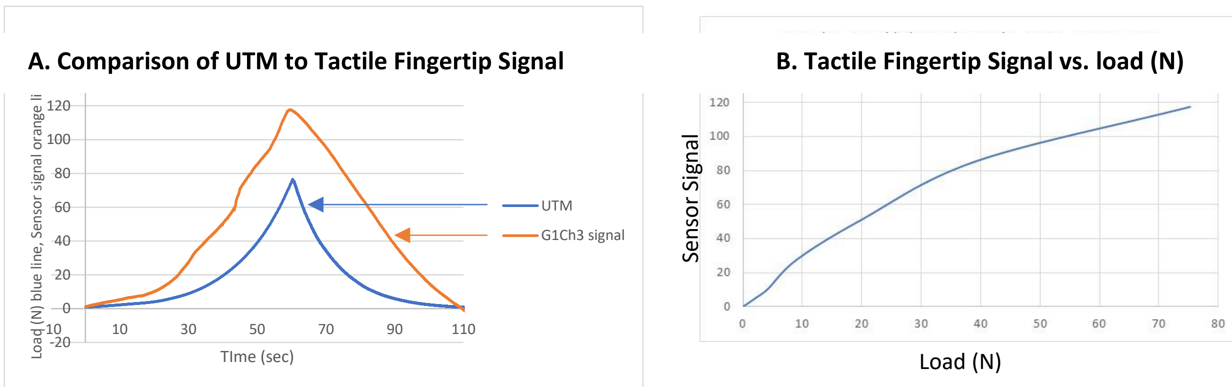


Figure 8. Linear range of Ras Labs' soft compliant Tactile FingerTip™: A. UTM compression data and the tactile fingertip's electronic signal, B. The fingertip's electronic signal as a function of load from 0 to 75 N (flat platens).

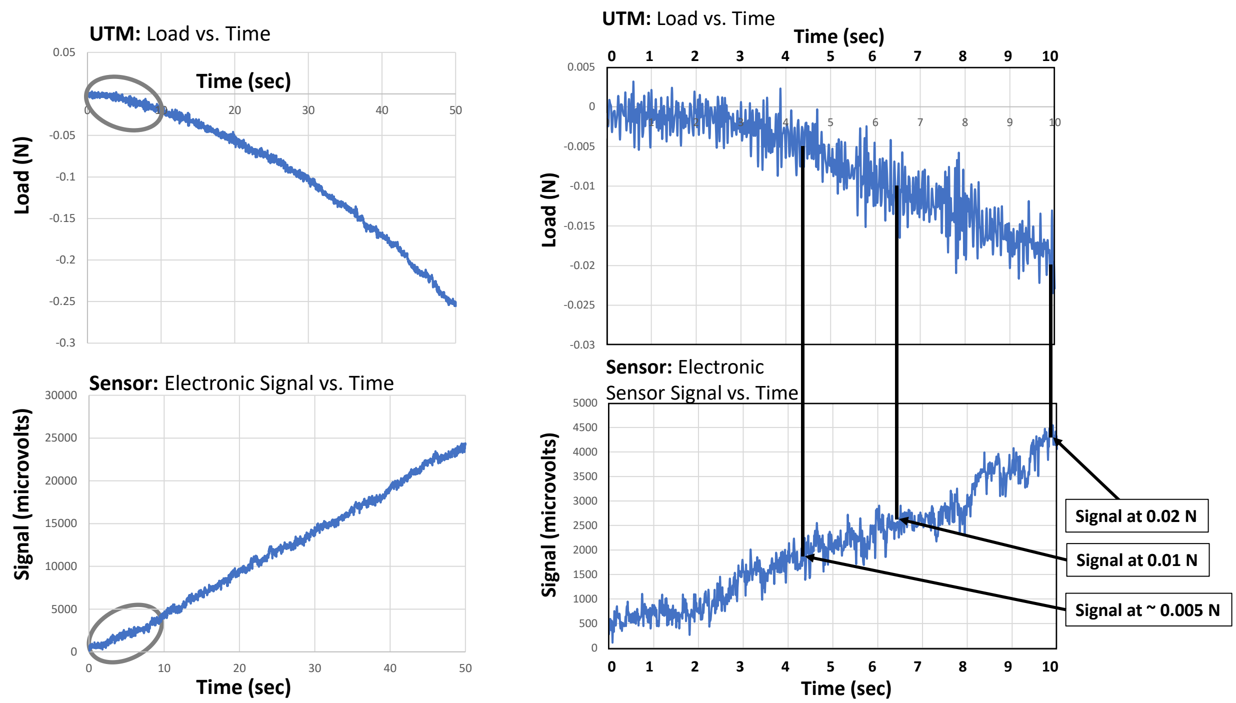


Figure 9. Sensitivity and linear range of the soft compliant Tactile Fingertip™: UTM mechanical analysis using flat platens and the 10-lb load cell in compression for a tactile fingertip at 0.25 mm/min to -0.20 mm, where the flat platen of the UTM began to touch the tactile fingertip at approximately 2 seconds into the run. On right is expansion of the circled first 10 seconds of the run.

Comparison of shape of object that is impacting the Tactile Fingertip™, loads achieved (N), and trends

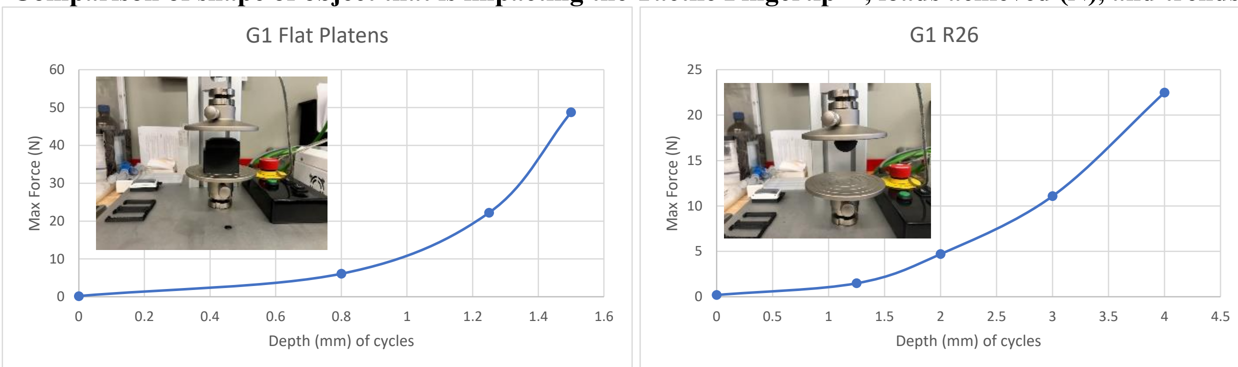


Figure 10. Comparison of shape of object pressing the Tactile Fingertip, showing trends with respect to force and force at final depth, 2 mm/min to specified depth (1.5 mm for flat platens on left, 4 mm for round 26 mm diameter hemisphere on right), return at 2 mm/min to original position, 3 cycles, with the max force plotted at various depths to final depth.

A TestResources™ single column universal testing machine (UTM) Model 2100024-01C with a 250-lbf load cell and a 10-lbf load cell was used to characterize the materials in compression and tension, and the entire tactile fingertip system was tested in compression. In addition to Shore 00 durometer, which indicates the softness or hardness of the sensing material and the tactile fingertips, UTM analysis provided more of a dynamic picture of the tactile fingertip's mechanical characteristics and an indication of its elasticity. Soft compliant grip is partly what makes the grip of these Tactile Fingertips so unique, but good elasticity, i.e., the ability to quickly rebound back to their original position after the pressure is removed, is also very important. This allows the Tactile Fingertip to be able to reliability determine the next object being gently gripped. Tensile testing was performed at 25 mm/min to break with samples prepared to DIN 53504 mini-dogbone shape dimensions (Figure 5). Percent elongation to break for these polymeric sensing materials was about 50 to 70 %. This work is ongoing. What we were really interested in these tactile fingertips was compression. Compression was tested three different ways:

1. Three cycles at 2 mm/min to 1.25 mm and release at 2 mm/min to 0 mm. This was to show extent of consistency in compression (and release) and to show any hysteresis in these viscoelastic materials.
2. Compression at 2 mm/min to 1.25 mm, hold for 60 sec, and quick release at 25 mm/min back to original position. This was to indicate extent of any creep under extended compression.
3. Compression at 5 mm/min to 1.25 mm followed by quick release at 25 mm/min to 0 mm. This was to indicate extent of elasticity (rebound) during the quick compress and quick release.

Typical spectra are shown in Figure 11. Trends with respect to the shape of the object being handled were determined with the UTM (Figure 10) and machine learning, as well as following the Tactile Fingertip's electronic signaling as load was increased and released in compression (Figure 8). The polymeric sensing material itself is a viscoelastic material. Even though these Tactile Fingertips are soft and compliant – they feel like human fingertips – they are also very elastomeric, with low mechanical hysteresis, low creep, and good rebound after the pressure is released.

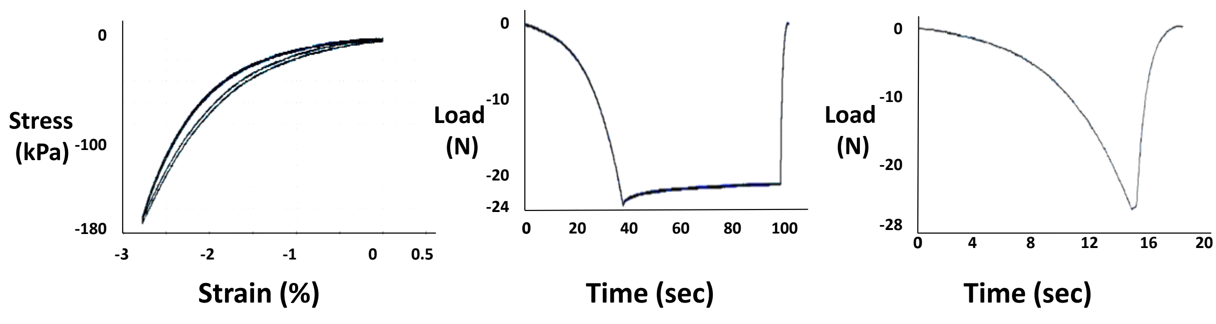


Figure 11. UTM mechanical analysis using flat platens in compression on a Tactile Fingertip. Left: 3 compression cycles at 2 mm/min to 1.25 mm, release at 2 mm/min to 0 mm. Middle: Compression at 2 mm/min to 1.25 mm, hold for 60 sec, quick release at 25 mm/min back to original position. Right: Compression at 5 mm/min to 1.25 mm followed by quick release at 25 mm/min to 0 mm. Note: in the cyclic analyses, after the first cycle, repeat of cyclic analyses on the tactile fingertip simply retraces the same profiles.

Even though the Tactile Fingertips are soft and complaint – they feel like a human fingertip – these sensors are also flexible and elastic (Figure 12). The sensing material also has a good amount of tack (stickiness), which is beneficial for adhesion to the electrodes. The soft modulus of the sensing polymeric material provides for the gentle manipulation of objects, while the elasticity provides for repeatability so that the sensing polymer quickly returns to its initial position once mechanical pressure is removed. Note the similarities in the Tactile Fingertip's UTM profiles to a rubber ball (high elastic modulus) rather than a ball of clay (viscous modulus, damping) in Figure 13. The Tactile Fingertips have low mechanical hysteresis, low creep, and good rebound after pressure is released. In addition, the multi-modality of the sensing material provides the Tactile Fingertip with the ability to handle a variety of forces, analogous to mammalian cartilage and muscle tissue, and thus expected superior durability.

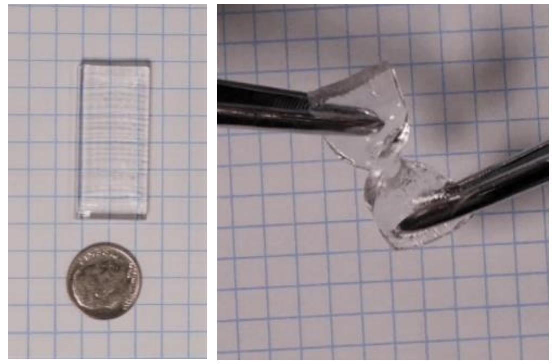
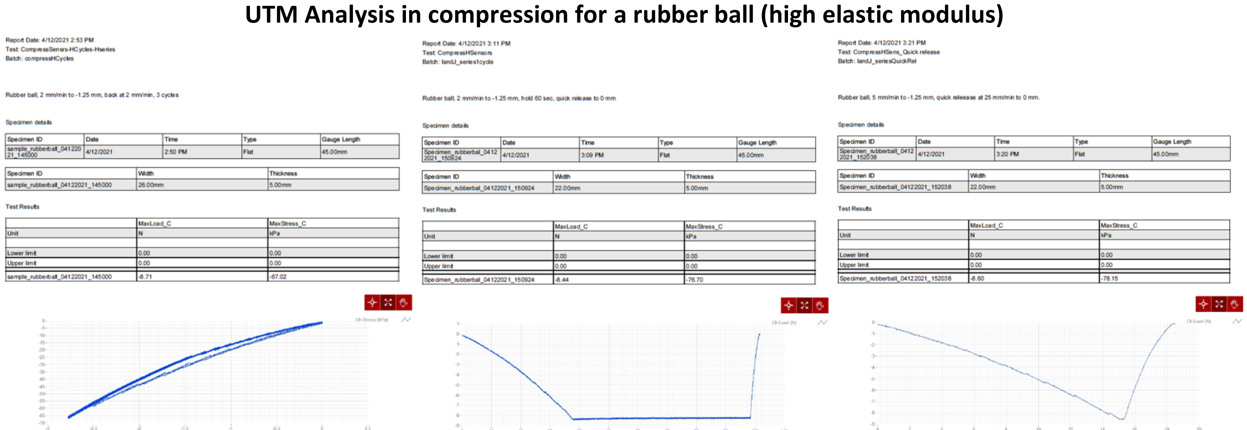


Figure 12. The soft and compliant yet flexible elastomeric sensing material.

UTM Analysis in compression for the Tactile Fingertip™

UTM Analysis in compression for a rubber ball (high elastic modulus)



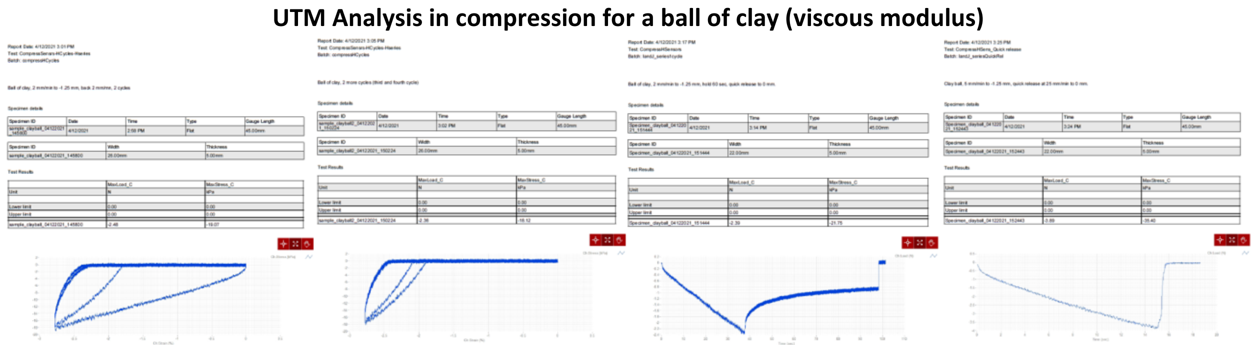


Figure 13. UTM mechanical analysis using flat platens in compression for the Tactile Fingertip. Top Left: 2 compression cycles at 2 mm/min to 1.25 mm, release at 2 mm/min to 0 mm. Top Middle: Compression at 2 mm/min to 1.25 mm, hold for 60 sec, quick release at 25 mm/min back to original position. Top Right: Compression at 5 mm/min to 1.25 mm followed by quick release at 25 mm/min to 0 mm.
For comparison, Middle profiles show the same UTM analyzes to a rubber ball (high elastic modulus) and bottom profiles show the same UTM analyzes to a ball of clay (viscous modulus, damping), where the cyclic analysis is repeated for the ball of clay to show further degradation (flattening, no rebound). Repeat of cyclic analyses on the sensor and rubber ball simply retraces their same profiles.

A test rig was constructed to test the durability of the Fingertip Sensor to millions of pressure cycles (Figure 14). The fatigue testing was stopped periodically (at ~300,000, 500,000, 750,000, 1,000,000, and 1,500,000 cycles) to visually look at the sensor and to test it electronically, before placing it back in the rig for more cyclic pressure fatigue testing. In repetitive mechanical fatigue testing, the Tactile Fingertip held up to 1,500,000+ cycles of compression force at ~ 1.3 Hz: 300,000 cycles at 5 N, 700,000 cycles at 10 N, and then 500,000 more cycles at 5 N, with full functionality and no visible breakdown. Producing large datasets for machine learning also put these sensors through many repetitive use cycles, with good retention of functionality. The fatigue testing is ongoing. These soft compliant Tactile FingerTips are extremely sensitive, have a wide pressure range, and are robust.

These extremely sensitive Tactile Fingertips have a richness that can be extrapolated using machine learning (ML) and artificial intelligence (AI) to truly develop intuitive human-like tactile touch. A geometric analysis program was created to determine the point of contact between each object and the Tactile Fingertip. Some of the shapes used are shown in Figure 14. Algorithm modeling and shallow learning were explored first, followed by neural networks. Several ML tooling methods were investigated, including k-nearest neighbor and random forests. Even with ML and AI added into these systems, it is highly desirable to have these tactile fingertips as consistent, reliable, and simple as possible to maintain low latency to keep the feedback speed near instantaneous in real time without delays.

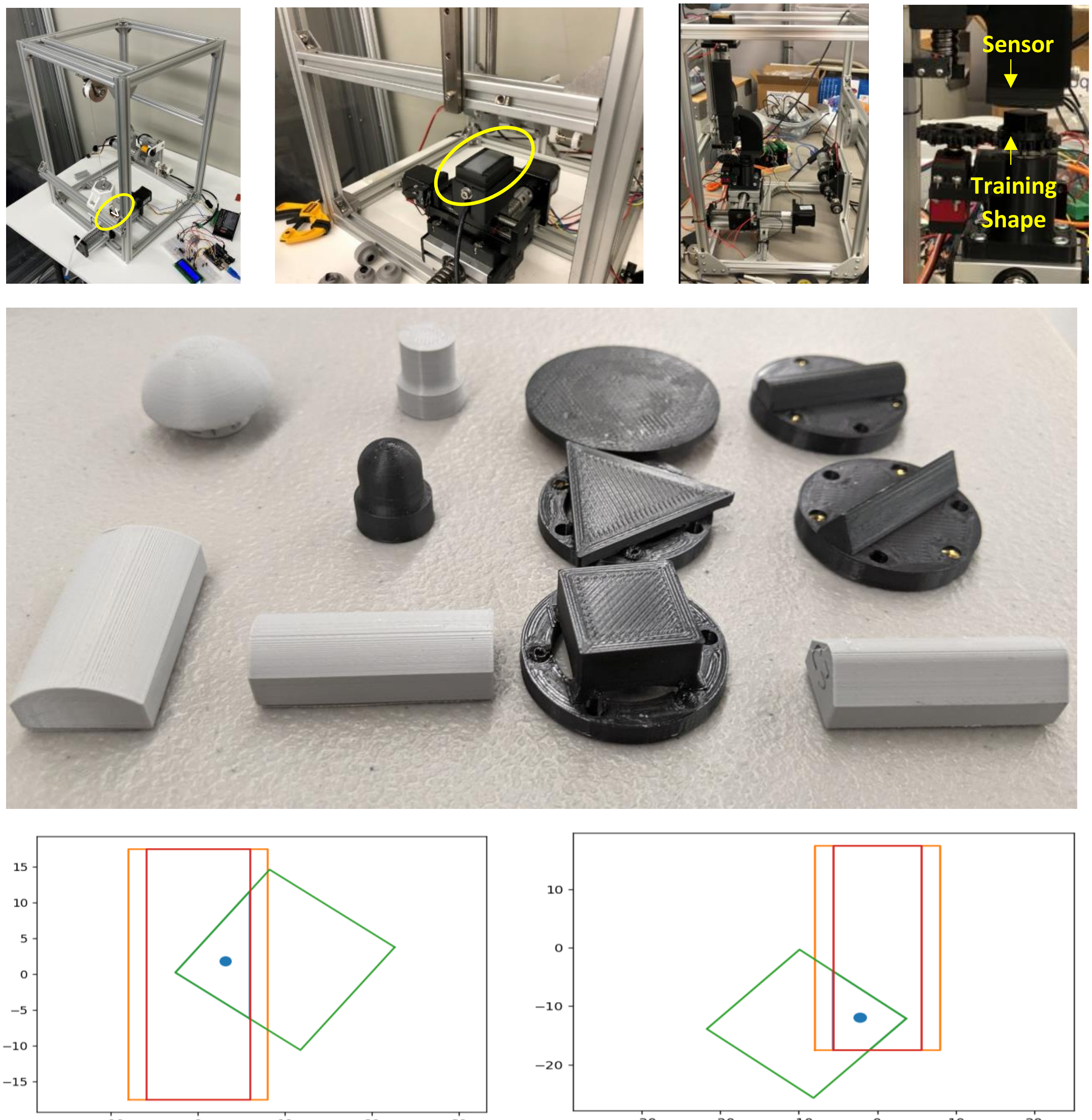


Figure 14. Top from left to right: Fatigue testing rig, testing a Tactile Fingertip™ circled in yellow; test rig ML training a Tactile Fingertip to a spherical shape; sophisticated ML training rig with very tight tolerances training a Tactile Fingertip to a flat shape; close-up of the ML training to a flat shape. Middle: Some of the 3D printed objects used to train the ML algorithms. Bottom: Visualization of point of contact algorithm, center of contact shown in blue.

Software was developed to follow and display touch in real time with the Tactile Fingertips: Intelligrasp™ is a suite of programs for the gentle handling of objects. Smart Grasp™ detects point of contact then stops to grip the object gently and detects any incipient slip. If slip is detected, then it grasps the object harder but gently, proportionally as needed for perfect grip. Tactile Grip™ grips objects to a designated force. Positional Grip™ moves to a specific position or depth and communicates the force, which can be used to determine the softness or firmness of the object being handled. Tactile Release™ is for a very quick release of the object once the force reaches a designated threshold, which can be used for stacking, binning/kitting, human-robot interactions, and hand-offs. ML and AI can be layered into the tactile fingertip systems, however, even with these add-ons for more intuitive feedback, it is highly desirable to have these tactile fingertip 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.

Figure 15. Front and back views of the Tactile Fingertip™. Tactile Fingertips can be made in a variety of sizes and shapes to spec.

The Tactile Fingertips were designed and shaped to feel like the pads of human fingertips. The sensing polymeric material itself had different electronic signals under different mechanical forces and pressures. The initial goal was to detect force below 0.2 N, which was met and then surpassed, with force detection down to 0.1 N, then 0.05 N, and in its maximum sensitivity mode, even down to 0.01 N and 0.005 N. Most extremely sensitive sensors are quite fragile [13]. These novel Tactile Fingertips are composed of soft, elastomeric, non-Newtonian semisolids, and are also tough and robust with a wide pressure range. In robotic grippers, by using the soft elastomeric pads as the sensors, near instantaneous feedback was provided at the first point of contact. The soft nature of the fingertip-like pad also naturally held and gently formed itself around the gripped object, much like the human fingertip, improving the gripper quality over rigid grippers without an increase in applied force. Detectable changes in the electronic signals from these soft yet robust Tactile Fingertips generated virtually immediate feedback with contact of the object. Because these elastomeric pads provided a soft compliant interface, the first point of contact did not apply excessive force, allowing the object to be gently handled and the force applied to the object to be controlled. In addition to point of contact, analogous to tactile touch, these tactile fingertips can also detect slippage. The Tactile Fingertip was able to detect a change in pressure location on its surface, i.e., directional glide provided real time feedback, making it possible to detect and prevent slippage by then adjusting the grip strength, without stutter, due to both the feedback and the soft gentleness of the fingertip-like sensing pads themselves. Analogous to human finger-like tactile touch, the polymeric sensing material with appropriate coatings and electronics in these sensing systems were positioned as tactile fingertips in the fingertip or end effector regions of robotic grippers.

3.2 Linked actuation using contractile EAP shape-morphing For the development of the human hand-like robotic gripper, the first iteration considered was a partial hand-like gripper focused on the first and second digit (thumb and forefinger) around the pincer grip (Figures 16 and 17). The components of the scaffolding, i.e., the "skeleton" for the hand were 3D printed and constructed. Most of the joints were low friction glass bearing for simple hinge-like joints, except for the joint at the base of the thumb, which is a low friction modified ball-and-socket joint, also known as a universal joint, to allow for multiple degrees of freedom. EAPs with different properties were synthesized, equilibrated in electrolytic solution, and characterized. The optimal formulation was used to construct contractile EAP based Synthetic Muscle™ actuators with corrosion free electrodes. The design is for two actuators to be placed on opposite sides of each simple hinge joint, i.e., antagonistic pairing, where one actuator expands while the other contracts, and vice versa when the polarity of the electric polarity is reversed. A minimum of three actuators can be placed around the universal joint. Prototyping of the human hand-like robotic gripper will continue with shape-morphing EAP segments positioned around the 3D printed scaffolding, with design iterations to follow (examples of extending the palm area in Figure 16). Sensors can then be added to the fingertip regions, with integrated feedback to the EAP shape-morphing actuation strategically positioned around the joints. This work is ongoing.

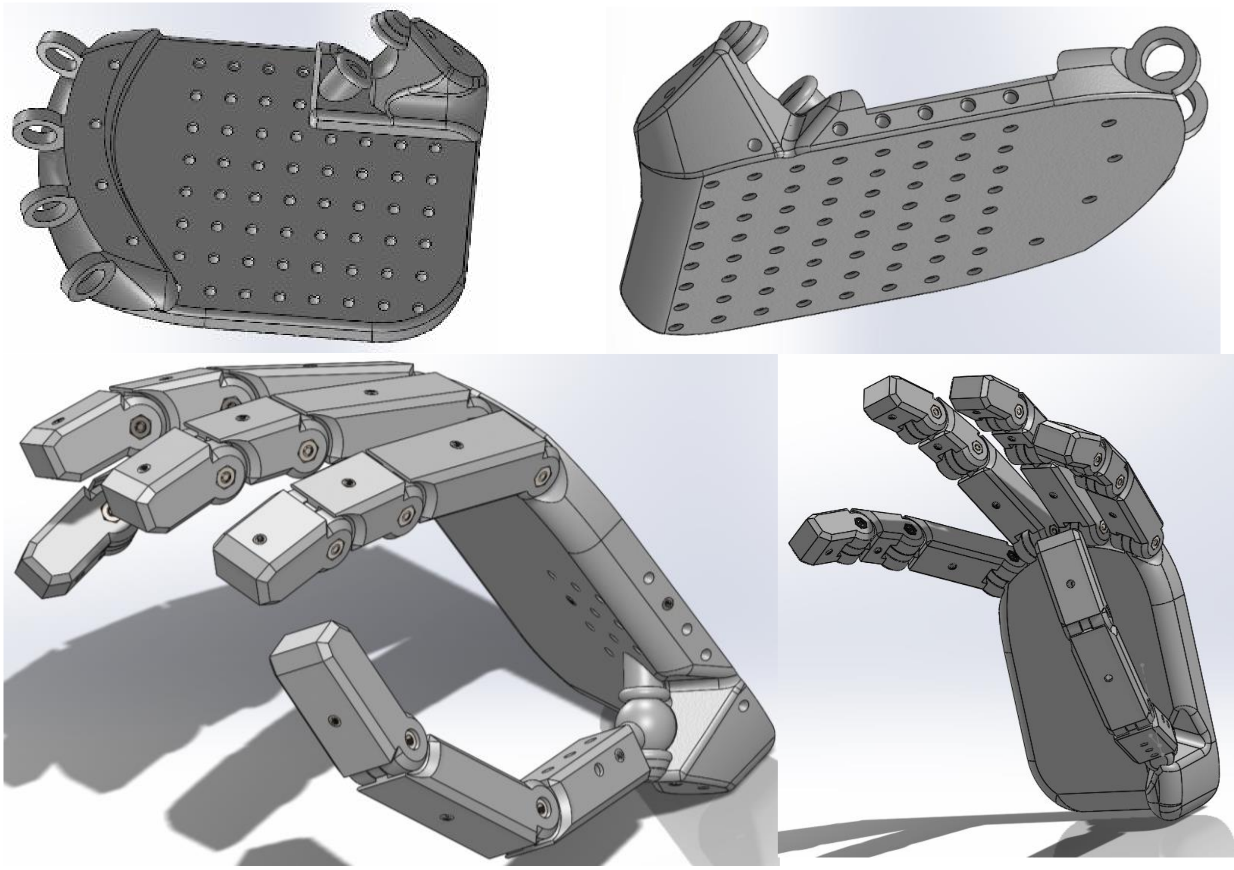


Figure 16. Top: Design of extending the palm area for the human-like hand gripper scaffolding and making it thinner (more lightweight). Bottom: CAD modeling for the entire hand.

Figure 17. Top: CAD Modeling and components of the finger pieces. Bottom: Fully assembled 3D-printed human-like hand scaffolding with low friction joints and threaded heatsets for the EAP attachment areas, biomimetically designed around the first and second digits (partial hand for first iteration on pincer grip).

3.3 Push-pull actuation using contractile EAP shape-morphing For the development of the push-pull actuator, optimized contractile EAP based Synthetic Muscle™ was considered for a cylindrical linear actuator system with radial constraints. These constraints radially are so that the EAP(s) can only expand in the linear direction desired for a push, or contract for the pull with reversed polarity of the electric input to the EAP(s) (Figure 18). Strategies that were used to actuate a small EMI® robotic gripper and to significantly increase the force outputs of that EAP system, as well as to control the amount of force outputted [9,10] are being used for consideration in this larger push-pull actuation system. A fuel cell tie-in is also considered for greater energy efficiency. For a contest against a human, a retrofitted Tactile Fingertip was added to the design so that when the human fatigues (often suddenly), through near instantaneous feedback the push-pull EAP system's force can be stopped, released, and/or significantly lowered, to *match* the human. If the human refreshes, then the system is expected to match that force again. Theoretically, even though the push-pull EAP system could beat the human, the salient point is to *match* each human's potential, every step of the way, with a full safety stop at mid-point to ensure the EAP's integrity and more important, the human's safety. The idea is that an EAP driven robot, cobot, or hubot will intuitively and safely perform its tasks and work safely with humans, who are prone to error, through its biomimetic motion, gentle nature, and its inherent tactile touch feedback.

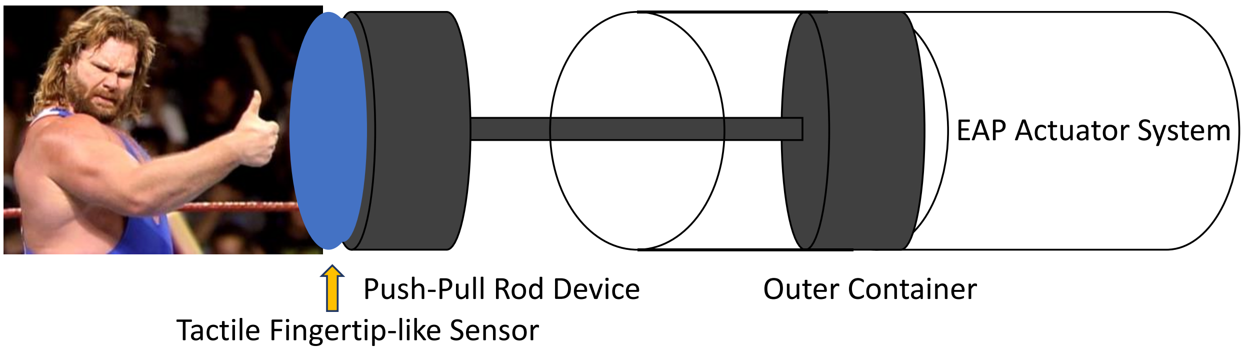


Figure 18. Design for Push-Pull EAP based actuator system.

4. CONCLUSIONS AND FUTURE WORK

Human grasp is intuitive and gentle, yet firm, at the same time. For many repetitive tasks where humans handle delicate or fragile objects, it makes sense to use robotics, whether for agriculture, medical surgery, therapeutic or personal care, or in extreme environments where humans cannot enter, including environments with contagions that have no cure. For robotic grippers to perform in these types of applications, tactile touch and human-like grasp is crucial. Tactility in robotic grippers and skins is expected to advance robotics, including collaborative robotics, to allow humans and robots to intuitively work safely and effectively together. However, the challenges to implementation are the simultaneous gentle yet firm grip of the human hand, the large amount of tactile information generated through touch, and the intuitive nature of the human grasp. To that end, tactile fingertip-like systems were developed to replicate human grip, with the additional benefit of mechanical pressure sensitivity and resolution that surpassed the human fingertip. While these polymeric sensing materials were soft and compliant, these novel materials were also quite elastic, with low mechanical hysteresis, low creep, and good rebound after the pressure was released. This tactile fingertip system feels like a human fingertip. The development of this technology provided for Tactile Fingertips™ that were able to provide for 1 mm resolution and to detect very light pressures down to 0.05 N and even 0.005 N in its maximum sensitivity mode. Further optimization in terms of shape, thickness, and viscoelastic characteristics of the polymeric sensing material and experimentation with the electrodes and electronics could potentially drive the sensitivity of these sensors to even greater sensitivity. The Tactile Fingertips are also robust, able to withstand up to 25 N (variety of shaped objects) and to over 75 N (flat surface) with high linearity, and mechanical fatigue durability to over 1,500,000 cycles. ML and AI were integrated to communicate the position, angle, shape, and force information for a variety of objects being handled. 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. This helps prevent injury, while for more sophisticated tasks like fine craftsmanship, most of the feedback to our hands is cerebral. These Tactile Fingertips

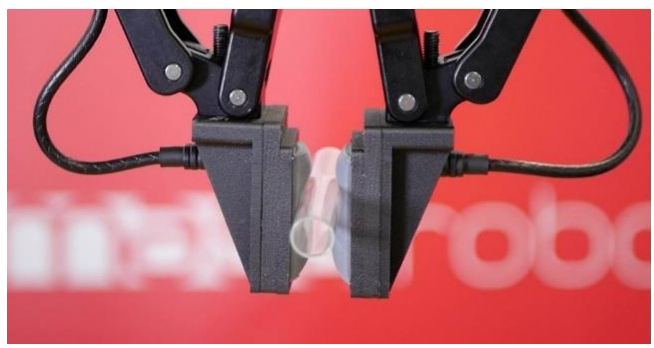


Figure 19. Extremely sensitive Tactile Fingertips™ retrofitted and with integrated feedback to a Robotiq® gripper, gently handling slippery Pyrex® glassware.

are expected to play a significant role in pick-and-place and unstructured bin sorting. The soft compliant Tactile FingerTips are extremely sensitive, robust, have a wide pressure range, and can communicate information about the object being handled and the grip quality. Slip can be detected, and the grip corrected, gently. These Tactile Fingertips were developed to replicate human fingertip-like touch for well-controlled gentle grasp in robotic grippers. Contractile EAP based Synthetic Muscle™ is being used in designs for linked actuation of a biomimetic human hand-like robotic gripper and a push-pull actuation system to compete with and match the push force of a human. In both of these actuation designs, the tactile fingertip zones could provide real time feedback to the shape morphing EAP zones of the actuation systems. By combining material science innovation, state-of-the-art data science, and precision engineering, the Tactile Fingertip is an integrated tactile system for a superior robotic grip that is remarkedly similar to the gentle yet firm grasp provided by the fingertips of the human hand.

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