A passively conforming soft robotic gripper with 3-D negative bending stiffness fingers

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Abstract

Robot grippers that lack physical compliance have a difficult time dealing with uncertainty: such as fragile objects that may not have well-defined shapes. Existing soft robotic grippers require a large empty workspace for their actuated fingers to curl around the objects of interest, limiting their performance in clutter. This article presents a three-dimensional structure that exhibits negative stiffness in every bending direction used as fingers in a class of soft robotic grippers. Our approach exploits a compliant mechanism in a conical shape such that a transverse external contact force causes the fingers to bend towards the contact, enabling passive conformation for an adaptive grasp, even in clutter. We show analytically and experimentally that the proposed fingers have a negative bending response and that they conform to objects of various diameters. We demonstrate a soft-robotic gripper with three self-conforming fingers performing: (i) fingertip grasping, (ii) power grasping, and (iii) semi-passive grasping in clutter. Grasping experiments focus on picking fruits, which exemplify delicate objects with unmodeled shapes with significant variation. The experimental results reveal the ability of the self-conforming structure to smoothly envelope a broad range of objects and demonstrate a 100% grasp success rate in the experiments performed. The proposed passively conforming fingers enable picking of complex and unknown geometries without disturbing nearby objects in clutter and without the need for complex grasping algorithms. The proposed structures can be tailored to deform in desired ways, enabling a robust strategy for the engineering of physical compliance for adaptive soft structures.

Keywords: Self-conforming, soft robotic gripper, 3-D negative bending stiffness, semi-passive grasping

1. Introduction

1.1. Problem addressed

Robotic grippers are arguably the most crucial components of robotic manipulators. Adaptive soft grippers have the potential not only to grasp fragile and highly variable objects, but also to interact safely with humans and environments. These benefits are especially convenient when they do not require sophisticated controls.[1,2]

However, some adaptive soft grippers have problems picking up desired objects in a cluttered environment. For example, suction grippers may be more suitable for grasping objects in a cluttered environment.[3,4] Suction cup grippers are non-fingered; they only require one point of contact. While they may fail to pick objects of irregular shapes, or smaller than the cup diameter, where they may not generate sufficient vacuum pressure.[5] Another non-fingered gripper is the jamming-based gripper. Brown et al.[6] used granular material and a vacuum to control the gripper. The universal gripper is then able to pick up multiple objects without changing orientation. But its gripper size may be too large to pick up objects in a cluttered environment. Other non-fingered grippers are adhesion-based grippers. Researchers are inspired by gecko adhesion early to address the issues of fiction-based grippers, since the shear adhesion force helps the grasp stability. For exam-

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ple, the size of object is larger than the gripper, or the objects are with smooth surfaces. More recently, researchers are more interested in switchable adhesion by utilizing different materials.[7–9] Swift et al.[7] used polydimethylsiloxane (PDMS) membrane to tune the adhesion forces pneumatically. Similarly, Testa et al.[8] used composite, mixed PDMS and magneto-rheological fluid, to switch adhesion. The authors enhanced the composite's adhesive properties and increase the pull-off force. Li et al.[9] use PDMS as gripper membrane with granular material and actuated pneumatically. Interestingly, they scaled down the gripper size to apply the multi-finger grippers, such as the humanoid hand. Therefore, the humanoid hand with adhesion-based grippers may be able to pick up objects in a cluttered environment. While multi-fingers may raise issues on the large numbers of controllable joints. In addition, adhesive grippers are mostly limited to clean and dry surfaces.

On the other hand, multi-fingered adaptive soft grippers can pick up objects in a cluttered environment if they can position their compliant fingers around an object of interest. Most existing self-adaptive finger mechanisms work only in a 2-D workspace, such as the Festo MultiChoiceGripper. The MultiChoiceGripper is a three-fingered gripper that relies on fingers with a negative bending response in 2-D, *i.e.* the FinRay effect. In general, it can grasp small, round, and rectangular objects. The fingers themselves can be adapted to a wide variety of shapes without additional sensor or control technology. However, for grasping rectangular objects, the configuration needs to be changed from spherical (radial) to parallel grip.[10] If the configuration does not change, the fingers will have to twist and may be in contact with the object only with their edges, which weakens their grasp and also removes their self-conforming behavior, potentially causing grasp failure.

Here, we present a new soft gripper that moves from 2-D compliance to 3-D. Our fingers exhibit negative bending in a 3-D workspace, which we call *the 3-D FinRay effect*. We don't need to change the finger configuration, the fingers themselves are adaptive to the shape of the object. They may even automatically take a parallel configuration for rectangular objects, by bending the fingers around the surface normal and not necessarily following the radial motion. Since the fingers have a conical shape, they can always provide surface contact with the object instead of edge contact. This means that the proposed gripper is more robust than existing FinRay grippers. It can adapt to various objects and interact with fragile objects, for example, grasping fruits without bruising them and grasping irregular-shaped apples without disturbing others in a plate of apples. We achieve these capabilities using a flexible underactuated finger mechanism that bends toward contact forces applied in any transverse direction in 3-D. The proposed fingers act as a metamaterial with negative bending stiffness. The mechanism of gripper enables simple electrical actuation with a single servo motor tilting the base of the fingers inwards towards the center, naturally conforming to objects in any direction. Therefore, the advantages introduced by 3-D compliance are beneficial for robust grasping and adaptability.

1.2. Related work

Adaptive soft grippers utilize elasticity for their function.[11] Early soft robots used flexible joints but rigid links.[1] Recently, however, some soft robots have become fully compliant and deformable to better interact with their environment.[12] Soft robotics is often inspired by biological organisms, such as cephalopods or invertebrates.[13,14] Soft robotic designs exhibit fully[13] or partially soft bodies constructed of materials with a low elastic modulus[14,15] to achieve physical compliance. The first soft gripper was developed by Hirose in 1978 and had joints that could softly and gently conform to the object,[16] with a behavior similar to continuum deformation, but whose linkages were still rigid. The words 'softly' and 'gently' used in the paper conveyed the idea of compliant and adaptive behaviors in this seminal work. Since then, this idea has inspired other researchers to create grippers similar to the Graspar hand.[17]

Biological organisms harness physical compliance and the principles of underactuation effectively to perform complex functions.[15] In engineered systems, soft materials can provide adaptability and mechanical compliance, allowing robot bodies to adapt to their environment to distribute contact forces and decrease stress concentrations.[18] Underactuation represents a systematic way to offer engineered mechanical properties by utilizing fewer controllable degrees of freedom and clever self-adaptive mechanisms to actuate a robotic system. Underactuation as used in robot grippers typically comes in the form of rigid linkages, allowing them to adapt to the shape of an object.[19,20] The combination of integrated compliance and underactuation leads to the idea of adaptive soft grippers.

Adaptive soft grippers have the ability to grasp unknown objects in unstructured environments, offering adaptability and compliance without sophisticated controls. Such advanced grippers not only grasp fragile and highly variable objects, but also interact safely with humans and environments. However, there are problems with existing adaptive soft grippers. Many soft grippers utilize pressure-based actuation of rubbers[21–23] to pick up fragile objects, such as underwater biological sampling.[24] Nevertheless, fluidic systems require the additional infrastructure of a compressor/pump, valves, control box, and tubing system, which limits their use and increases their cost. Inflating pressure cavities in a fluidic system may be unstable and prone to failure over the long run.[25] Furthermore, adaptive soft fingers to date function in a 2-D workspace[10,26–28] and are incapable of conforming to objects in multiple directions. This may cause instability or even failure if the object does not contact with the fingers in the normal direction. Many current soft robotic grippers require a large empty space around objects of interest for their relatively thick fingers to curl in and out, limiting operation in clutter.

Soft grippers have been either fully elastic or partially flexible, using compliant mechanisms and underactuation for their adaptive functionality. Fully elastic soft grippers have used elastomeric materials so that they can interact safely with humans and fragile objects. Notable examples of fully elastic grippers include universal gripper,[6] starfish gripper,[29] RBO Hand,[21,30] inflatable grippers,[31,32] groove-patterned grippers,[22,24,26] compliant grippers[33,34] , tentacle type gripper,[35–37] wrapping gripper,[38] and stimuli-responsive grippers.[39–46] In contrast, partially elastic grippers combine elastomeric materials with rigid linkages, allowing them to have the precision of rigid linkages and some of the tactile compliance and adaptability of soft actuators.[19,47] This compliance enables for stable grasps, as the elastic elements deform to deliver a normal force to the object to avoid slipping.[48] Elastic forces also simplify control as the gripper can maintain hold on objects without the use of complex grasping algorithms. In partially elastic grippers, the joints are often coupled elastically, reducing the number of required actuators. Due to these advantages, this kind of design is widely implemented in modern adaptive grippers. Examples of partially elastic grippers that were developed in the research field include the SDM Hand,[49] iHY Hand,[50] a gripper with passive rotational joint,[51] and a variable grasping gripper.[52] Some well-known commercial examples that effectively utilize underactuated mechanisms include the Kinova Jaco gripper, FESTO MultiChoiceGripper, and Robotiq Hand. Furthermore, some soft grippers break this paradigm and use different materials, such as origami grippers,[53–55] elastic thread gripper,[56] and adhesive grippers.[57–60]

2. Materials and Methods

2.1. A 3D self-conforming finger

The fabrication process was divided into three main steps: mold making, silicone rubber elastomer casting, and part-assembly (Fig. S1). The 3D finger was constructed out of eight different sizes of composite layers connected by elastic metal rods, and a finger's maximum physical dimensions are 32.47 × 32.47 × 84.45 mm (Table S1). Each layer is in the shape of a star with 8 points, tapering down in a conical manner from base to tip. The largest (base) layer has a diameter of 30 mm and the smallest (tip) layer has a diameter of 7.6 mm. The elastomer layers were each fabricated from DragonSkin 30 silicone rubber (Smooth-On), which were cast in eight differently sized 3D printed molds. Before silicone rubber has cured, 0.53 mm diameter elastic metal rods (piano wires) were inserted into each of the molds, providing a star-shaped skeleton, which increased their rigidity to be utilized as cross beams that transmit transverse forces between opposite sides, which is the basic principle that enables the FinRay effect.[27] After curing for 8 hours at room temperature, the layers were demolded, excess elastomer was removed, and the layers were joined using 0.53 mm diameter elastic metal rods. These rods were inserted into the center of the fingertip layer, through the corner points of each subsequent layer, and into the base, forming the conical shape. The base was fabricated out of a 2-mm thick acrylic sheet using a laser cutter (Epilog Zing 24 Laser, 40 watts). Two of these pieces were bolted together to form the base to firmly fix the elastic metal rods in between. The detailed process can be seen in Fig. S1, and the sizes of each layer of the finger are listed in Table S1.

2.2. Gripper base

Once three fingers are fabricated, we developed a three-fingered gripper base to combine a linkage mechanism, a servo motor, and a housing. The linkage mechanism is to tilt the base of the fingers radially inwards. All linkages were made from 2-mm thick acrylic sheets and cut using the same laser cutter and connected by screws acting as simple pin joints. A servo is used to drive all three fingers. A 3D printed housing was used to mount the gripper on a robotic arm. An exploded drawing of the gripper base can be found in Fig. S2. A list of parts used in the gripper is shown in Table S2.

2.3. Adaptive soft robotic gripper

The last step is to attach three fingers to the gripper base, which was done using the same screws that connected the base of the finger. The gripper is actuated by a single servo motor. A servo drives the rotational axis for all the bases of the fingers at the bottom to achieve open and closed states in unison for the gripper (Fig. 1). The gripper requires 5V and 1A at maximum load, determined by the power requirements of the servo actuator that controls the fingers. The servo that we use is a Hitec HS-645MG.

[Figure 1 about here.]

2.4. Platform of performance testing

In order to understand the performance of our gripper, we set up a testing platform to conduct three grasping experiments, which are fingertip grasping, power grasping, and semi-passive grasping. The testing platform included four main systems: ROS, Arduino, Jaco arm, and a webcam (Fig. S3). We installed ROS Indigo Igloo version to match Kinova Jaco arm and an Arduino Uno board. Arduino and ROS communicated via $rosserial\_arduino$ package in order to command the servo motor (HS-645MG) using ROS commands. We hard-coded the grasping position in advance for the first two grasping experiments, fingertip grasping and power grasping, such that the Jaco arm was tested to grasp fruit items for fifty times from the same location. For the last grasping experiment, semi-passive adaptive grasping in clutter, we used a webcam and a custom machine vision code performing color segmentation and circle detection to determine the position of the centroid of the apples for the gripper to grasp. The webcam (Microsoft LifeCam HD-6000 720p HD Webcam) was mounted above the plate of apples, pointing downwards. The view of the webcam was shown on the monitor via OpenCV. The experimenter manually selected an apple of interest via a graphical user interface from the monitor to tell the Jaco arm where to attempt the grasp, the vision system detected the centroid of that particular apple, and the grasp is performed. After implementing grasping action by the Jaco arm each time, the image of apples shown on the monitor was automatically updated. The system architecture of the testing platform is shown in Fig. S3.

3. Results

3.1. Force-Displacement testing

To understand how a finger changes when the payload increases, we conducted force-displacement (F-D) testing. The finger is first clamped to its base for working in a 2-D workspace. Due to the radially symmetric nature of the fingers, these experiments are performed in 2-D without loss of generality. We applied three different concentrated loads, 50 grams, 100 grams and 150 grams, at the connected joint on the fifth layer, as shown in Fig. 2. The results show that as payload increases the displacement at the contact point increases accordingly.

[Figure 2 about here.]

In addition, we built an analytical kinematics model for a FinRay finger. The finger is represented as a series of four-bar linkages with incorporated torsional springs. All links are considered rigid in a side view 2-D plane of the finger, and each layer is connected by revolute joints without friction and torsional springs that represent the elasticity in the walls. More details about the model can be found in the supplementary materials (Text S1 and Fig. S4). Simulation results in Fig. S5.A shows similar bending response to the experimental results, which means the model is capable of accurately predicting the bending of a finger.

As expected, the F-D testing we conducted shows that a finger bends in the opposite direction when it is loaded, which means that the curvature changes from zero to negative curvature, and the fingertip bends towards the load, resulting in a negative bending stiffness behavior. This behavior is why a finger self-adapts and self-conforms around an object.

3.2. Conformability testing

To understand what benefit a finger gives by moving from 2-D to 3-D compliance, we conducted conformability tests. Conformability testing was conducted in 2-D and 3-D workspaces. In the 2-D workspace, we investigated the amount of contact points to see how the finger conforms to cylindrical objects. We tested a series of cylindrical shapes as described in Fig. 3. We selected five points on the finger and measured their radial distances from the surface of the object during contact. The cylinders had three different radii (33, 16, and 8 mm respectively). A finger is pressed onto the cylinder surface until either the cylinder fully touches the five points on the finger, or the center of the cylinder reaches the bottom line of the finger base. Fig. 3A shows that five points perfectly contact Cylinder 1 even when there was an 8.3 mm gap between the center of the cylinder and the bottom line of the finger; Cylinder 2 has two points, B and C, in contact; Cylinder 3 with the smallest radius has only point C in contact. Fig. 3C shows the radial distances between the surface of each cylinder and the five points on our proposed finger.

[Figure 3 about here.]

Further testing was conducted in the 2D workspace to better characterize how the smaller radii cylindrical objects of 8 mm and 16 mm affect the finger at each of the elastomer layers. From this testing, the finger exhibits limited deformation due to small radii near the tip of the finger, due to the small size of the 8 mm cylinder as seen in Fig. 4 4 Column A. As the small radius cylinder is raised into the finger, as shown in Fig. 4 4 Column B, the finger makes better contact with the cylinder, although some parts of the finger are no longer able to deform around the object as it is moved to the base of the finger structure. In Fig. 4 Column C, a similar set of experiments is shown using a 16 mm cylinder, similarly to the 8mm cylinder, the finger has trouble conforming to the shape as the shape is brought closer to the base of the finger.

[Figure 4 about here.]

The results show that larger diameter objects will result in a larger surface area in contact with the finger, which provides a stronger grip that resembles a power grasp. However, smaller objects still induce a negative bending response and may be gripped with the fingertips, resembling a pinch grasp. Therefore, we can see that the finger passively adapts to various sizes of objects and can self-adapt to relatively small bending radii. It can smoothly transition between grasp types according to the size of the object, pinch grasp for small objects, and fully envelope power grasp for larger objects.

We also want to know if the finger has the same ability to grasp in 3-D workspace. We examined the conformability in the real world by contacting the finger on both sides and at 360 degrees. We first used a 8mm cylinder bar to touch the finger in a 2-D workspace (Fig. 5 A). Next, we touched the finger 360 degrees in a 3-D workspace. Touch it by increasing 45 degrees each time until 360 degrees (Fig. 5 B). The finger in both workspace is self-conforming and self-adaptive to the object successfully. This demonstration can be found in Movie S1.

[Figure 5 about here.]

3.3. Comparison to 2-D FinRay Fingers

Additional experiments were conducted comparing the proposed radial 3-D FinRay effect gripper to a radial 2-D FinRay gripper with an equivalent mechanism in grasps similar to the bundle of carrots. This grip was selected because it is a key weakness with radial 2-D FinRay grippers, and certain commercially available grippers such as the Festo Multichoice gripper account for this weakness by rotating the fingers such that the radial gripper switches to a three-finger parallel gripper configuration and back again as needed using a separate mechanism.[10] In order to test the performance of such 2-D FinRay grippers in comparison with the 3D finger-based gripper, two test targets were created, a 40 mm diameter 120 mm long cylinder, and a 50 mm $\times$ 40 mm $\times$ 140 mm rectangular prism. These objects were then picked up by both the proposed self-adaptive 3-D FinRay finger gripper and a second gripper base modified to utilize 2-D FinRay fingers cast out of Smooth-Sil 945 (Smooth-On) instead.

In testing, it was found that the 2-D FinRay based gripper struggled to make good contact with the objects, as only the edges of two of the three fingers made contact with both the rectangular prism and the cylinder when tested, while the third finger perpendicular to the object made contact in normal direction and conformed around the objects as expected. In comparison, when the 3-D FinRay fingers contacted both the rectangular prism and the cylinder, the fingers deformed in multiple directions, automatically transforming in a grip similar to that of a parallel configuration, while still conforming around the shape as illustrated in Fig. 6 From this testing, it is evident that a primary benefit of the proposed 3-D FinRay mechanism in this radial configuration is that is does not require a secondary mechanism to adjust the finger orientation in order to pick up objects with this wide encompassing power grasp, saving weight and complexity while maintaining capability.

[Figure 6 about here.]

Shaped weight experiments involved the comparison of the weight capacity of the 3D fingers and the 2D reference fingers when power grasping cylinders and spheres at the approximate center of the fingers. In order to reduce external variables, both the 2D and 3D fingers were mounted to the same exact gripper, with a servo rotation of 120 degrees to more than close the gripper and adequately grip the target object. To test the two grippers, the base gripper was installed on a Kinova Jaco arm and three of the finger to be tested. The gripper was then oriented in a downwards position and opened to permit insertion of the target item. The gripper was then closed around the target and weights were attached to the eyehook on the target in increments of 20 grams until the target and weights dropped out of the gripper. The total weight of the target and added weights was then recorded in table 1. Each of the 4 tests were repeated 5 times and then averaged, with an average weight at failure of 86.46 grams for the 2D fingers and the cylinder target, while the 3D fingers averaged 252.3 grams with the same target geometry. Spherical targets did not seem to have as large of a gap in performance, with the average weight of failure 135.4 grams with the 2D fingers and 251.4 grams with the 3D fingers. This suggests that the 3D fingers are less sensitive to non-rotationally symmetric objects.

[Table 1 about here.]

3.4. Performance testing

We conducted four different grasping experiments to quantify the gripper's performance when grasping various fruits and objects (Fig. 7). These three grasping experiments include fingertip grasping, power grasping, and semi-passive grasping (movies S2 to S4). We first evaluated the experiments on fingertip grasping (Fig. 7A) and power grasping (Fig. 7, B through I), calculating the success rate over fifty attempts at picking a collection of fruits and objects.

[Figure 7 about here.]

Grasping experiments are based on pick-and-place manipulation. To maintain consistency, we attach the gripper to a Kinova Jaco arm that follows a fixed standard motion trajectory. The Jaco arm moves directly over the target object, descends and closes the fingers to grasp it, and then rises back up. We had the gripper stay in the air for three seconds to make sure that the grasp was stable. Next, Jaco arm moves down and opens the fingers to place the object before returning to the home position. Fingertip grasping is used to grasp a single green grape, while power grasping is used to grasp various larger fruits and objects. The items in the power grasping experiment included a raw egg, an apple, a pear, a tomato, a sphere with weights, a cup with weights, a bunch of grapes, and a package of carrots. The weight range on fingertip and power grasping is from 16 grams to 312.5 grams. The data of weight was obtained experimentally by adding weights in a plastic cup and by repeating a power grasping experiment until the gripper was unable to lift the load. Demonstrations for power grasping and semi-passive grasping can be seen in Movie S2 and Movie S3, respectively.

The final experiment is passive conformation in clutter, that is to pick up an apple in a plate of apples. The purpose of this experiment is to demonstrate that the fingers can self-conform around a desired object in a cluttered environment. The control states we used to enable this grasping experiment are semi-closed, closed, and open, which was only used to release the apple and return to the semi-closed grasping configuration. The compliant properties of our fingers adapt to different sizes of apples in the pile. For the semi-passive grasping process, the gripper starts in a semi-closed state which moves the fingers to have a slightly smaller opening than the size of the apples. As the gripper is slowly lowered, the fingers make contact with the apple and passively conform to wrap around its surface, with minimal interaction with neighboring apples. At the bottom, the gripper is fully closed to achieve a tight grasp and the object is raised as before. A representative cycle in the grasping process in clutter is shown in Fig. 8, from A through E. We repeat this cycle to pick up each apple on the plate until all apples have been picked up as shown in Movie S4.

[Figure 8 about here.]

The results of Table S3 show that the gripper achieves a 100% success rate in grasping a collection of fruits and objects 50 times and picking up with semi-passive grasping from a plate of apples six times. These experiments indicate that the proposed adaptive soft gripper has stable grasping performance and is capable of grasping various fragile objects successfully and repeatedly. It is noteworthy that the gripper also demonstrated stable grasping in a nonnormal direction when grasping a package of carrots (Fig. 8I), where the circular arrangement of fingers self-adjusted and grasped in a different parallel opposing grasp configuration. The experiments also validated the ability of the fingers to passively conform to the shape of an apple while picking apples on a cluttered plate, where five other apples surrounded the central apple and in contact with it. The central apple was first grasped as the worst-case scenario. In these experiments the fingertips also showed resilience when coming in contact with the plate, deforming underneath the apple and aiding in grasping (Fig. 8F). Therefore, the semi-passive grasping experiment shows that the proposed gripper is able to repeatably and stably pick up all of the apples in a pile of apples in cluttered and unstructured environments.

4. Conclusion

This report presented a new type of soft robotic finger that consists of silicone rubber elastomer and elastic metal rods that are capable of grasping objects without internal cables or links, and without using pneumatics. The resulting force-displacement experiments and models show that the finger is highly adaptable, exhibiting negative bending stiffness, and hence bending towards contact forces. We investigated this phenomenon when the finger comes in contact with cylinders of various sizes, highlighting its adaptable nature. We combined the proposed fingers into a simple 3-finger gripper controlled by a single motor and tested its ability to grasp various objects. The gripper shows a stable grasping capability of various fruit items and everyday objects as representative fragile objects with irregular and highly variable shapes, demonstrating a 100% success rate. Moreover, we have demonstrated that our proposed 3D adaptive soft gripper achieves semi-passive adaptive grasp of a single apple from amidst a cluttered plate of apples. Finally, this work demonstrated that the proposed gripper did not require complex control or motion planning algorithms to grasp objects of widely varying sizes and shapes.

The proposed gripper is capable of lifting objects up to a maximum of 312.5 grams in power grasp. Using the selected dimensions and parameters of the finger, the weight of the full gripper is 171 grams. This represents an effective payload-to-weight ratio of 182.7%. Since the fingers showed a consistent adaptive grasping performance without the need for complex control algorithms, the next plan is to incorporate various sensors in the gripper to achieve proprioception which will monitor the grasp during semi-passive grasping and help identify objects using data-driven methods. Finally, based on our analytical model, the proposed mechanism can be tailored to generate the desired deformation responses with different loading conditions. We are excited to extend this design concept to other potential applications that may benefit from adaptive passive deformation, such as areas in soft locomotion and human interaction.

The proposed gripper has its limitations. Extending from 2-D compliance to 3-D, we found that the fingers are not resistant to torsion, similar to the 2D FinRay fingers we have tested. At higher loads, our 3D FinRay fingers may twist, which may cause the object to slip from the fingers. The proposed gripper is best at power grasping objects, not dexterous manipulation. It is not good at fingertip grasping thin and slender objects, such as credit cards or pencils. In fingertip grasping, we only show a potential ability to pinch grasp a single grape, which is the smallest tested object we can reliably grasp.

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Supplemental Material

Text S1. Analytical model of four-bar linkage.

Fig. S1. The process of fabrication of a 3D soft finger.

Fig. S2. The process of a 3D adaptive soft gripper.

Fig. S3. The system architecture for the platform of performance testing.

Fig. S4. Schematic of four-bar linkage on a 2D finger.

Fig. S5. The results of Force-Displacement testing on a 2D finger.

Table S1. The 2D drawing of a finger.

Table S2. Parts of a 3D adaptive soft gripper.

Table S3. The success rate of performance testing.

Movie S1. Conformability testing.

Movie S2. Fingertip grasping.

Movie S3. Power grasping.

Movie S4. Semi-passive grasping in clutter.

References

[1] A. Albu-Schaffer, O. Eiberger, M. Grebenstein, S. Haddadin, C. Ott, T. Wimbock, S. Wolf, and G. Hirzinger, "Soft robotics," *IEEE Robotics & Automation Magazine*, vol. 15, no. 3, pp. 20–30, 2008.

[2] G. Montúfar, K. Ghazi-Zahedi, and N. Ay, "A theory of cheap control in embodied systems," *PLoS computational biology*, vol. 11, no. 9, p. e1004427, 2015.

[3] C. Eppner, S. Höfer, R. Jonschkowski, R. Martín-Martín, A. Sieverling, V. Wall, and O. Brock, "Lessons from the amazon picking challenge: Four aspects of building robotic systems.," in *Robotics: science and systems*, 2016.

[4] L. Kang, J.-T. Seo, S.-H. Kim, W.-J. Kim, and B.-J. Yi, "Design and implementation of a multi-function gripper for grasping general objects," *Applied Sciences*, vol. 9, no. 24, p. 5266, 2019.

[5] A. Koivikko, D.-M. Drotlef, M. Sitti, and V. Sariola, "Magnetically switchable soft suction grippers," *Extreme Mechanics Letters*, vol. 44, p. 101263, 2021.

[6] E. Brown, N. Rodenberg, J. Amend, A. Mozeika, E. Steltz, M. R. Zakin, H. Lipson, and H. M. Jaeger, "Universal robotic gripper based on the jamming of granular material," *Proceedings of the National Academy of Sciences*, vol. 107, no. 44, pp. 18809–18814, 2010.

[7] M. D. Swift, C. B. Haverkamp, C. J. Stabile, D. Hwang, R. H. Plaut, K. T. Turner, D. A. Dillard, and M. D. Bartlett, "Active membranes on rigidity tunable foundations for programmable, rapidly switchable adhesion," *Advanced Materials Technologies*, vol. 5, no. 11, p. 2000676, 2020.

[8] P. Testa, B. Chappuis, S. Kistler, R. W. Style, L. J. Heyderman, and E. R. Dufresne, "Switchable adhesion of soft composites induced by a magnetic field," *Soft Matter*, vol. 16, no. 25, pp. 5806–5811, 2020.

[9] L. Li, Z. Liu, M. Zhou, X. Li, Y. Meng, and Y. Tian, "Flexible adhesion control by modulating backing stiffness based on jamming of granular materials," *Smart Materials and Structures*, vol. 28, no. 11, p. 115023, 2019.

[10] "Festo multichoicegripper." https://www.festo.com/net/SupportPortal/Files/333986/Festo_MultiChoiceGripper_en.pdf, 2014.

[11] J. Shintake, V. Cacucciolo, D. Floreano, and H. Shea, "Soft robotic grippers," *Advanced Materials*, vol. 30, no. 29, p. 1707035, 2018.

[12] C. Laschi, B. Mazzolai, and M. Cianchetti, "Soft robotics: Technologies and systems pushing the boundaries of robot abilities," *Science robotics*, vol. 1, no. 1, p. eaah3690, 2016.

[13] M. Wehner, R. L. Truby, D. J. Fitzgerald, B. Mosadegh, G. M. Whitesides, J. A. Lewis, and R. J. Wood, "An integrated design and fabrication strategy for entirely soft, autonomous robots," *Nature*, vol. 536, no. 7617, pp. 451–455, 2016.

[14] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature*, vol. 521, no. 7553, pp. 467–475, 2015.

[15] D. Trivedi, C. D. Rahn, W. M. Kier, and I. D. Walker, "Soft robotics: Biological inspiration, state of the art, and future research," *Applied bionics and biomechanics*, vol. 5, no. 3, pp. 99–117, 2008.

[16] S. Hirose and Y. Umetani, "The development of soft gripper for the versatile robot hand," *Mechanism and machine theory*, vol. 13, no. 3, pp. 351–359, 1978.

[17] J. D. Crisman, C. Kanojia, and I. Zeid, "Graspar: A flexible, easily controllable robotic hand," *IEEE Robotics & Automation Magazine*, vol. 3, no. 2, pp. 32–38, 1996.

[18] C. Majidi, "Soft robotics: a perspective—current trends and prospects for the future," *Soft robotics*, vol. 1, no. 1, pp. 5–11, 2014.

[19] L. Birglen, T. Laliberté, and C. M. Gosselin, *Underactuated robotic hands*, vol. 40. Springer, 2007.

[20] D. Petković, N. D. Pavlović, S. Shamshirband, and N. B. Anuar, "Development of a new type of passively adaptive compliant gripper," *Industrial Robot: An International Journal*, 2013.

[21] R. Deimel and O. Brock, "A compliant hand based on a novel pneumatic actuator," in *2013 IEEE International Conference on Robotics and Automation*, pp. 2047–2053, IEEE, 2013.

[22] R. K. Katzschmann, A. D. Marchese, and D. Rus, "Autonomous object manipulation using a soft planar grasping manipulator," *Soft robotics*, vol. 2, no. 4, pp. 155–164, 2015.

[23] "Soft Robotics Inc. Products." https://www.softroboticsinc.com/products/. Accessed: 2021-10-01.

[24] K. C. Galloway, K. P. Becker, B. Phillips, J. Kirby, S. Licht, D. Tchernov, R. J. Wood, and D. F. Gruber, "Soft robotic grippers for biological sampling on deep reefs," *Soft robotics*, vol. 3, no. 1, pp. 23–33, 2016.

[25] S. Bauer, S. Bauer-Gogonea, I. Graz, M. Kaltenbrunner, C. Keplinger, and R. Schwödiauer, "25th anniversary article: a soft future:

from robots and sensor skin to energy harvesters," *Advanced Materials*, vol. 26, no. 1, pp. 149–162, 2014.

[26] M. Manti, T. Hassan, G. Passetti, N. D'Elia, C. Laschi, and M. Cianchetti, "A bioinspired soft robotic gripper for adaptable and effective grasping," *Soft Robotics*, vol. 2, no. 3, pp. 107–116, 2015.

[27] W. Crooks, G. Vukasin, M. O'Sullivan, W. Messner, and C. Rogers, "Fin ray® effect inspired soft robotic gripper: From the robosoft grand challenge toward optimization," *Frontiers in Robotics and AI*, vol. 3, p. 70, 2016.

[28] W. Crooks, S. Rozen-Levy, B. Trimmer, C. Rogers, and W. Messner, "Passive gripper inspired by manduca sexta and the fin ray® effect," *International Journal of Advanced Robotic Systems*, vol. 14, no. 4, p. 1729881417721155, 2017.

[29] F. Ilievski, A. D. Mazzeo, R. F. Shepherd, X. Chen, and G. M. Whitesides, "Soft robotics for chemists," *Angewandte Chemie*, vol. 123, no. 8, pp. 1930–1935, 2011.

[30] R. Deimel and O. Brock, "A novel type of compliant and underactuated robotic hand for dexterous grasping," *The International Journal of Robotics Research*, vol. 35, no. 1-3, pp. 161–185, 2016.

[31] H. Choi and M. Koc, "Design and feasibility tests of a flexible gripper based on inflatable rubber pockets," *International Journal of Machine Tools and Manufacture*, vol. 46, no. 12-13, pp. 1350–1361, 2006.

[32] S. Sanan, P. S. Lynn, and S. T. Griffith, "Pneumatic torsional actuators for inflatable robots," *Journal of Mechanisms and Robotics*, vol. 6, no. 3, p. 031003, 2014.

[33] M. Issa, D. Petkovic, N. D. Pavlovic, and L. Zentner, "Sensor elements made of conductive silicone rubber for passively compliant gripper," *The international journal of advanced manufacturing technology*, vol. 69, no. 5-8, pp. 1527–1536, 2013.

[34] C.-H. Liu, G.-F. Huang, C.-H. Chiu, and T.-Y. Pai, "Topology synthesis and optimal design of an adaptive compliant gripper to maximize output displacement," *Journal of Intelligent & Robotic Systems*, vol. 90, no. 3, pp. 287–304, 2018.

[35] M. E. Giannaccini, I. Georgilas, I. Horsfield, B. Peiris, A. Lenz, A. G. Pipe, and S. Dogramadzi, "A variable compliance, soft gripper," *Autonomous Robots*, vol. 36, no. 1, pp. 93–107, 2014.

[36] M. Sfakiotakis, A. Kazakidi, and D. Tsakiris, "Octopus-inspired multi-arm robotic swimming," *Bioinspiration & biomimetics*, vol. 10, no. 3, p. 035005, 2015.

[37] K. Kumar, J. Liu, C. Christianson, M. Ali, M. T. Tolley, J. Aizenberg, D. E. Ingber, J. C. Weaver, and K. Bertoldi, "A biologically inspired, functionally graded end effector for soft robotics applications," *Soft robotics*, vol. 4, no. 4, pp. 317–323, 2017.

[38] V. A. Ho, "Grasping by wrapping: Mechanical design and evaluation," *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 6013–6019, 2017.

[39] G. Kofod, W. Wirges, M. Paajanen, and S. Bauer, "Energy minimization for self-organized structure formation and actuation," *Applied Physics Letters*, vol. 90, no. 8, p. 081916, 2007.

[40] M. Behl, K. Kratz, J. Zotzmann, U. Nöchel, and A. Lendlein, "Reversible bidirectional shape-memory polymers," *Advanced materials*, vol. 25, no. 32, pp. 4466–4469, 2013.

[41] E. Diller and M. Sitti, "Three-dimensional programmable assembly by untethered magnetic robotic micro-grippers," *Advanced Functional Materials*, vol. 24, no. 28, pp. 4397–4404, 2014.

[42] J. C. Breger, C. Yoon, R. Xiao, H. R. Kwag, M. O. Wang, J. P. Fisher, T. D. Nguyen, and D. H. Gracias, "Self-folding thermo-magnetically responsive soft microgrippers," *ACS applied materials & interfaces*, vol. 7, no. 5, pp. 3398–3405, 2015.

[43] F. Ongaro, S. Scheggi, C. Yoon, F. Van den Brink, S. H. Oh, D. H. Gracias, and S. Misra, "Autonomous planning and control of soft untethered grippers in unstructured environments," *Journal of micro-bio robotics*, vol. 12, no. 1-4, pp. 45–52, 2017.

[44] W. Wang and S.-H. Ahn, "Shape memory alloy-based soft gripper with variable stiffness for compliant and effective grasping," *Soft robotics*, vol. 4, no. 4, pp. 379–389, 2017.

[45] J.-H. Lee, Y. S. Chung, and H. Rodrigue, "Long shape memory alloy tendon-based soft robotic actuators and implementation as a soft gripper," *Scientific reports*, vol. 9, no. 1, pp. 1–12, 2019.

[46] D. Schönfeld, D. Chalissery, F. Wenz, M. Specht, C. Eberl, and T. Pretsch, "Actuating shape memory polymer for thermoresponsive soft robotic gripper and programmable materials," *Molecules*, vol. 26, no. 3, p. 522, 2021.

[47] A. M. Dollar and R. D. Howe, "A robust compliant grasper via shape deposition manufacturing," *IEEE/ASME transactions on mechatronics*, vol. 11, no. 2, pp. 154–161, 2006.

[48] L. U. Odhner and A. M. Dollar, "Stable, open-loop precision manipulation with underactuated hands," *The International Journal of Robotics Research*, vol. 34, no. 11, pp. 1347–1360, 2015.

[49] A. M. Dollar and R. D. Howe, "The highly adaptive sdm hand: Design and performance evaluation," *The international journal of robotics research*, vol. 29, no. 5, pp. 585–597, 2010.

[50] L. U. Odhner, L. P. Jentoft, M. R. Claffee, N. Corson, Y. Tenzer, R. R. Ma, M. Buehler, R. Kohout, R. D. Howe, and A. M. Dollar, "A compliant, underactuated hand for robust manipulation," *The International Journal of Robotics Research*, vol. 33, no. 5, pp. 736–752, 2014.

[51] S. B. Backus and A. M. Dollar, "An adaptive three-fingered prismatic gripper with passive rotational joints," *IEEE Robotics and Automation Letters*, vol. 1, no. 2, pp. 668–675, 2016.

[52] T. Nishimura, K. Mizushima, Y. Suzuki, T. Tsuji, and T. Watanabe, "Variable-grasping-mode underactuated soft gripper with environmental contact-based operation," *IEEE Robotics and Automation Letters*, vol. 2, no. 2, pp. 1164–1171, 2017.

[53] A. Firouzeh and J. Paik, "An under-actuated origami gripper with adjustable stiffness joints for multiple grasp modes," *Smart Materials and Structures*, vol. 26, no. 5, p. 055035, 2017.

[54] C. D. Onal, M. T. Tolley, R. J. Wood, and D. Rus, "Origami-inspired printed robots," *IEEE/ASME transactions on mechatronics*, vol. 20, no. 5, pp. 2214–2221, 2014.

[55] S. Li, J. J. Stampfli, H. J. Xu, E. Malkin, E. V. Diaz, D. Rus, and R. J. Wood, "A vacuum-driven origami "magic-ball" soft gripper," in *2019 International Conference on Robotics and Automation (ICRA)*, pp. 7401–7408, IEEE, 2019.

[56] H. Iwamasa and S. Hirai, "Binding of food materials with a tension-sensitive elastic thread," in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 4298–4303, IEEE, 2015.

[57] E. W. Hawkes, D. L. Christensen, A. K. Han, H. Jiang, and M. R. Cutkosky, "Grasping without squeezing: Shear adhesion gripper with fibrillar thin film," in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 2305–2312, IEEE, 2015.

[58] J. Shintake, S. Rosset, B. Schubert, D. Floreano, and H. Shea, "Versatile soft grippers with intrinsic electroadhesion based on multifunctional polymer actuators," *Advanced materials*, vol. 28, no. 2, pp. 231–238, 2016.

[59] S. Song, C. Majidi, and M. Sitti, "Geckogripper: A soft, inflatable robotic gripper using gecko-inspired elastomer micro-fiber adhesives," in *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 4624–4629, IEEE, 2014.

[60] P. Glick, S. A. Suresh, D. Ruffatto, M. Cutkosky, M. T. Tolley, and A. Parness,

"A soft robotic gripper with gecko-inspired adhesive," *IEEE Robotics and Automation Letters*, vol. 3, no. 2, pp. 903–910, 2018.

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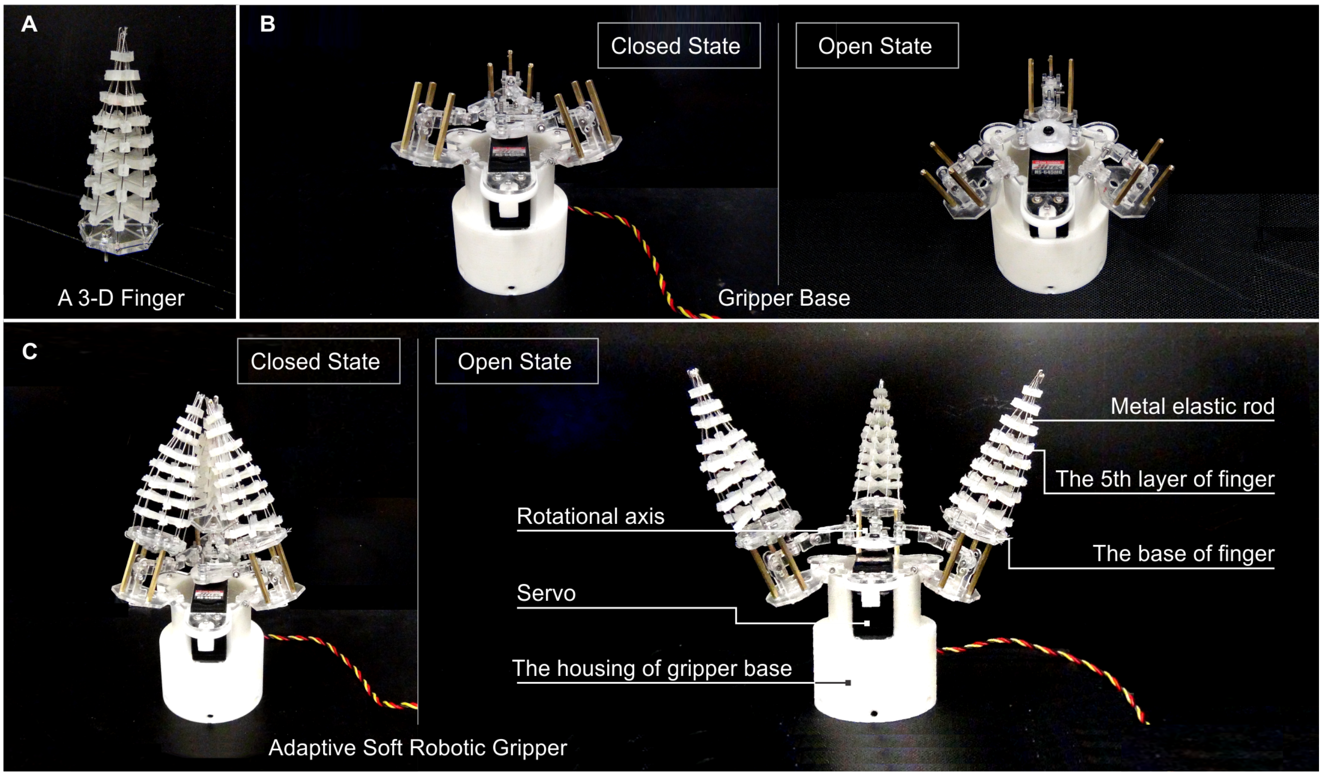

Figure 1. Design of a 3D adaptive soft gripper. (A) A 3D adaptive soft finger is manufactured from thin flexible metal elastic rods and elastomer layers. The metal elastic rods connect from the edges of the octagonal base to form a point at the tip of the finger. (B) A three-fingered gripper base at closed and open state. Gripper base is actuated by a single servo. The 3D adaptive soft gripper at closed (C) and open states (D): When the servo rotates, it actuates a linkage mechanism connected to the base of the fingers, causing them to tilt inwards to close the gripper or tilt back outwards to open it.

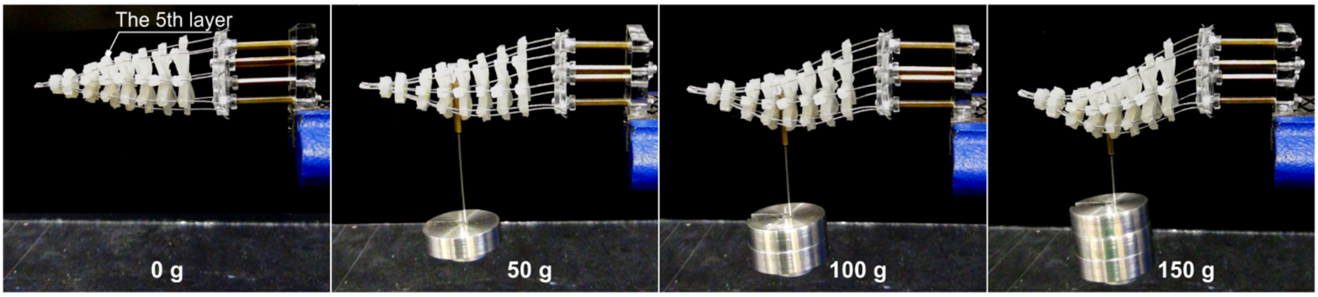

Figure 2. Force vs. Displacement testing. The finger bends in the opposite direction when it is loaded by three different concentrated loads, 50, 100, and 150 grams, at the connected joint on the fifth layer. The results show that the curvature of the finger changes from zero curvature to negative curvature as the load increases and the displacement increases accordingly, which enables the self-conformation behavior we exploit for grasping a broad range of objects in an adaptive gripper.

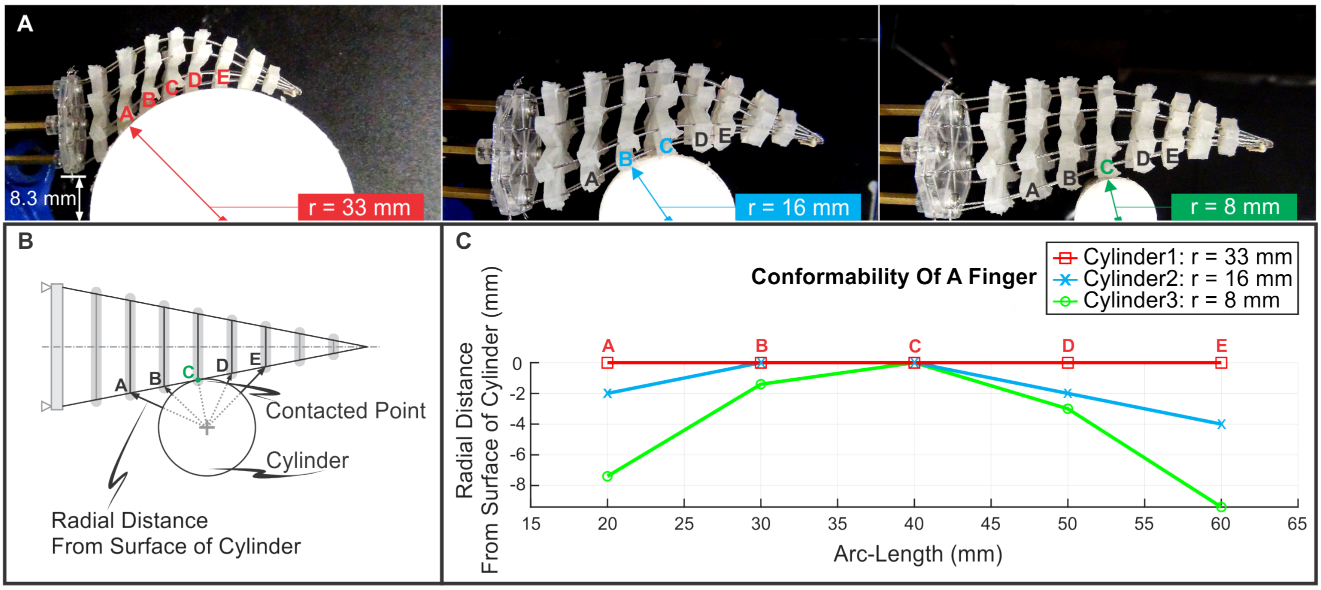

Figure 3. Conformability testing. More contact points achieve better conformation to objects leading to distributed contact forces and better form closure. (A) A finger touches three different cylinders of radii 33, 16, and 8 mm respectively. The 33-mm cylinder contacts with the finger over a longer distance (at all five tracked points). (B) A side-view cross-section drawing of a finger touching a cylinder of 8 mm radius defining the contacted point, cylinder and radial distance of each point from the surface of the cylinder. (C) Experimental results of conformability testing from the three different cylinders. Five points contact cylinder 1 perfectly; cylinder 2 has two contact points, B and C; cylinder 3 with the smallest radius has only the middle point C in contact with the finger.

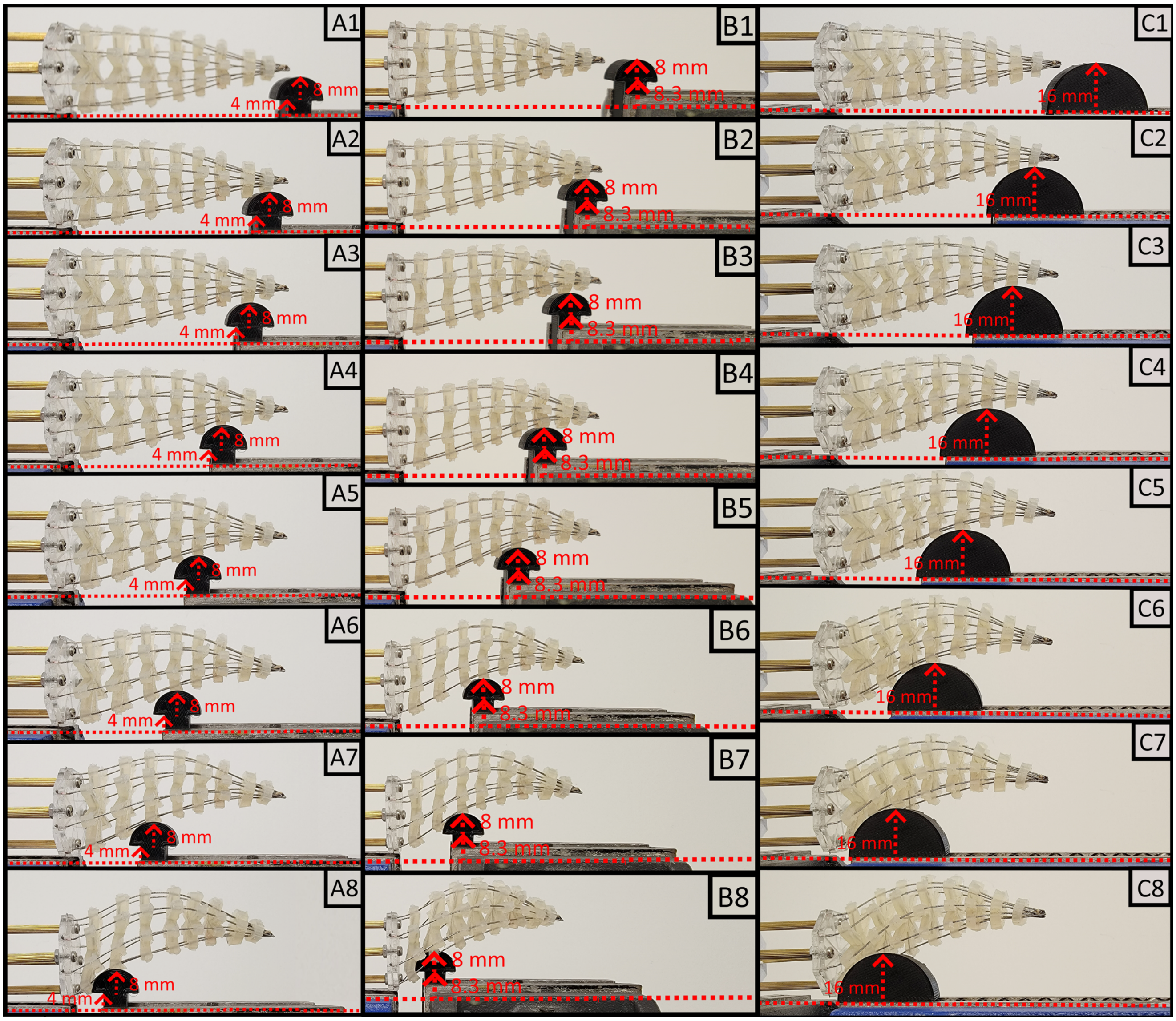

Figure 4. Snapshots of finger deformation due to radii of 8 mm and 16mm at each layer. Column A shows the effect on curvature of an 8 mm radius at a height of 8.3mm from the base of the finger at each of the elastic layers excepting the last layer which was too large to be placed above the 8 mm radii at the 8.3 mm offset. Column B shows the same 8 mm radii at a 4mm offset, again showing the difficulty reaching the last elastic layer with the center of a circular object. Column C shows the same experiment with a 16mm radius and no offset, in images C7 and C8 it can be again seen that the base of the finger limits how close to the base of the finger the cylinder can get.

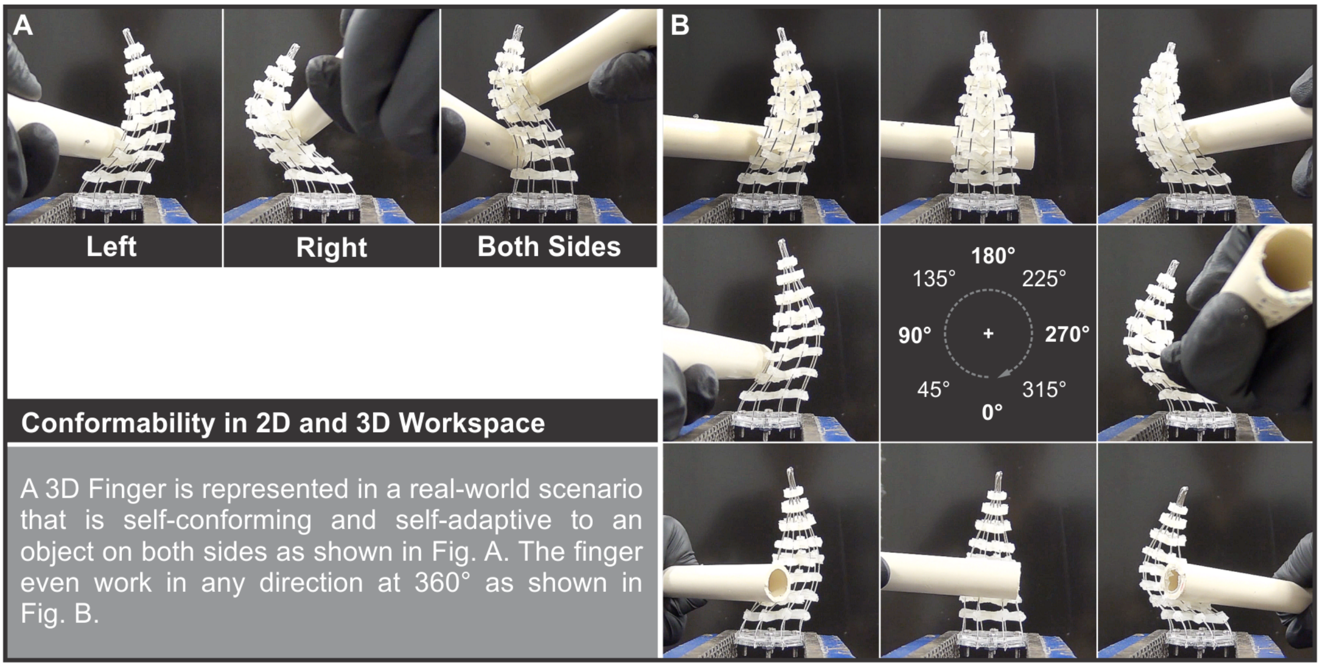

Figure 5. Conformability in 2-D and 3-D Workspace. (A) The finger was touched in a 2-D workspace. (B) The finger was touched in a 3-D workspace.

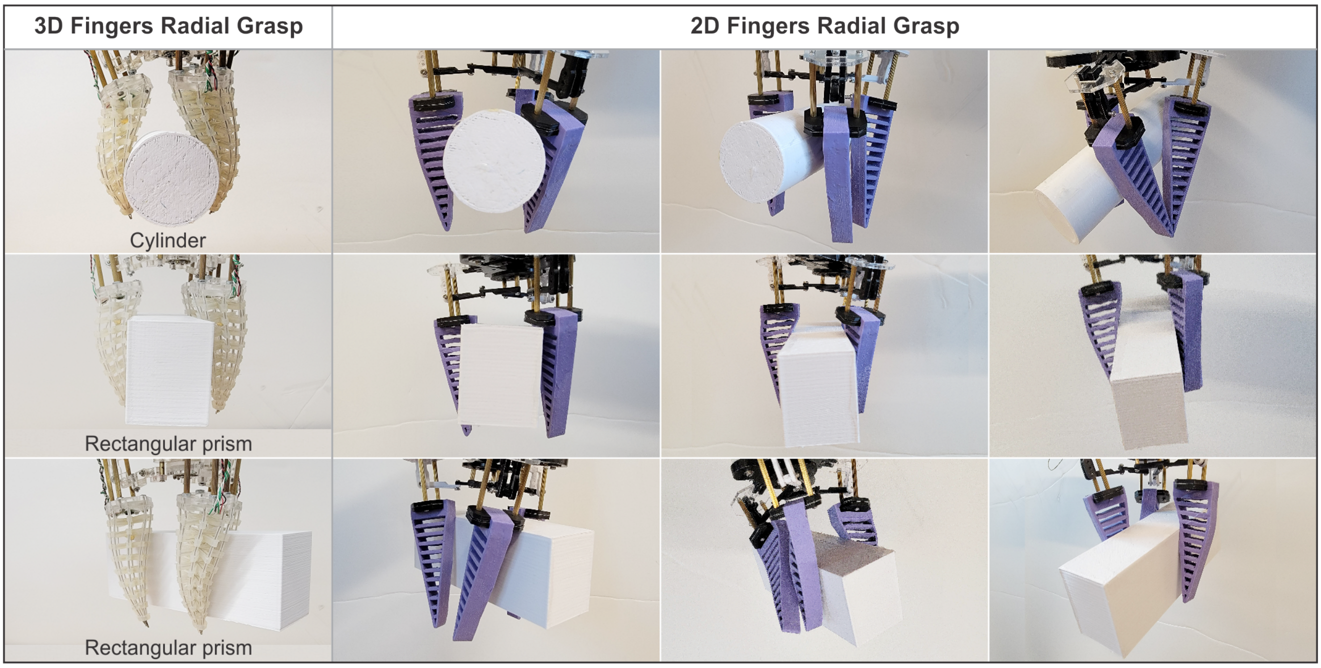

Figure 6. Snapshots of radial grasps of cylinder and rectangular prism using a set of 2D fin-ray fingers compared to the 3D finger grasping the same objects. made out of Smooth-Sil 945 (Smooth-On) with a shore hardness of 45A, these fingers were mounted to a similar gripper base as used for the 3D fin-ray experiments, and was built as an analogue to the Festo Multi-choice gripper. In each of the matched angle sets the 2D Fin-ray Fingers preformed consistently worse, while the 3D passively conforming gripper is able to conform around the prism and cylinder, effectively switching from a radial grasp to a parallel grasp.

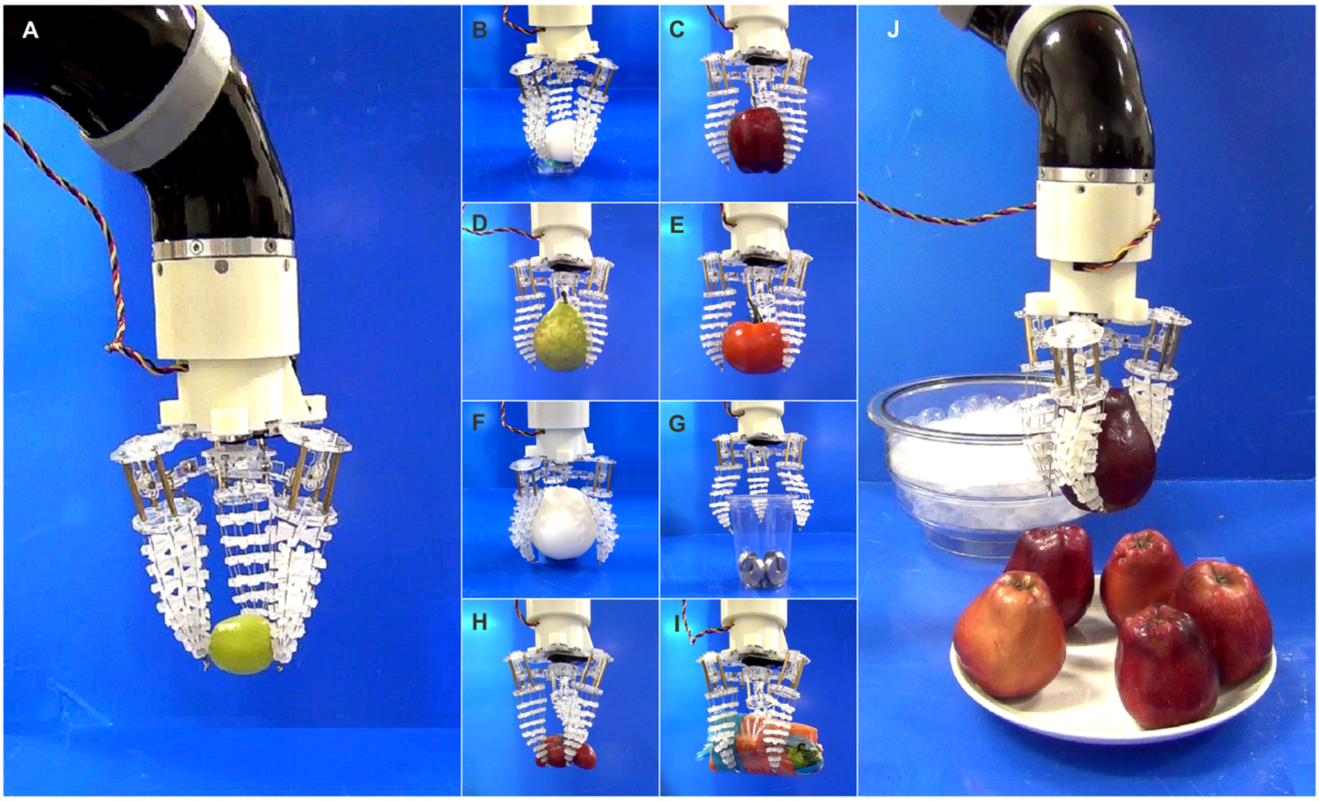

Figure 7. Performance testing on grasping various fruits and objects. We calculated the success rate over fifty attempts at picking a collection of fruits and other objects using fingertip grasping and power grasping. We also calculated the success rate over six attempts at picking six apples from a pile of apples for semi-passive grasping from a cluttered plate. (A) Fingertip grasping a green grape. (B) to (I) Power grasping a raw egg, an apple, a pear, a tomato, a sphere with weights, a cup with weights, a bunch of grapes, and a package of carrots. (J) Semi-passive grasping an apple in the middle of a pile of apples on a cluttered plate.

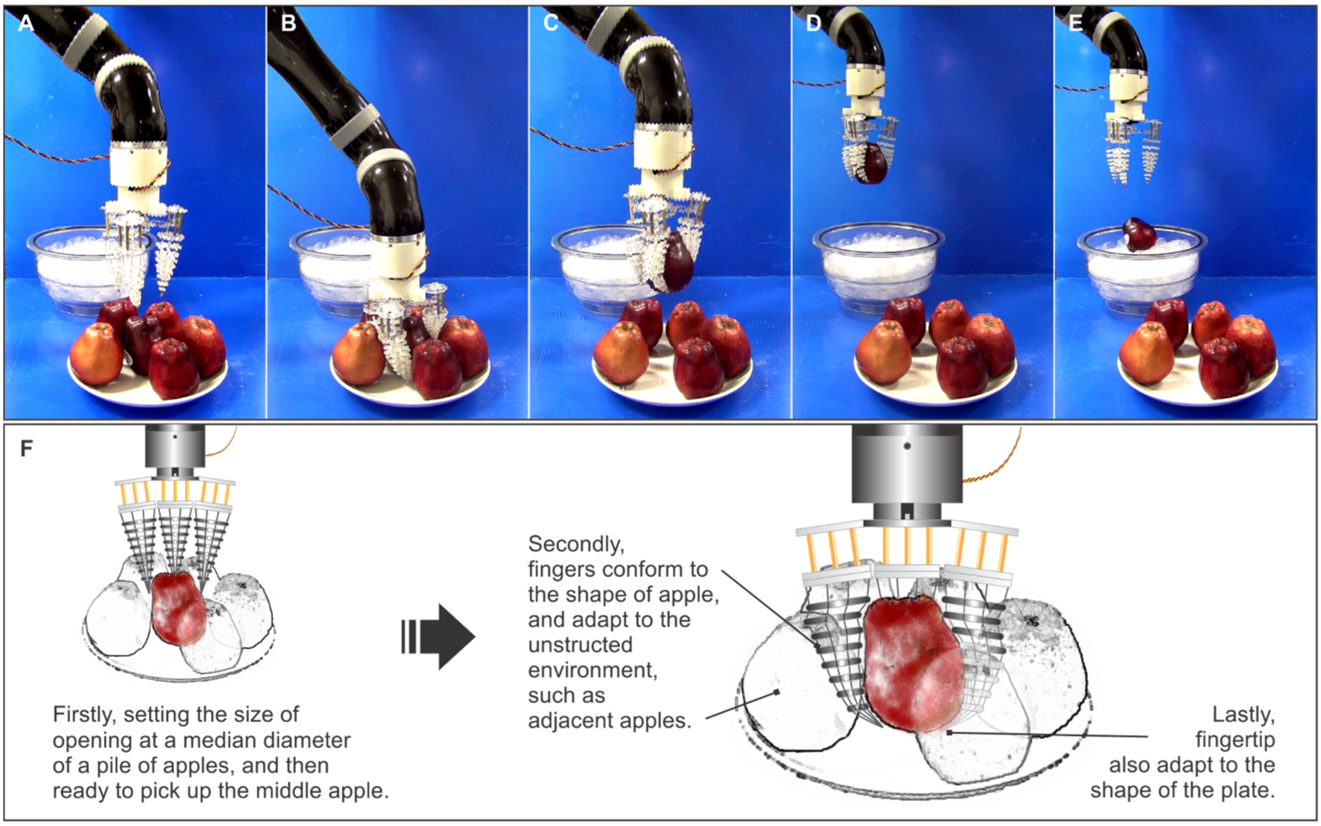

Figure 8. Snapshots of semi-passive grasping an apple from a closely packed pile of apples. The process of grasping starts with the robotic arm (Kinova Jaco) at home position and the gripper at a semi-closed state where the fingers are opened to an approximately median diameter of the apples. The gripper is positioned above the target apple and moves down along the vertical axis until the fingers almost touch the apple. At this point, the Jaco arm descends slower to allow the fingers to passively conform to the shape of the apple as well as deform appropriately as they come in contact with the surface of the plate. At the bottom, the gripper is fully closed to achieve a tight grasp of the apple, which is lifted up, and placed to a nearby basket. (A) Gripper at semi-closed state is ready to grasp the middle apple. (B) Gripper is passively conforming to the shape of the apple without disturbing its neighbors. (C) Gripper is closed fully at the bottom to finalize the grasp. (D) Gripper and apple are moved by the Jaco arm over the basket. (E) Gripper at open state to release the apple into the basket. (F) A closer look at semi-passive grasping in clutter.

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Target Weight in Grams for grasp to Fail				
	Cylinder Target		Sphere Target	
Finger type	2D	3D	2D	3D
	98.6	176.18	127.58	167.41
	78.44	296.23	147.28	287.53
	78.36	296.36	87.35	287.32
	78.32	236.44	167.24	247.35
	98.6	256.5	147.58	267.3
Average	86.46	252.34	135.4	251.38

Table 1. **Experimental Data Collected during weight and shape testing** these experimental data values help to demonstrate numerically the difference between the 2D and 3D fingers on rotationally symmetric and non-symmetric objects by grasping a 45mm sphere and cylinder. These values were generated by repeating each test 5 times, and averaging the measured values. It should be noted that these values are the weight required to cause the object to fall out of the gripper, the maximum weight the gripper can hold stably is no less than 20 grams from the weight recorded in the above table.