A Soft-Robotic Gripper With Enhanced Object Adaptation and Grasping Reliability

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***Abstract*—A novel soft-robotic gripper design is presented, with three soft bending fingers and one passively adaptive palm. Each soft finger comprises two ellipse-profiled pneumatic chambers. Combined with the adaptive palm and the surface patterned feature, the soft gripper could achieve 40-N grasping force in practice, 10 times the self-weight, at a very low actuation pressure below 100 kPa. With novel soft finger design, the gripper could pick up small objects, as well as conform to large convex-shape objects with reliable contact. The fabrication process was presented in detail, involving commercial-grade three-dimensional printing and molding of silicone rubber. The fabricated actuators and gripper were tested on a dedicated platform, showing the gripper could reliably grasp objects of various shapes and sizes, even with external disturbances.**

***Index Terms*—Soft robotics, grasping, pneumatic actuators.**

I. Introduction

SOFT robots attracted wide interests in the robotics research community [1]–[4]. With their inherent mechanical compliance, soft robots have unique advantages in environments requiring conformity and variable stiffness [1]. In grasping applications, the compliant soft grippers could adapt to object shapes without specific control inputs, dramatically reducing system complexity and cost, while improving grasping performance and safety [3], compared to rigid robotic grippers [5].

Global aging presents new challenges to robotic research: robots to assist human beings in *Activities of Daily Living* (ADL), in order for the society to cope with labor shortage in the service, elderly-care, and healthcare industries [6]. With humans being the main interaction target, the primary concerns of such service robots will be shifted from those for industrial robots (accuracy, strength, speed, etc.) to human-centered criteria, such as safety, adaptability, task-worthiness, and affordability [7]–[10]. Following the new requirements, soft robotic grippers are potentially ideal candidates, exploiting the intrinsic mechanical property of soft material. There are soft grippers, with one bending actuator [30], two fingers [15], tri-fingers [11], [16], [29], and multi-fingers [12], making compliant contact to objects and increasing grasping safety to fragile materials ranged from daily vegetables to deep sea reefs. Besides, soft dexterous anthropomorphic hands [13], [14] could realize most grasp types of human hand taxonomy, promising for interaction with human by using prosthesis. Furthermore, to achieve inherent compliance and adaptability, the soft material could combine conventional robotic hand designs with different finger joint actuating mechanisms, such as tendon-driven [17]–[19], gear and rod [20], [21], or driving rigid joints directly [22]. However, the inherent compliance of soft grippers often limits their maximum force output. hence limiting grasping reliability and payload capabilities [9], [10].

In this work, we aim to design a soft grasping system with both adaptation ability and robust grasping security. A novel tri-fingered soft-robotic gripper is proposed, comprising of three dual-chambered ellipse-profile soft pneumatic fingers, and a novel palm design with a compliant chamber. Both the fingers and the palm featured surface textures for enhanced grasping reliability. The resulting soft-robotic gripper with 406 g self-weight could securely hold 4 kg payload at an input pressure of 100 kPa, sufficiently covering most objects in ADL. The design of the soft-robotic gripper will be presented in Section II, followed by the fabrication process in Section III. Experimental results on the fabricated gripper will be presented in Section IV, with conclusions in Section V.

II. Soft Robotic Gripper Design

The proposed soft-robotic gripper is shown in Fig. 1, comprising of three pneumatic-driven soft fingers, a compliant palm, auxiliary components and pneumatic connection fittings.

A. Finger Design

Pneumatic bending soft actuators are widely adopted in soft robotic hands and grippers, combining actuation and structural components to enhance adaptability and inherent compliance [14], [23], [30]. However, the passive compliance will also limit the structural rigidity, both actuated and in free-state, resulting in the gripper failing to grasp heavy objects firmly. Continuous single-chambered soft bending actuators could follow the unique pre-defined motion trajectory, however without adapting to multiple object contours, which often

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Fig. 1. The proposed Soft-Robotic Gripper.

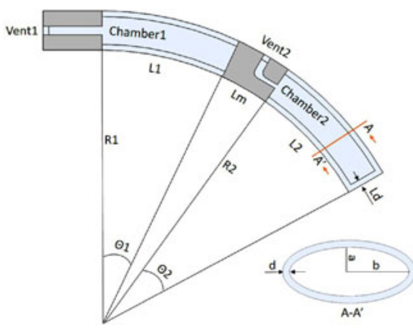

Fig. 2. Finger design.

resulted in the limited contact area and hindered grasping reliability.

The proposed soft bending actuator in this study comprises of two axially-aligned sections, with each section actuated independently, as shown in Fig. 2. Each section has a continuous fiber-reinforced inflatable air chamber similar to the actuator design featured in [23]. However, the cross section of the proposed actuator is ellipse-shaped, compared with the hemi-circular shape in [23], to reduce material stress at the edge of hemi-circular actuator caused by limiting layer surface bulging [24]. In Fig. 2, *L1* and *L2* are the lengths of the two chambers, Chamber1 and Chamber2, respectively; *Lm* is the length of the inter-sectional silicone wall; $\theta 1$ and $\theta 2$ are the bending angles generated by each section. The independent sections enabled two actuation modes of the finger:

1) If the two chambers are pressurized with the same input pressure, the deformation of the proposed finger will be similar to the single-chamber actuator in [23] with similar dimensions.
2) If the two sections are actuated independently, resulting in different $\theta 1$ and $\theta 2$ angles, the actuator could reach larger area than the first mode, allowing the finger to conform to complex-shaped objects.

Additionally, the passive compliance of the bending section enables new features for the proposed finger when grasping large convex-shaped objects. The concept of the novel grasping mode is illustrated in Fig. 3. For a convex-shape object larger than the gripper volume, the first section of the fingers will be actuated to maintain contact, while the second section of the fingers will be passively conforming to the object contour, exploiting their passive compliance to adapt Fig. 3(b), significantly increasing the contact area between the gripper and the object surface compared to point contact resulting from actuating both sections uniformly Fig. 3(a).

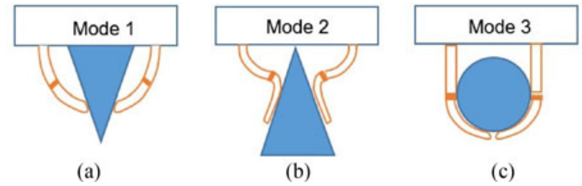

Fig. 3. Three grasping modes with passive compliance: (a) Both sections actuated; (b) Section I only. (c) Section II only.

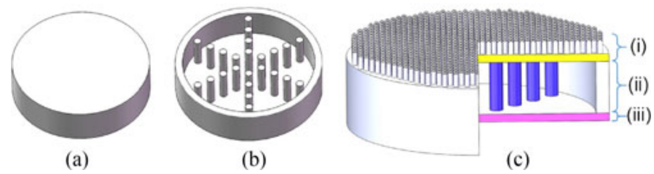

Fig. 4. Palm design. (a) Palm model. (b) Sectional view of inner support silicon pillars. (c) Sectional view of three compliance levels: (i) Unsupported surface, (ii) Supported surface, (iii) Hard bottom.

Inversely, actuating the second section of the finger and set the first section free as shown in Fig. 3(c), the gripper could lift objects with relatively small contact force. During this process, the second section of the finger just hold the button of objects, therefore the contact force is only caused by the self-weight of grasping target. This grasping method is promising when dealing with fragile and soft objects, which are easily damaged under large contact force.

Besides, to deal with light small objects, we design a triangular nail for the finger. With the help of nail, the gripper could pinch up small objects, which are relatively difficult to accomplish for gripper without such nail structure.

B. Palm Design

The palm plays an important role in power grasping both for the human hand and robotic hands, it could substantially affect grasping successfulness and reliability [14], [15]. Active particle jamming was reported to be helpful to object grasping [26]. In this work, we propose an alternative approach to soft robotic palm design, by using passive compliance to achieve reliable grasping without requiring additional actuation.

The proposed cylindrical palm design consists of a passive air chamber with a soft material passive compliant surface supported by supporting pillars as shown in Fig. 4(a) and (b). The pillars were aligned in a hexagon pattern and divided the chamber into six segments. Therefore the palm could offer three different compliance levels as shown in Fig. 4(c): a) unsupported surface: lowest stiffness, easiest to deform; b) supporting surface: medium stiffness, still deformable; and c) hard bottom surface: highest stiffness, non-deformable. By carefully selecting the dimensions of the pillars and the palm surface, the

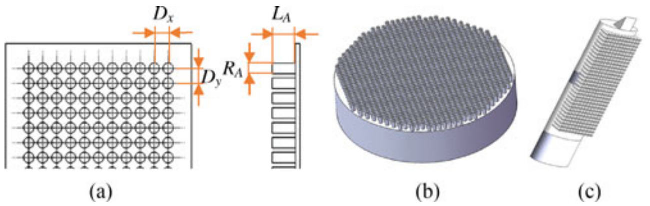

Fig. 5. Contact surface feature design. (a) Surface feature details. (b) Surface feature of a finger. (c) Surface feature of the palm.

proposed palm design could provide both compliance and sufficient support.

C. Contact Surface Feature Design

The contact surfaces of both the fingers and the palm are covered with a specific surface feature to improve grasping performance and reliability. The proposed contact surface feature is illustrated in Fig. 5(a), with raised soft-material cylinders of diameter R_A and height L_A forming an array pattern along the contact surface. The distances between two adjacent cylinders are denoted D_x and D_y respectively. All the above parameters could be varied according to each application. In this work, cylinders with uniform $R_A = 2$ m $L_A \geq 3$ mm are aligned in uniform array ($D_x = D_y = 3$ mm) For the palm surface Fig. 5(b), the cylinders have uniform height $L_A = 5$ mm. while for the finger surface, the cylinders have different heights to form an uniform distal contact surface ($L_A \geq 3$ m) as shown in Fig. 5(c). The proposed contact surface feature serves the following purposes:

1) Reduce input pressure: the raised surface features could be easily rearranged with actuator bending, without material stretch or compression, therefore the actuator could be bent with lower input pressure, compared to the same dimension actuator without these surface feature, because rubber poles could fill the small gap before the finger surface contact the object.
2) Improve contact: the small features will easily fit to object features with similar sizes, improving contact on a small scale and contribute to grasping reliability.
3) Compensate the convex finger surface: the ellipse finger shape will result in a point contact with objects with flat surfaces; the raised feature will compensate the finger surface and maintain a flat distal surface.

D. Soft-Robotic Gripper Design

In the gripper design, we aim to achieve reliable grasping from the compliant nature of the proposed soft actuators, while maintaining a simple structure. A tri-finger-single-palm setup was selected, with reference to the thumb, index and middle finger as the most important fingers in grasping [12], [13], [21]. There is a 120 degree angle between each pair of adjacent fingers [15], [16]. The design parameters and modeling variables of the soft gripper are shown in Fig. 6. The grasping volume of the gripper is adjustable by changing the finger mounting angle θ own in Fig. 6(a).

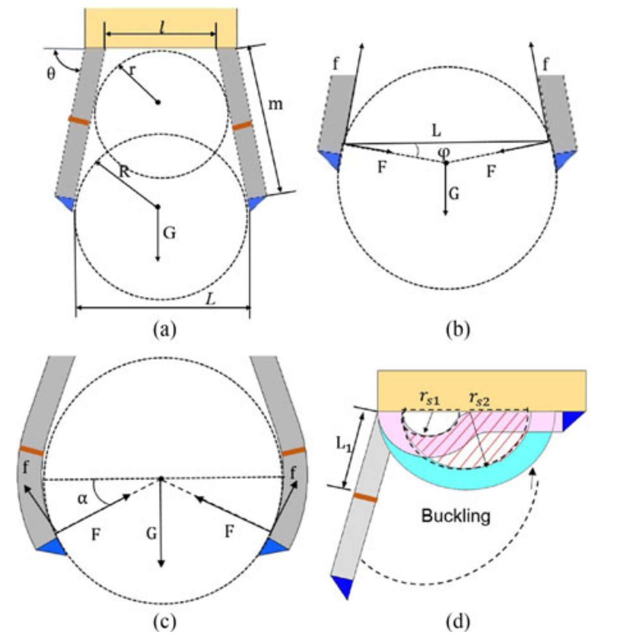

Fig. 6. Soft robotic gripper design. (a) Finger mounting. (b) Passive grasping. (c) Active grasping. (d) Buckling finger.

For soft gripper, the bending deformation of the finger is continuous, therefore the relationship of grasping volume and design parameters is different from the rigid joint gripper. We attempt to find out the relationship between design parameters and grasping volume of soft gripper, then we could depend on the proposed relationship adjusting design parameters to adapt different working requirements. The grasping volume of soft gripper could be estimated using the finger mounting angle θ, the mounting distance *l,* and the finger length *m* [26]:

1) The maximum sphere size for passive grasping is illustrated in Fig. 6(b) and (c), where Section I is actuated and Section II in free-state so as to passively conform to the shape of the grasping target. The maximum grasping size is defined by the distance *L*:

$$L = l + 2m\sin\theta \tag{1}$$

$$R_{\max\_\text{passive}} = R = \frac{L}{2} = \frac{l + 2m\sin\theta}{2} \tag{2}$$

2) For active grasping, both sections are actuated. If the fingers could encircle the spherical object in Fig. 6(c):

$$G = 2F(\mu\sin\theta + \cos\theta) \tag{3}$$

$$F = \frac{G}{2(\mu\sin\theta + \cos\theta)} \tag{4}$$

$$m - \frac{R\sin\theta - \frac{l}{2}}{\cos\theta} > \beta R \tag{5}$$

where:$\beta = \frac{\pi}{2} - \theta$. Therefore,

$$R_{\max\_\text{active}} < \left(m + \frac{l}{2\cos\theta}\right) \Big/ \left(\frac{\pi}{2} - \theta + \tan\theta\right) \tag{6}$$

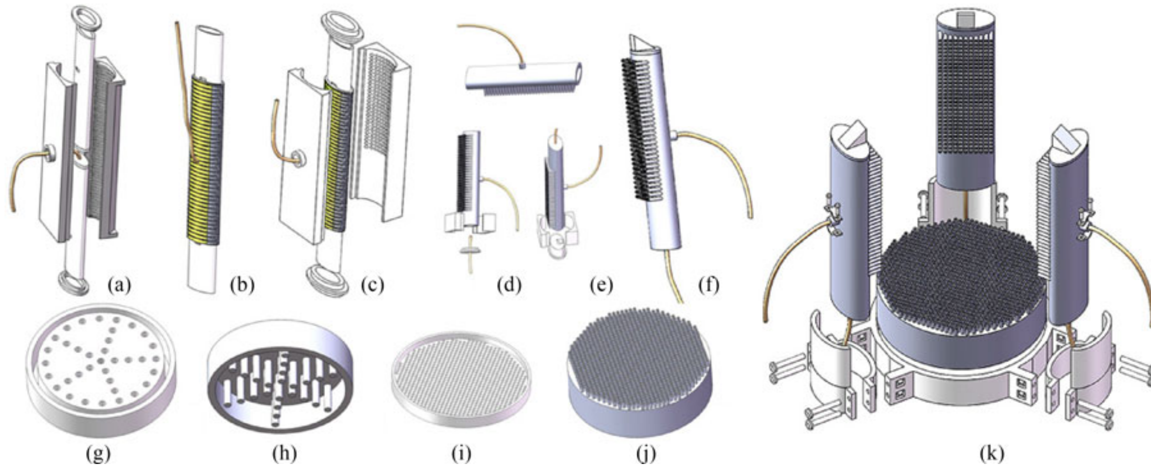

Fig. 7. Fabrication process. (a) Mold the inner two chambers using 3D printed molds. (b) Attach stain limiting layer and reinforcement fiber. (c) Mold the outer layer and the surface pattern. (d) Finished chamber wall. (e) Seal both ends and mold finger nail. (f) Finished soft finger. (g) Mold of palm base. (h) Finished palm base. (i) Mold of palm surface with surface pattern. (j) Finished palm. (k) Final assembly with three fingers and palm with the mounting scaffold to get the soft robotic gripper.

Besides, compared to one chamber finger, our proposed finger could reach the red shadow area shown in Fig. 6(d). The larger area where our proposed gripper could reach created by buckling one of the three fingers. In this case, Section I of the finger is fully actuated, while Section II is passive. As a result, the finger is fully buckled towards the palm and formed a small area with radius r_s:

$$r_s = \frac{L_1}{\pi} \tag{7}$$

The proposed soft-robotic gripper could use three fingers manipulating objects ranging from r_s to $R_{\max}$, calculated using (2), (5) and (6).

III. Fabrication

The manufacturing process was based on silicone molding uses 3D printed molds as shown in Fig. 7. Silicone rubber *Dragon Skin 10* was used in this study.

The two sections of each soft robotic finger were fabricated together as shown in Fig. 7(a).The inner mold was 3D- printed with an ellipse profile. In order to isolate the two adjacent chambers, two inner rods were inserted in opposite directions and the middle region was filled with silicone to separate the chambers. The inner mold had a small vent on one side to insert air tube. The air tube was attached at the base of the finger for Chamber1, and the middle part for Chamber2.

A strain-limiting layer and reinforcement fiber were attached to each chamber to constrain expansion and generate bending in the desired direction Fig. 7(b). Glass fiber sheet with a shear strength of 320N per inch was used as the strain-limiting layer. The reinforcement fiber used was nylon fiber line with 0.6mm diameter. The outer protection layer were molded next, followed by sealing both ends Fig. 7(c)–(e). The finger nail could be molded together with the upper sealing end to improve small object handling Fig. 7(f). The palm was fabricated using a two-step molding process: 1) mold the lower layer with the supporting pillars; 2) mold the upper layer with the surface features Fig. 7(g)–(j). Finally, the gripper was assembled Fig. 7(k) with 3D-printed auxiliary components.

IV. Experimental Validation

In this section, the fabricated soft robotic fingers, palm, and gripper will be validated by experiments.

A. Single Finger Motion in Free-Space

In this experiment, we present the relationship between the supplied pressure and the bending motion of the finger. Since the proposed finger has two individual chambers, let *P1* be the supplied pressure of the Chamber1, and *P2* for Chamber2, different *P1* and *P2* values would result in various finger motions, as shown in Fig. 8. Without external load, the soft finger could reach a full bending of 360 degrees with 80 kPa supplied to both chambers.

B. Finger Compliance and Force Test

Another novel function of the proposed soft robotic finger is the passive compliance of the unactuated section. When the soft pneumatic actuator is pressurized, the deformation ability is determined by the supplied pressure. A zero-pressure section will exhibit the largest passive compliance. In this experiment, the soft finger was mounted to a mounting base, with a fixed board near the bending direction. The first finger section was actuated while the second section was kept passive. As the first section bent, the second section was gradually buckled against the board mounted opposite to the finger, with the entire first section in contact with the board at a very large contact area, as shown in Fig. 9. The passive compliance is especially useful for grasping large and flat objects.

Force test of soft fingers was conducted following a similar procedure to [17], where the soft finger was firmly mounted at the proximal tip, with the distal tip free, and the middle

Fig. 8. Finger bending at different pressure levels.

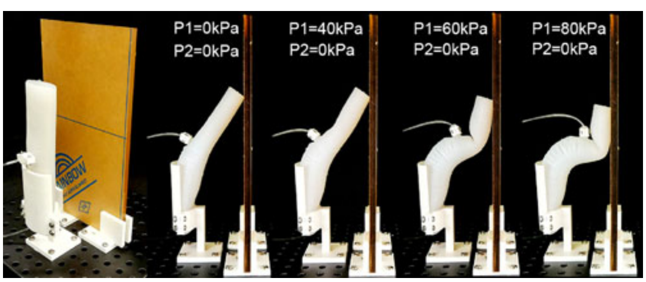

Fig. 9. Finger passive compliance test.

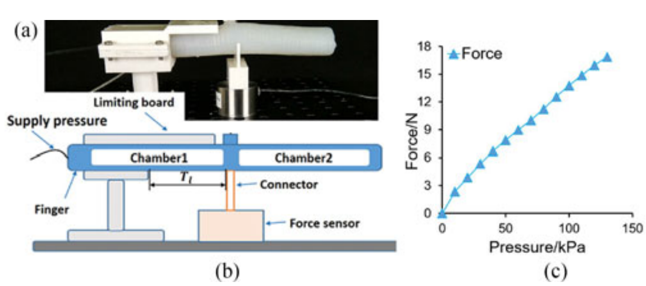

Fig. 10. Finger P-F test. (a) (b) Test platform. (c) Test result.

section of the actuator pressed against a fixed force sensor as shown in Fig. 10(a) and (b). Different pressures were supplied to the Chamber1 of the soft finger, the resulting forces were recorded from a force sensor in contact with the middle point. Each pressure level was repeated 6 times and averaged. The results exhibited good linearity as shown in Fig. 10(c).

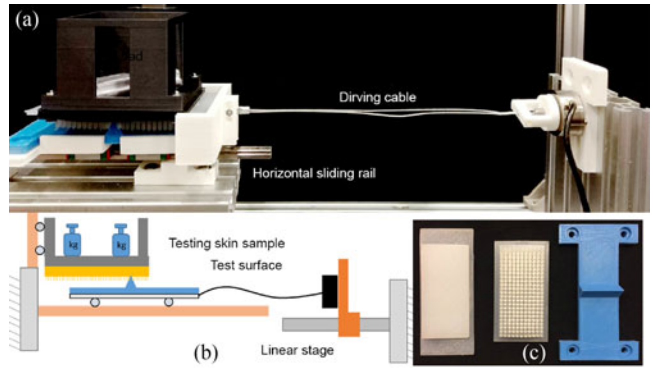

Fig. 11. (a) (b) Surface feature test platform. (c) Featured skin, smooth skin (2 mm), and printed bulge surface.

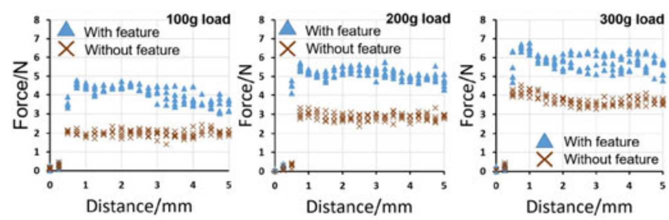

Fig. 12. Feature skin friction performance comparison.

C. Palm Feature and Palm Passive Adaptation Test

To evaluate the performance of the surface feature, a comparison test was conducted on the test platform presented in Fig. 11(a). Two kinds of test skins were made as shown in Fig. 11(c): a surface featured skin and a smooth surface skin. The process in Fig. 11(b) was using each test skin rubbing through a 3D-printed triangular bulge material shown in Fig. 11(c), which simulates the common edges and corners of objects. The test skin was clapped at the button of load connector, which mounted on one vertical slide rail. The printed bulge surface mounted on one horizontal slide rail and was driven by one tendon linked to the force sensor. Three different loads at 100 g, 200 g, 300 g applied on the load connector were used to adjust the contact positive pressure between the test skin and the bulge material.

The results in Fig. 12 showed significant improvements of contact friction for the group with featured skin compared to the group with smooth surface. The improvement suggests that the gripper with featured skin maintained grasping security, whereas the counterpart gripper without featured skin failed under the same contact force.

To assess the effectiveness of palm passive adaptation, two objects were tested: a sphere and a tetrahedron as shown in Fig. 13(a) and (b). The palm conformed well to the contour of each object, which suggests that the passive adaptable palm is easy to wrap edges, corners, and curved surface of objects.

D. Gripper Grasping Force Test

The fabricated gripper was tested for its grasping capability on a dedicated test platform as shown in Fig. 14(a). A dedicated test object of spherical shape was 3D-printed and connected by

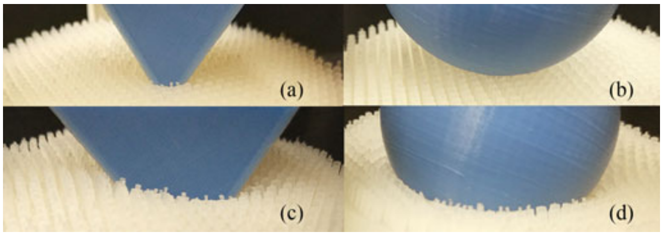

Fig. 13. Well compliance of passive palm. (a) (b) Test pyramid and sphere on the surface of palm, (c) (d) pressed indent into the palm.

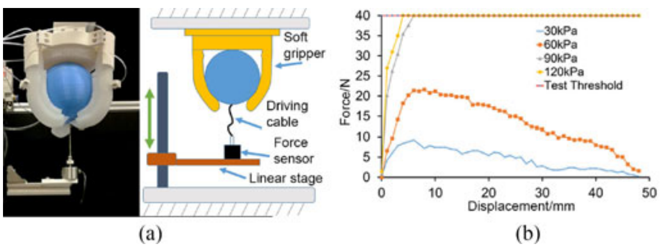

Fig. 14. (a) Grasping force test platform (b) Test result.

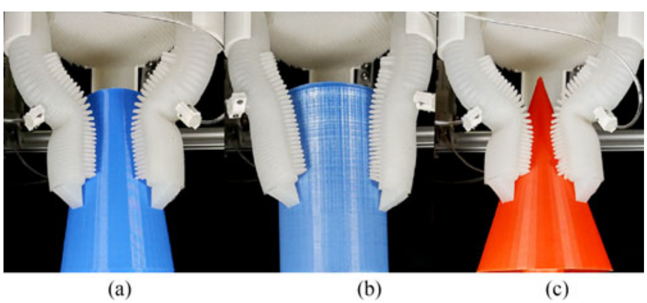

Fig. 15. Passive deformation. (a) Cylinder. (b) Slant cylinder. (c) Cone.

an inextensible cable to a force sensor mounted on a motorized platform movable along the vertical z-axis.

For each test trial, the soft gripper first grasped the object firmly at a pre-set pressure, then the force sensor was moved downwards by the motorized platform until the object was pulled out of the gripper. The experiment was repeated at 30 kPa, 60 kPa, 90 kPa, and 120 kPa input pressures. Forces were recorded throughout the entire test procedure. The test force threshold was set as 40 N and the test results were presented in Fig. 14(b). At 30 kPa and 60 kPa, the object could be pulled out, while at 90 kPa and 120 kPa the force reached the 40 N threshold earlier. This indicated that combining the contributions of the proposed soft actuator and the surface feature, the resulting soft gripper could carry 4 kg payload in practice, at a very low actuation pressure below 100 kPa.

E. Grasping Performance

In the final test, the soft gripper was used to grasp a series of daily objects. As shown in Fig. 15, three sample objects were 3D-printed with inclining sliding surfaces. With the passive first section and the proposed surface features, the soft gripper

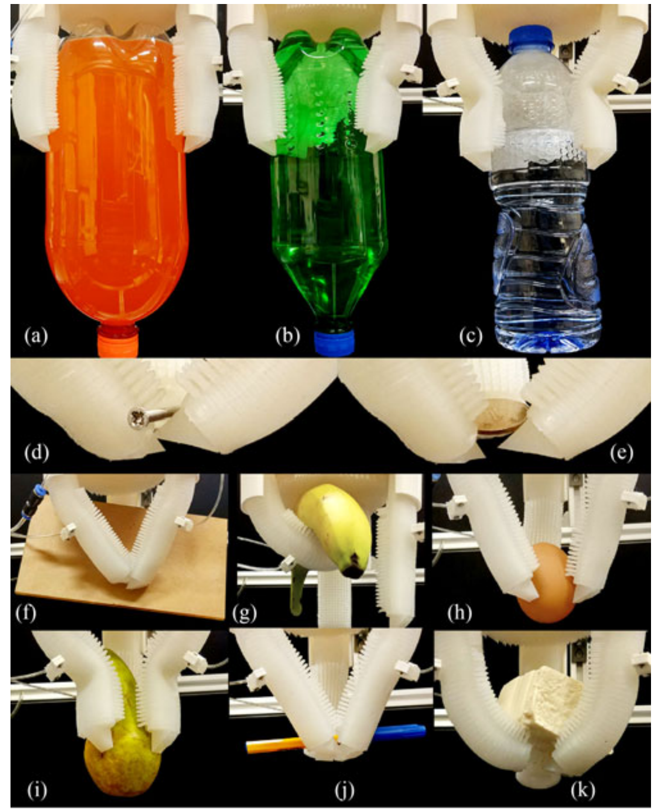

Fig. 16. Daily objects grasping. a) Large bottle. b) Medium bottle. c) Small bottle. d) Screw. e) Cain. f) Flat board. g) Barana. h) Raw egg. i) Pear. j) Pen. k) Tofu.

could handle all of the objects reliably. Next, the gripper was tested with a list of objects of ADL, as shown in Fig. 16. The soft gripper could grasp objects of various shapes, stiffness levels, and sizes reliably. The proposed surface feature helped to maintain a firm grasp even with odd-shaped objects. The proposed finger nail could pinch up small cylindrical objects as in Fig. 16(d) and (e).

V. Conclusions and Future Work

In this letter, a novel soft-robotic gripper design was presented with one passively adaptive palm and three soft pneumatic fingers. By using the proposed ellipse-profile, two-chambered finger, combined with the palm with passive chamber and the surface array pattern, the proposed soft gripper could achieve 40 N grasping force in practice, at a very low actuation pressure below 100 kPa. The two-section finger design offered a new possibility of passively buckling the first section during object grasping, allowing the gripper to conform to large convex-shape objects with reliable contact. The passively adaptive palm design offered additional conformation to convex object shape and improved grasping reliability without requiring additional actuation. The proposed surface-feature of raised cylindrical array pattern contributed significantly to improve grasping reliability. The small features on the surface could fit the shapes and features of the object, offering additional support, and help to maintain a firm grasp even under dynamic environments.

The fabricated actuators and gripper were tested on a dedicated platform, where the gripper could grasp a wide range of test samples and ADL objects of various shapes and sizes securely, even under external disturbances.

Future works include: characterizing the actuator behavior for further design refinements; detailed analysis on the featured surface on its influence on grasping performance; further investigation on soft grasping control and strategies for improving object adaptability and grasping reliability.

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