Soft Robotic Gripper for Packaging of Japanese Lunch Box

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***Abstract*— This study presented a prestressed soft gripper fabricated with 3D printing technology. The gripper can realize a large contact area while grasping and simultaneously generate large initial opening without deflating the soft actuators. The soft actuator was 3D printed as two separate parts: the soft chambers with a rigid connector and a cover to seal the chambers. The chamber part was stretched longitudinally and sealed by gluing the cover onto it. The actuator was then released, and an initial curl occurred due to the remaining prestress. Actuator fabrication and experimental tests were presented. A gripper consisting of four prestressed actuators was constructed and experimentally tested by picking-and-placing food materials in different weights and different sized containers. The results showed that the prestressed gripper could stably handle various types of food and still remain compact with a simple supporting system.**

I. Introduction

Soft robots have been receiving attention from researchers because the robots can be made sufficiently flexible to adapt to various tasks and safe to work alongside with human. Although many fundamental issues, such as the design principle, mathematical modeling, and control methodology, still remain unsolved, soft robots have shown many promising applications, such as a soft glove for rehabilitation [1], a jamming gripper for adapting to multiple tasks [2], and a soft gripper for biological sampling [3].

Pneumatically actuated soft grippers date back to the 1990s of the last century. Suzumori *et al.* first presented a microactuator with three degrees of freedom: pitch, yaw, and stretch [5]. A soft gripper with four microactuators was constructed to grasp and manipulate various objects. In recent years, many pneumatically actuated soft actuators and grippers were proposed, such as a starfish-like gripper made of Ecoflex and PDMS [6], three-finger [7] and four-finger [8] soft grippers made of Dragon Skin, a soft exoskeleton actuator for hand assistance and rehabilitation [9], a soft planar grasping manipulator [10], and a novel soft robotic hand for dexterous grasping [11]. In a recent review [12], Marchese *et al.* summarized the design and fabrication of soft robots driven by fluidic elastomer actuators and divided them into three categories: ribbed, cylindrical, and pleated, based on their morphology and chamber structures. The pleated type was widely used to construct soft grippers due to its abilities to generate a large curvature and force. The fabrication of the abovementioned soft robots was based on an iterated casting process, which is usually complex and time-consuming. Additionally, the manual fabrication and air bubbles remaining within the material often result in significant individual differences and limit the repeatability of robot performance.

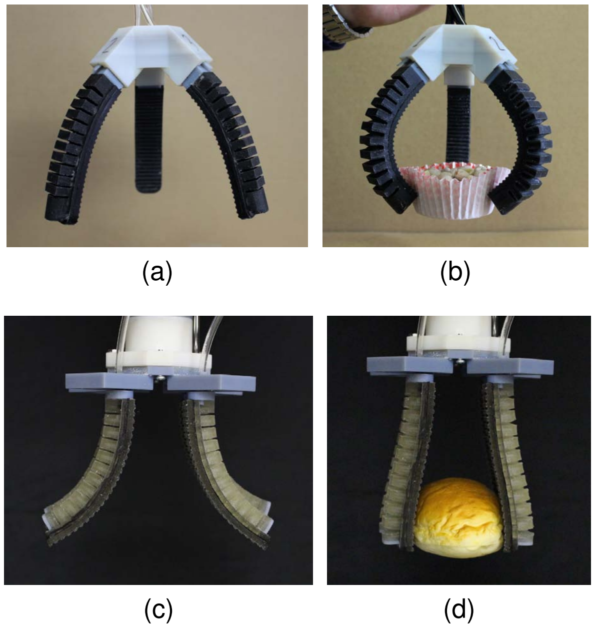


Fig. 1. The previously proposed three-finger gripper (a) and its ability to grasp a paper container filled with peanuts (b), the current prestressed gripper (c), and its test of lifting a bread (d).

To simplify the fabrication process, 3D printing technology has been adopted and several gripper designs have been proposed. MacCurdy *et al.* presented a two-finger gripper using printable hydraulic technology [13]. Peele *et al.* proposed a 3D printable soft actuator using projection stereolithography [14]. Recently, Yap *et al.* presented a high-force soft gripper fabricated with a common 3D printer and fused deposition modeling (FDM) [15]. This gripper is promising for handling heavy objects and it can lift as much as 5 kg, with a maximum payload-to-weight ratio of 1805%. However, the authors concluded that the gripper is not suitable for applications that require low pressure and delicate force due to the relatively hard material properties of NinjaFlex (Shore hardness of 85A).

In our previous work, we proposed a 3D-printed soft gripper for packing a Japanese lunch box [16]. Each actuator was printed as two separate parts and was fabricated in less than two hours. Due to the high resolution of the 3D printer, the homogeneity and repeatability of actuator performance were validated in terms of the pressurized bending angle [17]. A gripper with three such actuators can grasp various objects including a highly deformable paper container filled with peanuts. However, due to the angle of the initial configuration (Fig.

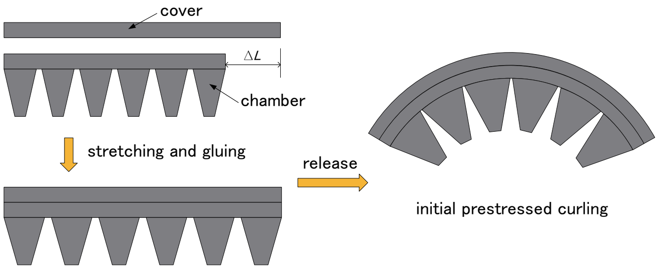


Fig. 2. Prestressed soft actuator.

1a), the contact area while grasping was limited and therefore affected the grasping stability (Fig. 1b). To increase the contact area, a parallel configuration is usually preferred, as presented by [3], [7], and [8]. However, parallel configuration limits the initial opening space, and only objects that fit in the opening space can be grasped. Otherwise, a vacuum system is required to deflate the actuator before grasping so a large opening can be achieved [8]. Accordingly, this requires a control system to switch between air inflation and deflation.

In this study, we presented a prestressed soft gripper that retains the same contact area (Fig. 1d) and creates a larger initial opening space (Fig. 1c) compared to the grippers with parallel configuration. Further, it only requires one air system to inflate the soft actuators. The remainder of this paper introduced the design, fabrication, and experimental tests of the soft actuator and gripper.

II. GRIPPER DESIGN

A. *Idea*

In nature, layered structures with different physical properties (*e.g.* expansion and shrinking) generate the natural folding [18] or wrinkling [19] phenomenon, such as a drying leaf or drying grape. This phenomenon is caused by the prestress generated at the boundary between two layers. Prestress is commonly used in the concrete engineering to increase the strength and fatigue resistance of concrete slabs [20]. In this study, we generated the prestress by stretching the soft chamber part and then gluing a non-stretched cover onto it (Fig. 2). After releasing, the actuator curled naturally towards the chamber side due to the prestress.

B. *Actuator Design*

The soft actuator (Fig. 3) consists of 12 air chambers, a rigid nail (1.5 mm thick) to limit the tip inflation, a rigid connector for easy assembly, a rigid stretcher for stretching the chambers, and a soft cover to seal the chambers. The soft actuator has a length of 87 mm before stretching, and the cover has a longer length (*e.g.*, 97 mm) than the soft actuator. The chamber part was stretched to the same length as the cover and then glued to the cover. After stretching and gluing, the stretcher was cut off, and the actuator was freely released to generate the initial curling. Wrinkle structure was designed on the cover surface to mimic human fingerprint and increase contact friction.

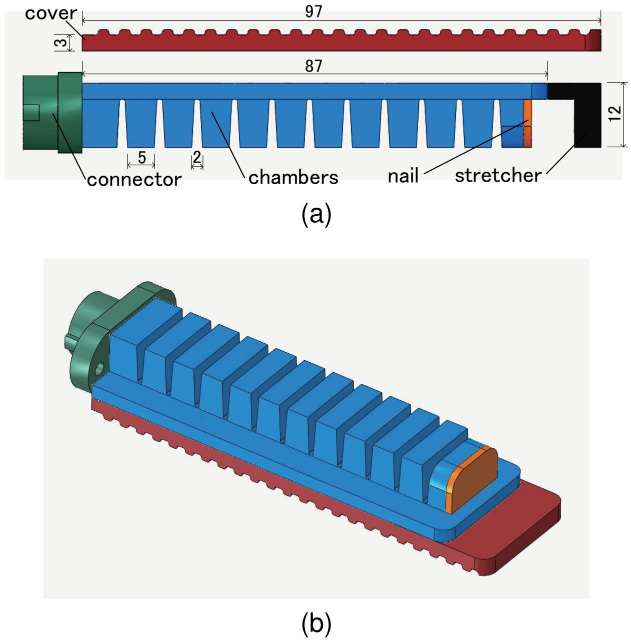


Fig. 3. Actuator design: (a) front view and (b) isometric view without the stretcher.

A rigid connector (Fig. 4a) on the actuator side and a rigid base (Fig. 4b) were designed for the easy assembly of a four-actuator gripper. To avoid using screws, we designed an insert-rotate-position mechanism on the connector and base. When assembling, the position convex (connector side) can be easily pressed through the convex enter (base side), and the connector is rotated counterclockwise (red arrow in Fig. 4b) to the concave position, where the connector can be fixed by fitting the convex into the concave. Additionally, we designed several position holes on the base and connector to guarantee the positioning. A cylinder pin can be easily inserted into the holes to fix the connector position. To grasp objects with different shapes, the base was designed to have two configurations for connecting the actuators: (1) the perpendicular configuration (Fig. 4c), in which the actuators are perpendicular to each other and is adaptable for grasping objects with circular shapes, and (2) the parallel configuration (Fig. 4d), in which the actuators are parallel and is suitable for grasping elongated objects. To adapt to objects with different sizes, the gripper base was designed to have two different openings (narrow and wide, as denoted by the different distances in Figs. 4c and 4d) for each configuration.

III. FABRICATION AND TEST

A. *Actuator Fabrication*

One soft actuator was printed as two separate parts using the Objet260 printer (Stratasys, MN, United States). The printer can simultaneously print soft rubber-like and hard resin materials. The cover (top image in Fig. 5) and the soft chambers (middle image in Fig. 5) were printed with the soft rubber-like material (TangoPlus). The rigid connector and the stretcher were printed using the hard material (VeroBlue). The soft chambers, the

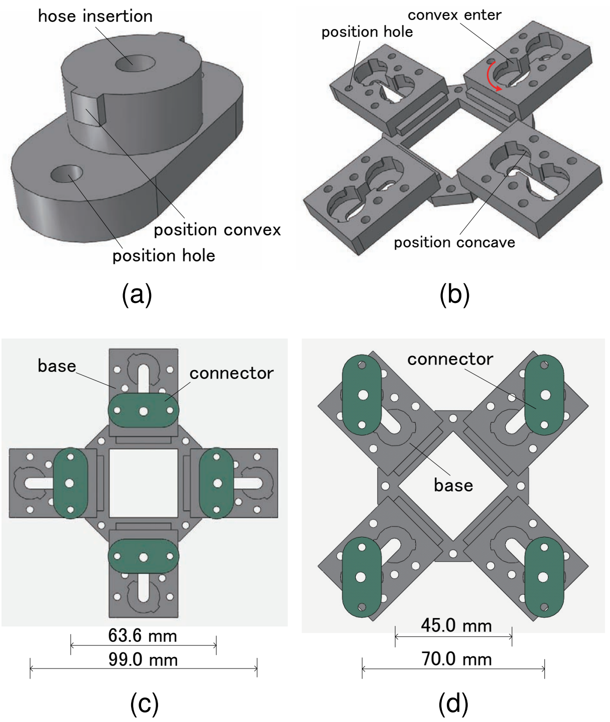


Fig. 4. The rigid connector (a) and base (b) for the easy assembly of a four-actuator gripper. The red arrow indicates the rotation direction. Two configurations for connecting the actuators are available: (c) perpendicular and (d) parallel configurations. Each configuration has two different base openings indicated by the distances.

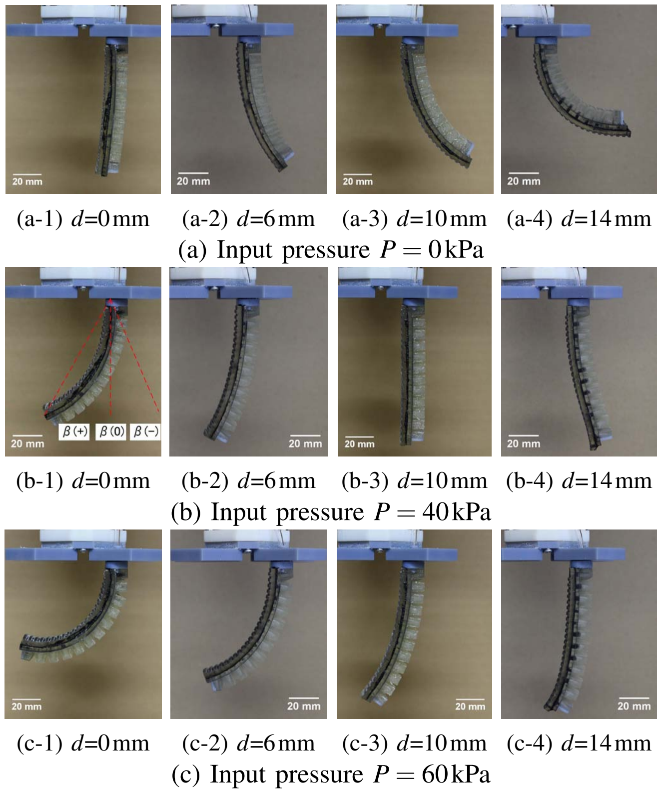


Fig. 6. Comparisons of the pressurized bending behaviors among the soft actuators without and with prestresses. d indicates the stretched distance.

connector, and the stretcher were printed simultaneously as an assembly. The chamber was stretched using a linear stage (bottom of Fig. 5). The cover was glued on the top of the soft chamber to seal them by using a rubber targeted glue (ThreeBond 1521B). The stretcher was then cut from the soft chamber to complete the fabrication of a single actuator. The initial curled states after stretches are shown in Fig. 6a.

B. Actuator Tests

An air compressor (JUN-AIR 3-4) and electro-pneumatic regulator (SMC ITV2030) were used to pressurize the soft actuator. Both soft actuators without and with prestresses were tested, and the differences were compared in terms of the pressurized bending angle β, which was defined as the angle between the vertical line and the base-to-tip line of the actuator (Fig. 6b-1). Examples using 40 kPa and 60 kPa pressures are shown in Fig. 6b and 6c. Each actuator was tested 5 times,

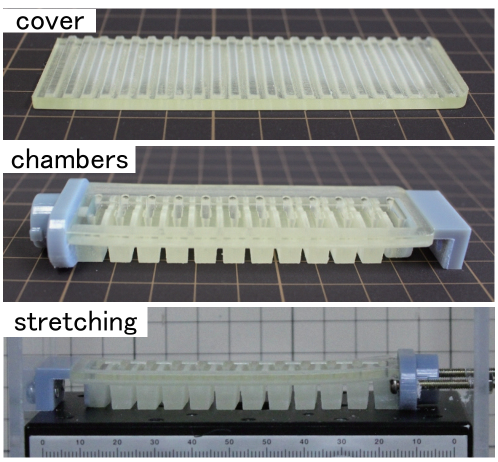


Fig. 5. Two fabricated parts of the soft actuator and the stretching snapshot using a linear stage.

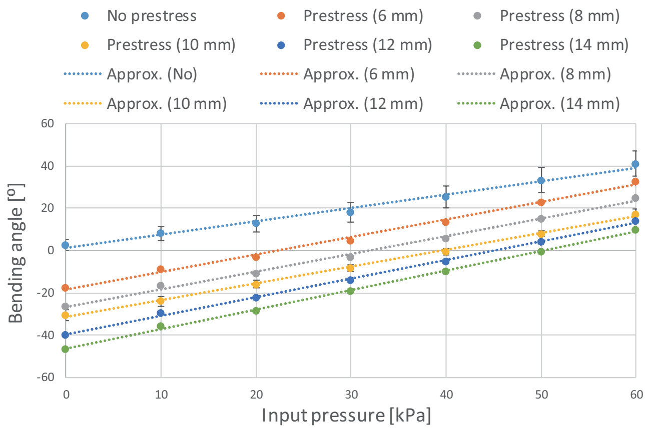
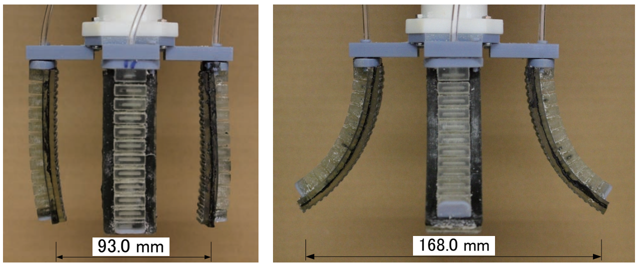


Fig. 7. Relationship between input air pressure and the bending angle for the actuators without and with prestresses.



(a) (b)

Fig. 8. The perpendicular configured grippers using the soft actuators: without (a) and with (b) prestress. The numbers indicate the initial openings for both grippers.

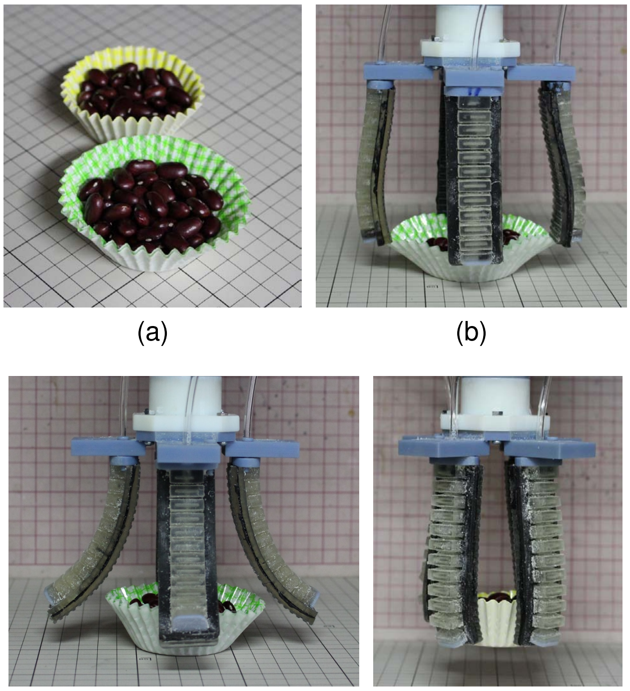
TABLE I
THE OPENING DISTANCES OF GRIPPERS IN DIFFERENT CONFIGURATIONS USING ACTUATORS WITH AND WITHOUT PRESTRESS

Configuration	Without prestress		With prestress	
	Narrow	Wide	Narrow	Wide
Perpendicular	57.0 mm	93.0 mm	132.0 mm	168.0 mm
Parallel	32.0 mm	63.0 mm	118.0 mm	139.0 mm

and the bending angles are plotted in Fig. 7 against different input pressures. We found an approximately linear relationship for all soft actuators despite the amount the actuator was stretched. We did not find significant individual differences in bending angle for all actuators. The largest standard deviations were 4.56° and 1.96° for actuators without and with prestress, respectively. Apparently, the prestress increased the actuator stiffness and reduced the individual difference. Interestingly, different stretches yielded approximately parallel curves. This indicates the influence of the prestress is independent from the input pressure. Pressures of 30 kPa and 40 kPa were required to straighten the soft actuator after an 8-mm and 10-mm stretch, respectively. After a 14-mm stretch, the pressurized bending behavior became inhomogeneous (Fig. 6c-4). To balance the initial curling and pressurized bending behavior, we chose the soft actuator with a 10-mm stretch to construct our soft gripper.

C. Gripper Assembly

The base (Fig. 4) was 3D printed, and the grippers using the actuators without and with prestress (10-mm stretch) were assembled. Examples with the perpendicular configuration are shown in Fig. 8 for comparison. We summarized the opening distances of the grippers with and without prestress in Table I. The gripper with prestressed actuators was found to generate more than 2 times larger opening distances compared with the gripper without prestress. Fig. 9b shows a case of entering failure when using soft actuators without prestress. With the prestressed actuators, the target could easily enter the grasping space (Fig. 9c), and the gripper could lift the target without significant effort (Fig. 9d).



(a) (b) (c) (d)

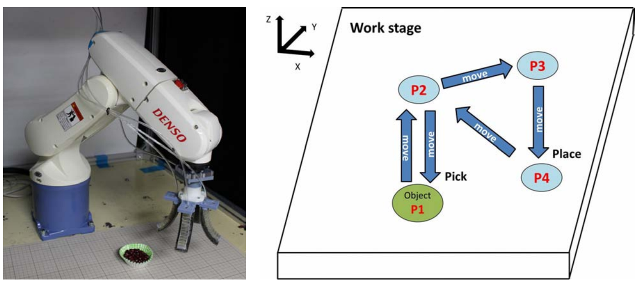
Fig. 9. Experimental snapshots: (a) targets of red beans filled in paper containers, (b) entering failure using the gripper without prestress (wide opening), (c) successful enter using the gripper with prestress (narrow opening), and (d) lifting the target with the prestressed gripper.

IV. EXPERIMENTS

In our experiments, we focused on handling food materials filled in soft paper containers which appear commonly in a Japanese lunch box. Several million lunch boxes are consumed every day in Japan and they are generally packaged by human labors [22]. Our current work focuses on the automation of lunch box packaging.

A. Weight Grasping Test

To test the grasping ability, the girpper was mounted onto a commercial DENSO robot arm (Fig. 10a), and a pick-and-place motion was programmed considering the working pattern of packaging a lunch box. As shown in Fig. 10b, the target was placed at position P1, and the gripper was initially located



(a) (b)

Fig. 10. The prestressed gripper mounted on the DENSO robot arm (a), and the motion procedure for the pick-and-place test (b).

TABLE II

EXPERIMENTAL RESULTS OF THE WEIGHT GRASPING TESTS

Weight (g)	50.7	60.2	70.3	73.2	75.2	80.2
Trial no.	10	10	10	10	10	10
Succeed no.	10	10	10	9	8	6

TABLE III

TEST RESULTS OF FOOD MATERIAL GRASPING

Target	Size (mm)	Weight (g)	Succeed No. P=50kPa	Succeed No. P=60kPa
Rec-L (Spaghetti)	100×75×35	40	10	10
Rec-M (Higiki)	85×75×30	30	10	10
Oval-L (Spaghetti)	118×72×30	40	10	10
Oval-S (Ohitashi)	90×52×30	30	10	10
Cir-S9 (Higiki)	Φ75×H30	30	10	10
Cir-S8 (Ohitashi)	Φ65×H26	30	10	10
Cir-S6 (Higiki)	Φ55×H23	30	10	10
Bread	96×58×41	26.6	10	10
Fried chicken	59×41×22	29.7	6	9
Salmon	73×36×9	19.6	8	8
Omelet	49×24×10	11.3	10	10

at P2. When the program started, the gripper moved down to grasp the target and lift it back to P2. Before placing the target at position P4, the arm moved the gripper in the horizontal plane to position P3. After releasing the target, the gripper was brought back to P2 and waited for the next circle. The total procedure was completed in 10 seconds. The inflating and releasing of the gripper were manually controlled using two switches through two solenoid valves (VQ110-5M-M5, SMC). The target is a yellow paper container filled with red beans. The starting weight of the target was equal to 50 g and increased by 10 g every time the gripper successfully completed 10 pick-and-place tests. If the gripper failed two times using one weight, the red beans were reduced by 5 g, and the test was repeated. If successful, the weight was increased by 1 g every time, and the test was repeated until the gripper failed more than 3 times at a final weight. The air pressure was set to 60 kPa as a constant in all of the tests. The succeeded trial numbers and the corresponding weights are listed in Table II. Considering an 80% success rate, the prestressed gripper could pick-and-place a target with a weight of 75.2 g, which is heavier than most of the dishes in a Japanese lunch box.

B. *Grasping Tests of Food Materials*

Grasping tests of real food materials (Fig. 14) were carried out. Different sized paper containers were filled with spaghetti, higiki, and ohitashi, which often appear in Japanese lunch boxes. Ten pick-and-place tests were performed for each target, and a 10 s lift without dropping was considered a successful lift. The weights and approximated sizes of all of the targets are listed in Table III, with the successful trail numbers using pressures equal to 50 kPa and 60 kPa. Examples of successful trails are shown in Fig. 12. Grasping and lifting food materials in paper container were relatively stable, and there were also no difficulties in lifting a bread and a piece of omelet. However, picking up targets with irregular shapes, such as fried chicken and salmon, had lower success rates compared with other targets. Increasing the input pressure could increase the success rate of picking up the fried chicken but did not affect the performance of picking the salmon because of the thin and irregular geometry. Fig. 12d shows a case in which air leaked (chamber and cover were separated) from the glued interface at the actuator tip.

V. DISCUSSION

Soft robots development involves soft materials, robot design, modeling, fabrication, control, and experimental tests. As stated by Rus *et al.*, soft materials are essential for creating soft robot bodies [23]. Using 3D printing technology, multiple materials (soft to hard) can be simultaneously printed and the fabrication process can be significantly simplified. Due to the high printing resolution, the homogeneity and repeatability of the fabricated robot can be better guaranteed. Additionally, the mechanical properties of the printable soft materials are well defined. Using the parameters in the datasheet, we could simulate and predict the behavior of the soft actuator presented in this paper. The 3D printable soft materials also have disadvantages. The softest printable material is harder than Ecoflex but similar to Dragon Skin 30. The stretchability is significantly less than Ecoflex or Dragon Skin. The maximum elongation of the softest material is approximately 100%.

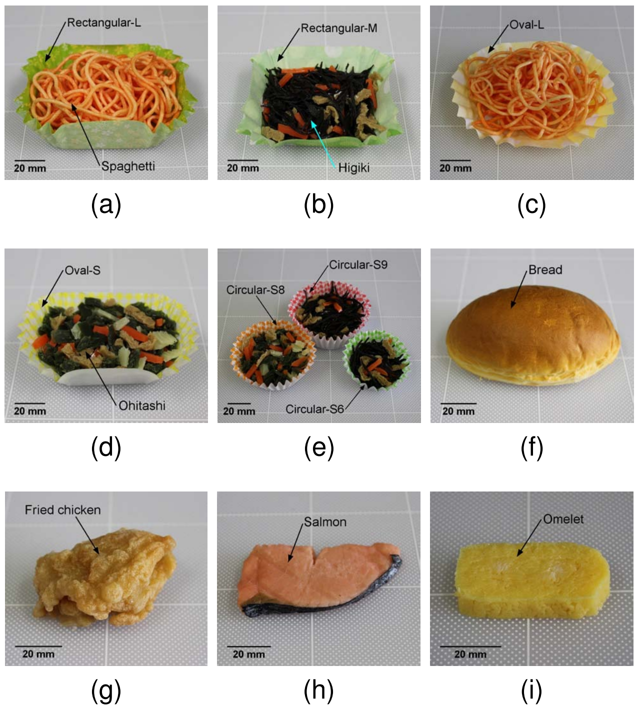


Fig. 11. Tested targets of real food materials.

The prestressed gripper presented in this study could generate initial openings more than twice as large as the gripper without prestress and simultaneously maintain the large contact area while grasping. It improved the adaptability of the gripper and maintained a simple and compact system. One downside of the gripper is that extra pressure is required to overcome the prestress. We have also investigated a pre-curled actuator without prestress. Actuation tests showed similar bending behavior comparing to prestressed actuator. However, the pre-curled actuator requires complex design, increases gluing difficulty, and fills more support material into the air chambers. The resulted surface after removing support material significantly affected the gluing quality.

We designed an insert-rotate-position mechanism on the connector and the base for easy assembly without screws. This is important for industrial applications to improve the efficiency of changing soft actuators and configurations. While designing the base, adaptability to different sizes and shapes of the possible grasping targets was considered. Configurations and openings can be easily interchanged according to the applications.

We found a linear relationship between the input pressure and the bending angle. This could help to predict the pressurized behavior of the prestressed actuator. Weight grasping tests showed that the prestressed gripper could lift a maximum weight of 75.2 g with an input pressure of 60 kPa, which is sufficient for packaging most dishes in a Japanese lunch box. Grasping tests of real food materials showed that the proposed gripper can successfully handle regularly shaped food materials and chopped food materials in paper containers. It had slight difficulty in picking up an irregularly shaped thin salmon fish.

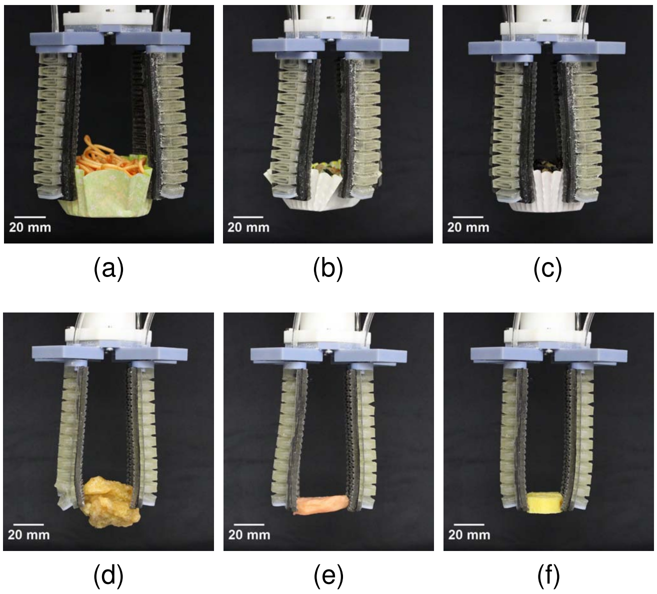


Fig. 12. Successful grasps: (a) spaghetti in a large rectangular container, (b) ohitashi in a small oval container, (c) higiki in a No. 9 circular container, (d) fried chicken, (e) salmon, and (f) omelet.

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