Proceedings of the 2021 IEEE
International Conference on Robotics and Biomimetics
December 27-31, 2021, Sanya, China

2021 IEEE International Conference on Robotics and Biomimetics (ROBIO) | 978-1-6654-0535-5/21/$31.00 ©2021 IEEE | DOI: 10.1109/ROBIO54168.2021.9739548

A Soft Gripper Driven by Bellow Actuators and Twist Actuators for Dexterous Grasping

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Abstract— **Human hands are dexterous and capable of grasping objects of various shapes and manipulating the objects within the hands. Conventional soft grippers are able to grasp, but few can manipulate objects within the grippers. To fill this gap, this work designs a soft gripper with soft bellow actuators and soft twisting actuators, which can adaptively clutch objects and handle them in different postures in the gripper. Compared with the previous rigid grippers, this soft gripper possesses a higher adaption to complex shapes and fragile objects and greater reliability against a strong impact due to its compliance. We demonstrate its successful grasping on more than 15 daily items of different profiles and surface textures, rolling and picking up a piece of thin plastic film, and reversing the posture of a ball within the gripper. It has also survived brutal hammer attacks and robustly grabbed an object while experiencing strong impacts.**

I. INTRODUCTION

Grasping and manipulation are ubiquitous in the daily activities of animals, such as preying, climbing, feeding, and fixing [1], [2], which are critical for their survival. These functions are also necessary and extensively applied in industrial assembly, robot-assisted surgery, and outer space exploration [3], [4]. Since the last century, many researchers dedicated themselves to studying robotic grippers to replicate animal hands' dexterity and versatility [5]–[7]. Inspired by human hands, abundant robotic grippers have been developed, including the Stanford/JPL hand, DLR/HIT Hand, and Utah/M.I.T. hand [8]–[10], primarily through a highly anthropomorphic design in structure and a complex integration of joints and electronics. Due to the challenges on developing actuators of small form factors, underactuated structures become an acceptable option [11], although sacrificing some of the flexibility and degrees of freedom. Only a tiny fraction of these robotic hands can conduct in-hand manipulation, which is more complicated than simple grasping even for a person. In recent studies, robotic hands with highly non-anthropomorphic features have emerged. For instance, using rollers or conveyors at the fingertips of the grippers, researchers have completed complicated tasks, e.g., rotating the orientation of a cube and grasping a soft tissue [12], [13].

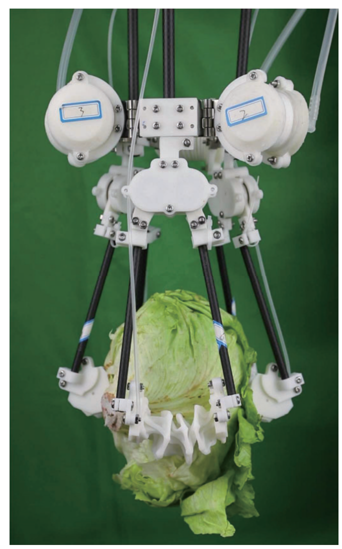

Fig. 1. The soft gripper.

However, made of rigid components, the conventional robotic grippers can barely grasp objects of being soft and fragile or complex shapes. As promising alternatives, soft robotic grippers are attracting increasing interest from scientists and engineers recently. Based on materials of low Young's modulus, the soft grippers show great adaptability to the shape of the gripped objects due to the soft materials compliance. For example, soft robots can grasp shoes, bananas, and fragile eggs [14]–[19]. Nevertheless, few soft robotic grippers can practice in-hand manipulation until now [20], [21].

Herein, we propose a soft gripper integrating soft bellow actuators and soft twisting actuators for grasping and in-hand manipulation as shown in Fig. 1. By controlling the shrinkage of the soft bellow actuators, this gripper can deform the

*This work is supported by the National Natural Science Foundation for Young Scientists of China (51905256), the Natural Science Foundation of Guangdong Province of China (2020A1515010955), the Natural Science Foundation of Liaoning Province of China (State Key Laboratory of Robotics joint funding, 2021-KF-22-11) and the Science, Technology and Innovation Commission of Shenzhen Municipality (ZDSYS20200811143601004).

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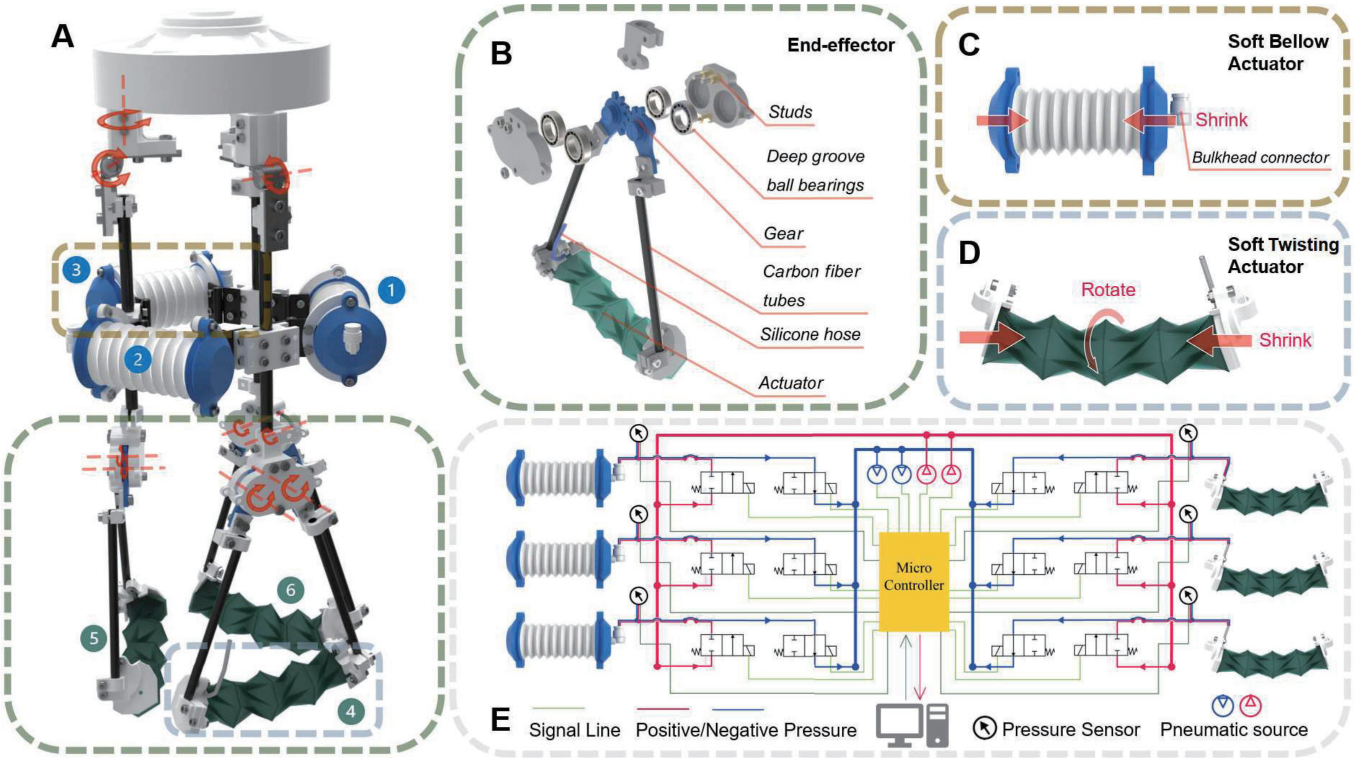

Fig. 2. Overview of the structure and driving system of the soft gripper (A) The structure. (B) The structure of an end effector. (C) The soft bellow actuator. (D) The soft twisting actuator. (E) The pneumatic circuit diagram.

relative positions of the end effectors to clamp different objects. The soft twisting actuators at the fingertips can generate a lateral force to alternate the grasping posture, e.g., rolling the object. Based on soft materials, this gripper can passively adapt to the shapes of the objects and has great robustness in grasping and reliability to an impact.

The contributions of this works are as follows. We propose a soft gripper capable of both adaptive grasping and in-hand manipulation. We design a soft actuation structure based on a six-bar mechanism driven by soft bellow actuators and three end-effectors driven by soft twisting actuators in this gripper. For the clutching structure, we build a kinematic model to explain the actuation mechanism and the shape formation of the gripper. With this gripper, we demonstrated its versatility by grasping various daily objects, e.g., a ball, a pitaya, a corn cob, and a celery stalk, and measured and compared the grasp forces on these items to showcase the capability of adaptive grasping. This gripper also displayed its in-hand manipulation capability by reversing the posture of a ball within the gripper and rolling and picking up a piece of thin plastic film. Due to the reliability of the soft materials, this gripper has survived a brutal hammer crash.

The structure of this paper is as follows. The next section introduces the design and control system of the gripper and the working mechanism of the gripper. Section III establishes the kinematics model of the grasping mechanism. Section IV displays and discusses the experimental results in this work.

II. Design and Fabrication

A. Gripper Design

The structure of the soft gripper is shown in Fig. 2A. To facilitate grasping, we design three identical end effectors to contact objects, as shown in Fig. 2B. Each end effector is made of a rigid chassis composed of carbon fiber tubes and passive joints. The end effectors are connected to the top basement with revolution joints. Each two end effectors are connected by a soft bellow actuator. These actuators shrink while being vacuumed as shown in Fig. 2C. By driving Actuator 1, 2, and 3, we can tune the relative angle and position of the three end effectors. On the distal end of each end effector is a soft twisting actuator. The rotary actuators are made of soft shells with twisted shapes. While being vacuumed, they rotate and shrink simultaneously. By driving Actuator 4, 5, and 6, the end effectors can generate an in-plane force on the object. By intentionally controlling these six actuators, we can vary the relative position of the three end effectors and roll the object to facilitate grasping and in-hand manipulation.

B. Driving and Control System

The soft gripper contains six pneumatic actuators driven by four miniature diaphragm pumps (model C183, Parker Inc.), as shown in Fig. 2E. The actuators are inflated and deflated by the pumps via twelve two- and three-way miniature solenoid valves and two relief valves. The power of pumps can be controlled by a micro-controller unit with PWM output.

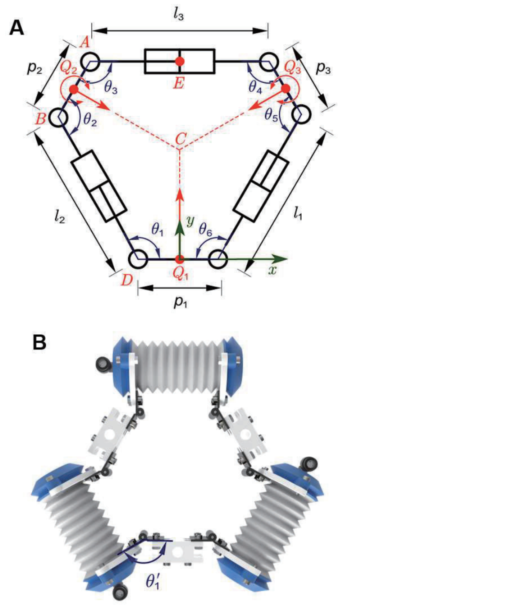

Fig. 3. The six-bar linkage mechanism with the soft bellow actuators. (A) The schematic diagram. (B) The 3D drawing.

The air pressure of the soft actuators is controlled in a closed-loop system. Controller (model ATMega2560) obtains the real-time air pressure data of the six soft actuators by the pressure sensors (model XGZP6847, CFSensor) acquired through 16-bit ADC (model ADS1118) and transmits the data to the computer. By comparing the aim pressure values coming from the computer and current pressure, the controller determines the open/closed states of the valves. The air pressure in the soft actuators is controlled by a bang-bang controller. When the measured pressures in the actuators drop below the set-points. The controller opens the inflation relief valves. Oppositely, when the measured pressures rise above set-points, the controller opens the deflation relief valve instead [22], [23].

C. Fabrication and Assembly

The soft bellow actuators were made by a 3D printer (Z600, HORI) with thermoplastic polyurethane (TPU) (Polymaker. Inc.). The design parameters are displayed in Fig. 4. During the printing, we set the layer height as 0.1 mm, printing speed as 30 mm/s, and print head temperature as 220 °C.

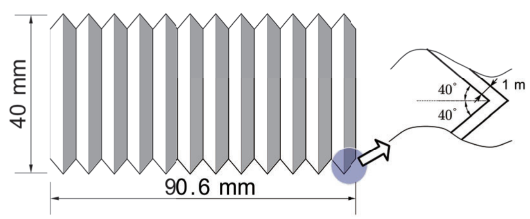

Fig. 4. The structure and design parameters of the soft bellow actuator.

The soft twisting actuators are composed of a softshell with twisted ridges. To make the softshell, we 3D printed the mold at first, and then filled it with the prepared silicone and rotated the mold to coat silicone homogeneously on the mold inner wall (see Fig. 5). After the silicone viscosity increased and the thickness of the gel became stable, we cured the silicone by heating (45°C) for 30 minutes in an oven. Then the elastomer shell was peeled off from the mold. With only this softshell, the actuator will unfavorably collapse in the radial direction. To avoid this deformation and generate a larger rotation motion, we inserted three internal skeletons made by Polylactic Acid (PLA) to support the structure as shown in Fig. 5.

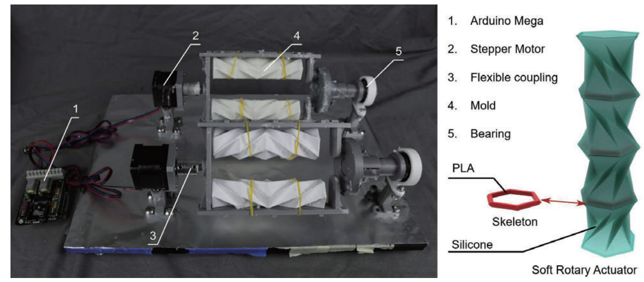

Fig. 5. The coating device and the structure of the soft twisting actuator.

III. Kinematics Modeling and Analysis

The deformation of the gripper is mainly driven by the three bellow actuators. These actuators are connected with each other by joints in the same plane. They can be simply regarded as rigid cylinders that can only move linearly. The deformation of the gripper is governed by the planar six-bar linkage mechanism as shown in Fig. 3A. By controlling the shape of this planar linkage, we can arrange the three end effectors for different shapes to grasp various objects.

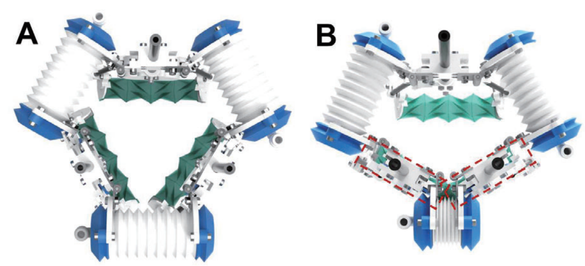

Fig. 6. Formations of the three end effectors. Driven by the six-bar linkage, the three end effectors together can become (A) a regular triangle, or (B) an obtuse triangle shape to grasp objects of different shapes.

For the actual model of hinges and mechanism sketch, the following conversion equation exists,

$$\theta_i' = \frac{3\pi}{2} - \theta_i, \tag{1}$$

where θ_i' represents the angle of the hinges, as shown in Fig. 3B. The rest parameters are also displayed in this figure. We can also have the following relationship,

$$\overrightarrow{Q_1D} + \overrightarrow{DB} + \overrightarrow{BQ_2} + \overrightarrow{Q_2A} + \overrightarrow{AE} + \overrightarrow{EQ_1} = 0. \tag{2}$$

In the structural sketch, we have,

$$p_1 = p_2 = p_3 = p. \tag{3}$$

For the x-direction projection, there are,

$$\begin{aligned} &\frac{1}{2}(l_3 + \Delta l_3) + p_2 \cos(\pi - \theta_3) \\ =&\frac{1}{2}p_1 + (l_2 + \Delta l_2)\cos(\pi - \theta_1); \end{aligned} \tag{4}$$

$$\theta_1 + \theta_2 + \theta_3 = 2\pi; \tag{5}$$

$$l_2 \cos\theta_1 - p\cos\theta_3 = \frac{1}{2}(p - l_3). \tag{6}$$

Assuming that $L_1 = L_2 = L_3$ and the point Q_1 is fixed, i.e., when the rod where Q_1 is located in a rack. Using the rod group method to build the system, that is, the projection in the direction of Q_2C, with Q_1 as the origin, we have,

$$(l_2 - L_2)\sin\theta_1 = \frac{\sqrt{3}}{6}l_3 + \frac{\sqrt{3}}{3}L_2\cos\theta_1, \tag{7}$$

where L_i represents the initial length of the bellow actuators, and l_i is the actual length of the bellow actuators. Δl_i refers to the difference between L_i and l_i.

Fig. 7. The objects used for the grasping test of the soft gripper. (A) Items with a regular shape, including a drink can and a frustum. (B) Items with complex shapes, including a sweet potato, an avocado, a pitaya, and a cabbage. (C) soft and fragile items, including two cake slices, a bread slice, a block of tofu, and a head of broccoli. (D) Long items including a corn cob, a media controller, a bubble level, a celery stalk, and a banana.

IV. Experimental Results

A. Object Grasping

According to the kinematics analysis aforementioned, the middle six-bar linkage mechanism can deform to various shapes to facilitate grasping. For instance, if Actuator 1, 2, and 3 shrinks simultaneously, the six-bar linkage is a regular hexagon, and the end effectors become a triangle shape, as shown in Fig. 6A. This shape can grab most of the objects with the assistance of the compliance of the actuators, which can adapt to the shape of the objects to a certain degree to grasp objects with regular shapes (e.g., a drink can) or complex shapes (e.g., a sweet potato and a pitaya) in Fig. 7. Since the end effectors of the gripper are soft actuators, which can deform themselves to adapt to the objects, this gripper can also grasp soft or brittle objects (e.g., a bread slice and a block of tofu).

However, the regular triangle formation of the end effectors cannot handle all of the profiles of objects, e.g., a long slender object. Instead, we can actuate the six-bar linkage to make the three end effectors become another shape (an obtuse triangle shape) as shown in Fig. 6B. With this shape, the soft gripper can pick up, e.g., a corn cob, a media controller, and a banana as shown in Fig. 7D.

Furthermore, we tested the grasping force using a universal testing machine (C42.503Y, MTS). The gripper was inversely fixed on the ground, and an object was mounted on the moving stage of the testing machine by an adapter. During the test, the object was pulled up at a speed of 0.833mm/s when all the soft actuators are vacuumed (from -20 kPa to -40 kPa). The grasping force on the objects wass acquired with a load cell (LPS.253). By this setup, various objects of different shapes and surfaces are tested, respectively as shown in Fig. 7. At each condition, we have at least 3 trials.

As shown in Fig. 9, during the pulling test, the grasping force on the ball increases at the beginning and then diminishes since the grasping area (the area enveloped by the three contact points between the objects and the three end effectors) becomes larger and then smaller, when the air pressure in the soft actuators is -20 kPa. This tendency is similar for different air pressures. A similar curvature can also be found in the test on the pitaya and frustum. This phenomenon results from that the soft bellow actuators (Actuator 1, 2, and 3) generate a larger blocking force when their shrinkage is small. Due to a similar reason, the grasping force on a drink can has less fluctuation during the pulling test since its cross-section has little variance. As shown in Fig. 9, the pulling force on the pitaya has a more considerable fluctuation and noise because it has a rough surface texture.

The maximum grasping force on different objects is compared in Fig. 8. Generally, the grasping force increases linearly with the air pressure for different objects. The grasping force on the pitaya is larger than the others since its cross-section area is the largest and the surface is rough. The grasping force on the orange is the smallest among the force on those objects when the negative air pressure is -20 kPa. However, when the negative air pressure increases to 40 kPa, it becomes medium among various objects' grasping force. Perhaps this phenomenon is because the orange is soft and has more deformation and adaptation with the soft gripper when the negative pressure is larger.

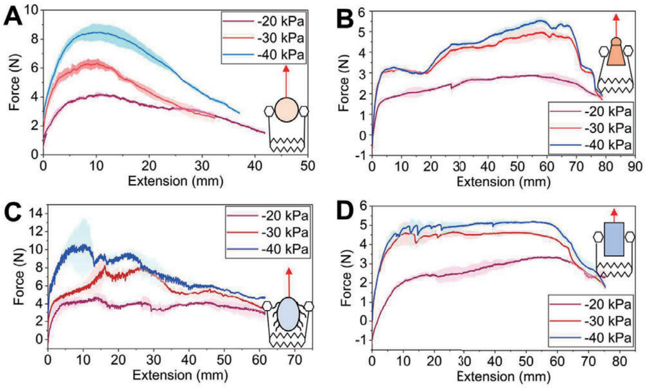

Fig. 8. Grasping force for different extension distances on (A) a plastic ball, (B) a pitaya, (C) a frustum, and (D) a drink can.

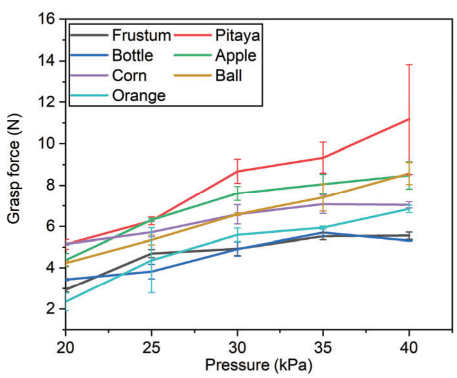

Fig. 9. The grasping force for different objects.

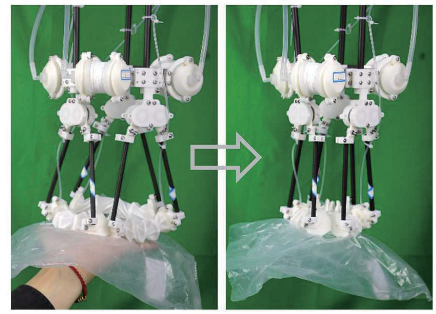

Fig. 10. The gripper catches a piece of thin plastic film using the rotary actuators.

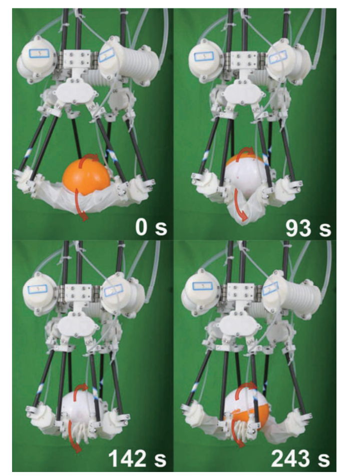

Fig. 11. Rolling a ball within the gripper.

B. In-hand Manipulation

The end effectors, made of soft twisting actuators, can generate rotating motion while being vacuumed and thus endow more versatility to the gripper. For example, with the rotation of the soft twisting origami actuator, the gripper can catch thin and flat materials, e.g., a piece of thin plastic film, as shown in Fig. 10. which is impractical for conventional soft grippers. During this grasping, we vacuumed all the actuators and generated rotation on all the end effectors.

With the rotation of Actuator 4, 5, and 6, we can complete more complex manipulation in the gripper, e.g, rolling a ball. As shown in Fig. 11, at first, we vacuumed Actuator 1, 2, and 3 to grasp the ball. Then we vacuumed Actuator 4 and generate a rotation motion in the middle of Actuator 4, which rolled the ball with an angle. Then we inflated Actuator 4 to its initial state and repeated these steps several times. Consequently, the top and bottom of the ball were reversed in 243 s, as shown in Fig. 11.

If all the soft twisting actuators work together, the object is expected to be lifted. The lifting height of a balloon was tested by a laser distance sensor (Panasonic HG-C1200) as shown in Fig. 12. The displacement of the object is 28.37 mm for each actuation cycle. After being vacuumed, the displacement of the objects (and the rotation of the actuator) increases stably until the maximum value and keeps almost constant until the valve becomes open.

C. Reliability Test

Finally, the reliability of the soft gripper was tested. We attacked it with a hammer several times, and it survived successfully, as shown in Fig. 13A, since the compliant materials absorbed the impact energy. It could also robustly grab an object with the compliant material even though experiencing a strong impact, as shown in Fig. 13B. These features can be beneficial for the application of cooperative robots that contact and collaborate with human beings due to the gripper's great safety, reliability, and tolerance to impacts.

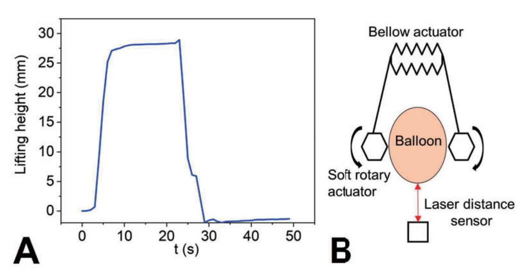

Fig. 12. Displacement measurement while lifting the balloon within the soft gripper using the rotary actuators. (A) Experimental results of the lifting height of the balloon. (B) The illustrative diagram of the measurement setup.

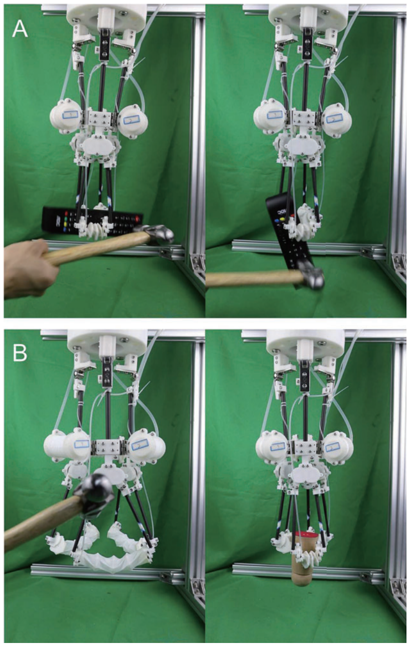

Fig. 13. Impact testing. (A) The soft gripper robustly grasps a media controller while being impacted. (B) The soft gripper survives brutal hammer attacks.

V. Conclusion

This work devises a soft gripper capable of both grasping and in-hand manipulation. We design the structure with three end effectors and drive them by soft bellow actuators for adaptive grasping. This gripper completes the grasping test successfully on more than 15 daily items of various shapes and material properties, including a ball, tofu, and celery. We embed soft twisting actuators on the fingertips of the end effectors to generate torque for the manipulation within the gripper. The gripper exhibits this capability by rolling a ball and shifting a piece of thin paper. Impact test shows that this dexterous gripper has great reliability and robustness too.

At this stage, the soft gripper cannot grasp and manipulate an object accurately and automatically. We can improve it on this aspect by more sophisticated modeling on the actuators and transmission structure. We can also demonstrate more complicated in-hand manipulation tasks by exploring better controlling strategies in the future.

Acknowledgment

The authors acknowledge the assistance of SUSTech Core Research Facilities.

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