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Lip-Inspired Passive Jamming Gripper

Jooyoung Hong, Dhruv C Mathur, and Joohyung Kim

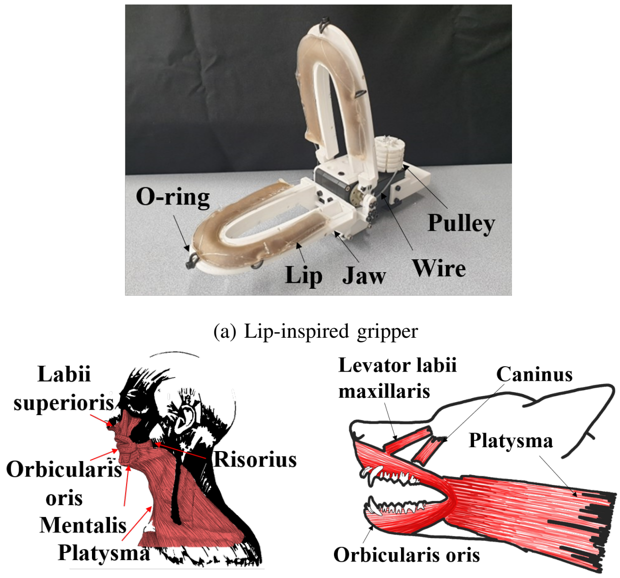
***Abstract*— Soft robotic grippers have an advantage in grasping objects with various shapes as compared to conventional rigid grippers. Soft grippers have been researched to hold objects which are fragile. Recently, researchers have utilized the jamming effect using particles, which makes stiffness varied to hold the objects tightly. In this paper, we propose a lip-inspired soft robotic gripper. This gripper is motivated by animals' oral structure, especially from lips. Lips have various functions: holding, re-grasping, sucking in, and spitting objects. This gripper especially focuses on the functions of holding and re-grasping. The lip-pouch is fabricated including granular particles inside for passive particle jamming. This paper describes how the gripper is motivated by lips with explanations of the anatomy and functions of the lip. An explanation of the passive particle jamming effect follows. We validated the capability of the lip-pouch of the gripper with various objects through experiments. Moreover, we demonstrated re-grasping objects with this gripper.**

I. INTRODUCTION

Robotic grippers, which are usually equipped at the end of manipulators, are required to grasp and manipulate objects where autonomous tasks are likely to be performed. Researchers have developed grippers to grasp various objects. Most of conventional grippers have rigid links and joints [1]. These grippers have a high payload, but they are not good at grasping complexly-shaped objects, and need complicated control techniques for grasping fragile objects. To overcome the limitation of these problems, grippers have compliant components and linkage mechanisms to adapt to the various shapes of objects [2], [3]. However, for multi-point contacts, more than three fingers are needed to grasp, and the complexity of the mechanism is always challenging for design. Plus, there is still a limitation to grasping objects which have complicated surfaces.

Recently, soft grippers have been researched to grasp more objects with complicated surfaces [4], [5]. These soft grippers are using different actuators and soft materials compared to traditional grippers, not only to simplify the mechanism design but also to enhance grasping performance. Fluidic Elastomer Actuators (FEAs) and Shape Memory Alloys (SMAs) are used on grippers to contact softly using properties of materials [6], [7]. To enhance friction force, researchers applied gecko-like or electrostatic adhesive materials on contacted surfaces [8], [9]. Pouch actuators and origami, kirigami grippers are quickly fabricated and easily used to grasp for safe contact [10]–[12]. Although these soft grippers have shown remarkable flexibility and adaptability

All the authors are with the Kinetic Intelligent Machine LAB (KIMLAB) at the University of Illinois, Urbana-Champaign, IL 61801, USA {jh97, dmathur2, joohyung} @illinois.edu



(a) Lip-inspired gripper

(b) Lip muscles of human (c) Lip muscles of dog

Fig. 1. Lip-inspired gripper and anatomy of lips.

to handle fragile objects with simple actuation, low stiffness is a problem in grasping application.

Particle jamming effect shows a much simpler design and assures rigid stiffness by tuning stiffness via jamming transition [13]–[17]. To jam the particles, the volume of the chamber should be reduced. Most of the grippers use air pressure to make volume changes. As the air in the chamber is vacuumed out of the chamber, the particles are closer together, and the chamber becomes stiffened while retaining the shape of the object. This vacuum jamming method demands lots of parts, such as solenoid valves and pumps, and is hard to control.

An alternative way to solve this problem recently is to utilize this particle jamming principle passively [18]–[20]. Without making a chamber where particles are being vacuumed, the particles can be firm together. When an object contacts a membrane, the contour of the contacted surface along the object changes only by the contact force. By changing the contour of the surface, its volume is changed near the contact points. Because of this volume change, particles near the object get firmer and the stiffness becomes more rigid.

In this paper, we present a lip-inspired soft robotic gripper which uses a passive particle jamming effect. Motivated by various roles of the lip, this gripper is designed to imitate holding objects with lip-like structures [21]. With our gripper, the gripper can re-grasp objects by repeating holding and releasing motions. The lip-pouch in the gripper, including the particles inside, have similar structures to ones of mammals which have dermis and muscle inside. If the lip-pouches contact an object upside and downside together, passive jamming occurs and helps to hold the object during grasping.

In Section 2, the motivation and design of the gripper are introduced. More details about the anatomy and function of the lip and passive particle jamming are explained. In Section 3, the fabrication process using a heat sealing machine is presented. In Section 4, grasping ability and re-grasping performance are validated by experiments with various objects.

II. DESIGN

Our design goal is mainly implementing a gripper by utilizing passive particle jamming to hold objects. The main contribution is realized by inspiration from the lips of animals. In this section, with an explanation of passive particle jamming, we will describe a design of this gripper with how we mimic the functions of the lip by explaining the anatomy of the lip and muscles near lips.

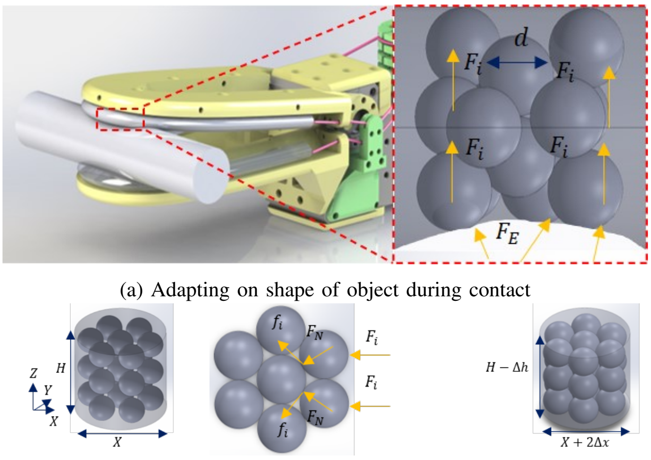
A. Functions and anatomy of lip

Animals' lips have interesting functions. For example, the lips of dogs protect their gums from sharp canine teeth. For humans, the lips have more functionalities other than eating. Human lips help to hold objects and to put them into the mouth when eating. If we want to drink using straws, lips can make the space inside the mouth sealed and help to suck liquid into the mouth. If there is something which we do not want to take inside the mouth, we use the lips to spit the object out. Plus, the lips play a role to make sounds by opening and closing, and to make diverse facial expressions.

Mammals, especially dogs, use their lips and jaws to regrasp objects into space behind canine teeth. First, they bite an object using their jaws at the front side of the mouth. To firmly hold this object, they open and close their jaws repeatably to send the object to the back with shaking their head. In the meantime, when the object is located in the space behind the canine teeth, they use their lips to hold tight.

Near the lips, there are lots of muscles for these kinds of movements. Among those muscles, the levator labii, mentalis, risorius, platysma and orbicularis oris muscles are closely related to lip movement (Fig. 1b, Fig. 1c) [21], [22]. Lip depression is caused by the risorius and mentalis muscles. Lip elevation is caused by the levator labii. Traction of the lips is caused by the orbicularis oris and platysma muscles.

As we look inside the lips, there are dermis, collagen, and orbicularis oris muscles inside. Since the lips are muscular hydrostats, their stiffness is variable. When the normally soft lips are compressed, they become rigid rigid structures. For adult males, the maximum voluntary lip closing force (MVCF) is 4.4N for the upper lip, and the MVCF is 14.1N for the lower lip. The total lip closing force is about 18.5N, which is enough force to hold objects firmly [23].



(a) Adapting on shape of object during contact

(b) Before contact (c) Internal force on particle (d) Compressed cylinder volume

Fig. 2. Passive particle jamming effect.

B. Passive particle jamming

Changing the stiffness of the lips is realized by a passive particle jamming effect. Before introducing the lip-inspired design, we will briefly introduce the passive particle jamming effect, and how it works inside and on the surface of the lip-pouch.

When the gripper makes contact with an object, an external force is applied on the membrane. This force is applied to the particles as the membrane is deformed and adapted to the shape of the object (Fig. 2a) [18], [19]. Fig. 2b presents granular particles filled in a chamber with some distance between each other. In an initial state, the outer membrane surface does not apply force to the particles, and the particles do not apply forces to each other since they are not compressed by the membrane. By the deformation, particles get jammed with each other as the gap between them decreases, and they apply an internal force to each other (Fig. 2c). Therefore, without actuation, the particle jamming occurs passively.

This passive particle jamming effect can be modeled by simplifying particles as spheres having diameter d [19]. First, we assume that the volume is constant in the chamber. In Fig. 2a, a distributed contact force, F_e, is applied on the membrane, and this force is directly delivered to particles on the contacted area, $A_F = \frac{\pi d^2}{4}$, with pressure $P = \sigma dA/dV$ [24]. P is constant as we assumed that volume is constant, and area change on the membrane is relatively small when compressed. The surface tension is also constant, as it is determined by the volume of the particles within. This yields that the internal force is $F_i = A_F P = \frac{\pi d^2 P}{4}$. Thus particles receive a normal force, $F_N = \frac{\sqrt{3}}{3} F_i$, and a friction force on particles, f_i.

$$f_i = \mu F_N = \frac{\mu\sqrt{3}\pi d^2 P}{12} \tag{1}$$

If we set a small cylinder volume, there are gaps between particles. When an external force is applied, this volume is constant and the cylinder is compressed (Fig. 2d). From this volume, we can obtain the number of particles and the

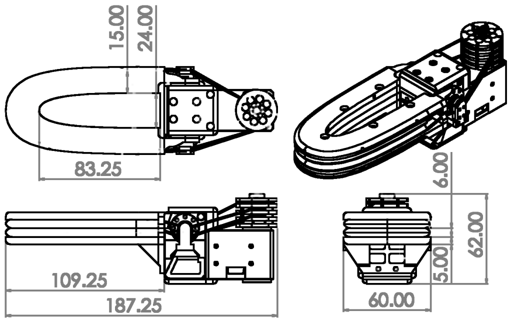


Fig. 3. Dimensions of the lip-inspired jamming gripper

change of diameter of cylinder model, Δx, as follows:

$$n = \frac{3X^2H}{16d^3}, \Delta x = \frac{\pi X \Delta h}{4(H - \Delta h)} \tag{2}$$

The gap distance between particles in the x-direction, l_x, and in the z-direction, l_z are calculated as follows:

$$l_x = \frac{d\Delta x}{X}, l_z = \frac{2d\Delta h}{H} \tag{3}$$

From Fig. 2c, resultant works by the friction forces for particles in XZ-plane and YZ-plane are as follows, respectively:

$$W_{f,xz} = 2\sqrt{3}nf_il_x, W_{f,yz} = 2\sqrt{3}nf_il_z \tag{4}$$

From energy conservation, the work generated by external force has to be same as the work by friction force, so $W = n(W_{f,xz} + W_{f,yz})$, where $W = F_e\Delta h$. Therefore, we can obtain an equation from Eq. (1) to Eq. (4).

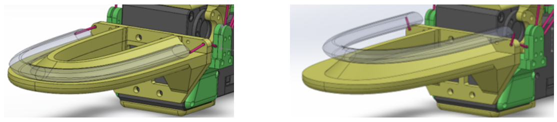
$$F_e = \frac{3\pi\mu X^2HP}{32}(\frac{\pi}{4(H - \Delta h)} + \frac{2}{H})) \tag{5}$$

From Eq. (5), the external force varies with parameters, such as object width, lip-pouch height, and particle filling volume and friction coefficient. For our gripper, if the grasping force is constant, a large contact area (large X) results in a shallow indentation of the lip (small Δh). Therefore, a narrow shape object can be adapted better to the lip-pouches, and the gripper can grasp the objects better. If we want to increase the jamming effect, the grasp force should increase.

C. Lip-inspired design

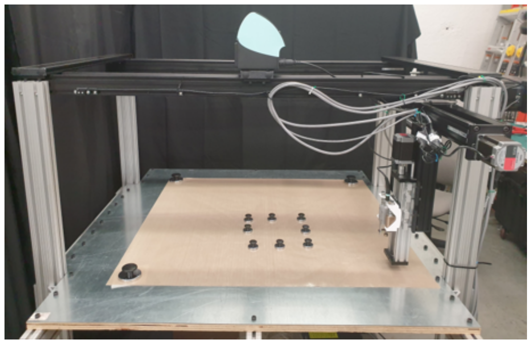
Based on the anatomy of the lip, this gripper is designed to imitate muscle functions which are mostly related to the holding motion of the upper and lower lips. In addition, we targeted the shape of this gripper to look like the mouth of a dog, consisting of upper and lower jaws and lips. Fig. 3 shows the dimensions of the gripper. The holes in the jaws are for a camera to see through.

For the functionality of the lip, we used o-rings and wires to imitate the muscles that are connected to lips (Fig. 1a). Lip-pouches are connected by wires to motors, which pull and release lip-pouches so that it makes them go up and down along the slope (Fig. 4). When releasing the lip-pouches, o-rings retract them so that they go to their original location.

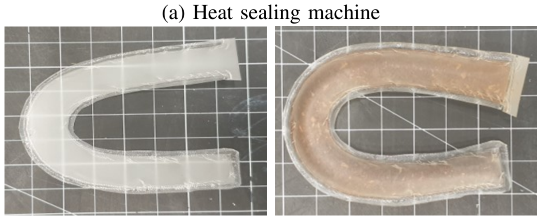


(a) Depression state (b) Traction state

Fig. 4. Lip-pouch moves along slope.



(a) Heat sealing machine



(b) Heat sealed lip-pouch (c) Lip-pouch filled with particles

Fig. 5. Fabrication with heat sealing machine.

If the slope is too steep, a large traction force is needed to climb up, so we set the degree of the slope as 30°. Inside the layer of the lip, there are the dermis and orbicularis oris with fat. When we bite our lips, we can feel that it becomes rigid if we bite deeper because of these components. We generate this effect with passive particle jamming by putting particles inside the lip-pouches. If an object is in contact with arbitrary direction on the lip-pouch, the contacted side is dented by its contact force. In the meantime, particles get jammed and they become stiffened, so it helps to increase the number of contact points, and the lip-pouches can hold the object. The gripper's upper jaw is connected directly to the motor. For the decoupling wire actuation and jaw actuation, we designed a wire routing so that the length of wire is not changing during rotation of jaw. This simplifies the control, and we can easily re-grasp an object with isolated lips.

III. FABRICATION

For the lip-pouch fabrication, we developed a heat sealing machine, shown in Fig. 5a. This machine is similar to the heat sealing machine in [25] and we modified some parts for our use. The fabrication process and software were also developed for the convenient design. Using the machine and the developed process, we could easily fabricate air-tight bubbles and pouches with complicated 2D shapes, generated by CAD tools or drawn by hand.

The lip-pouch fabrication process is as follows: First, two 0.381 mm thick polyurethane sheets are overlapped on the

TABLE I. Specification of Gripper

	Specification
Dimension	187 × 60 × 59 mm
Weight	285 g
Motor	XM430-W210-R, ROBOTIS(3.0 Nm, 12V)
Wire	Berkely Trilene Big Game Mono fishing line, (22.68 kg)
Material	Particle : ground coffee (∼3 mm) Lip : 0.381 mm polyurethane Jaw : PLA

machine table and fixed with multiple magnets. Then, the heating tip with a ball transfer is heated up to 382° Celsius. The heated tip seals the sheets with pressure by following a lip-shaped trajectory. The tip is controlled by the XYZ-gantry in the machine and the commanded trajectory is generated by the developed software on the connected computer. The lip-shaped pouch from this process is presented in Fig. 5b. We put granular particles inside the lip-pouch, as shown in Fig. 5c. We used ground coffee around 1∼3 mm for the granular particles. After heat-sealing the filled pouch completely, a 0.71 mm thick nylon line wire is threaded through a lip pouch. The wires are connected along the outside edge of lip-pouches, and one o-ring is used in the middle on each lip-pouch for depression. Two servo motors are used for actuators; one is for jaw motion, and the other is for wire-driven actuation. Upper and lower jaws, teeth, pulley, and wire routing parts are all 3D printed with PLA. Additional specifications of the gripper are in Table I.

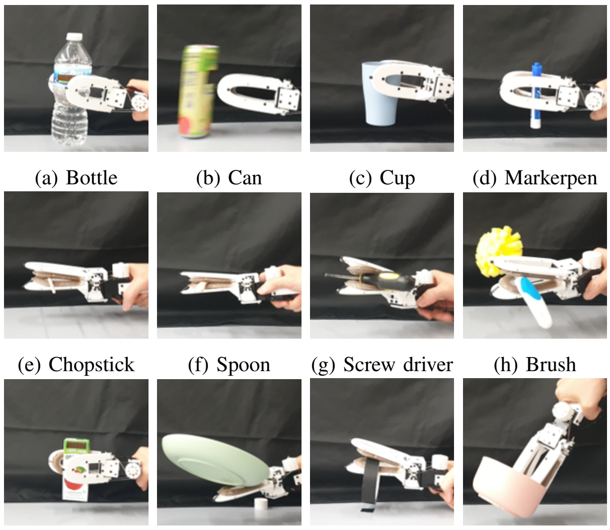
IV. EXPERIMENTAL VALIDATION

The gripper shows unique features with its degree-of-freedom with its lip-pouches. For validation of the ability of this gripper, we conducted experiments. One of the experiments is to see the versatility of this gripper. Furthermore, to show one of its interesting functions, we explored re-grasping objects with this gripper. The second experiment is to show how this gripper re-grasps objects like dogs.

A. Holding performance

As this gripper has a hinge-like jaw with one degree of freedom, it is easy to fail to grasp objects which are thick and have an uneven surface. However, with lip-pouches, the capability of grasping performance is enhanced. The gripper can grasp a maximum of 9.8 N when holding a stick vertically thanks to the passive particle jamming effect inside of the lip-pouches. Maximum values are different depending on shape and size of objects from Eq. (5). If the gripper would try to hold in this direction without the lip-pouches, any object might slip out.

In this experiment, we validated this capability by trying numerous objects with different thicknesses and shapes. We conducted tests on the gripper with and without lip-pouches. The subjects are chosen as what we can easily find in our surroundings: bottle, can, cup, bowl, dish, juice pack, spoon, chopstick, brush, marker pen, screw driver, and tape (Fig. 6.) Experiments for each item are conducted 10 times grasping. As this gripper is a 1-DOF hinge-style gripper, it is hard to grasp objects with a convex surface. For these kinds



(a) Bottle (b) Can (c) Cup (d) Markerpen (e) Chopstick (f) Spoon (g) Screw driver (h) Brush (i) Juice pack (j) Dish plate (k) Tape (l) Bowl

Fig. 6. Holding objects with the lip-inspired gripper.

TABLE II. Success rate of holding experiments

Object	With lip-pouch(%)		Without lip-pouch (%)	
	Holding	Shaking	Holding	Shaking
Bottle	100	50	0	0
Can	0	0	0	0
Cup	100	100	0	0
Markerpen	100	100	0	0
Chopstick	100	100	100	40
Spoon	100	100	100	0
Screw driver	100	100	100	0
Brush	100	100	50	0
Juice pack	100	90	0	0
Dish	100	100	0	0
Tape	100	100	100	0
Bowl	100	100	0	0

of objects, we hold them in upright positions. Stick-shape objects are placed on the gripper directly because the gripper cannot pinch from a surface, as the front side of the gripper has a gap. For this test, we shake and rotate the objects to test stable grasping.

Table. II shows that a gripper with lip-pouches grasps objects better than one without lip-pouches. The gripper with lip-pouches succeeded to hold and shake most of the objects. Without lip-pouches, the gripper could not grasp and shake most of the objects well. For objects with convex surfaces, such as a bottle, can, cup, and markerpen, the gripper without lip-pouches cannot hold the objects because the conditions for force closure are not satisfied. However, a gripper with lip-pouch is able to hold and shake all objects except a can. Even though a cup has a larger diameter than the can, it failed because the aluminum can has a slippery surface. As a result, when the lips were retracted, the can rolled out. A bottle was half-filled with water, which was weighed 250g. The success rate for holding a bottle with the lip-pouch was 100%, but the one for shaking was 50%. This bottle also has a slippery surface, so it was easy to fail. However, the lip-pouch enhanced the grasping performance for the bottle while shaking. For stick-shape objects, such as a chopstick, spoon, screw driver, and brush, the gripper without lip-pouches can hold the objects. However, when shaking, all the objects fall, and only a chopstick shows 40% success rate because its thickness is even and thin. The gripper with lip-pouches shows that it succeeded to hold and shake the objects with 100% success rate. The lip-pouch helps the objects to be adapted on the membrane according to their shape. For a juice pack, dish, bowl, and tape which have a square shape or convex and concave shape, a gripper without lip-pouches only succeeded to hold the tape, but failed to shake. The gripper with lip-pouches succeeded to hold and shake the objects. The surface of the juice pack is slippery, so it failed one time to shake, but it is enough to hold tightly in upright position.

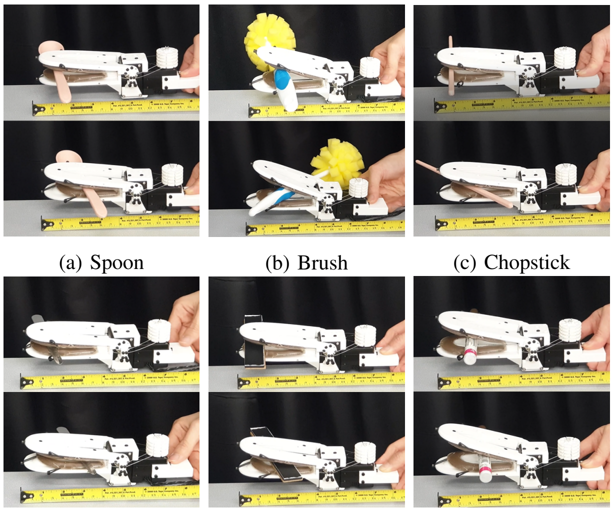
B. Re-grasping

The second experiment shows re-grasping objects with this gripper. Yuan et al. and Spiers et al. developed grippers that are able to do in-hand manipulation with additional actuators [26], [27]. As our proposed gripper has an additional actuator for the lip-pouches, we explored with this actuator that handling objects could be implemented by repeated movements of the jaw and lip-pouches, like how dogs re-grasp.

The procedure for repeating motions is as follows: First, bite an object using the gripper with lip-pouches. Next, release the wires with full torque power of jaw so that the object can lie on the teeth at the same position where the object was first contacted. Then, pull the wires to hold again and move the object back with lip-pouches. At this point, while pulling wires, open the upper jaw slightly and then close again with low motor power so that the object moves back easily.

We conducted this experiment with several objects: stick-like objects such as a spoon, brush, chopstick, sticks, and a markerpen. The reason why we chose stick-like shaped objects is to show how objects with different thicknesses and shapes move backwards efficiently.

As shown as Fig. 7, the gripper could move objects to the back of the gripper. We repeated a different number of cycles for each object because each object has different friction coefficients and shape. The number of cycles are as follows: 36 for spoon, 50 for brush, 20 for chopstick, 14 for metal stick, 42 for wood stick, and 10 for marker pen. Most objects are moved about 20mm. After re-grasping, all objects are slightly rotated randomly. For brush, it rotates because its handle is not an even cylinder shape. So during the re-grasping motion, it changes direction randomly.



(a) Spoon (b) Brush (c) Chopstick
(d) Metal stick (e) Wood stick (f) Markerpen

Fig. 7. Results of re-grasping with lip-pouches and jaws before(up), and after(down) re-grasping.

C. Discussion

The lip-inspired gripper shows the apparent effects of lip-pouches with two experiments. The gripper could hold objects better than one without lip-pouches. Moreover, it could re-grasp objects inside the gripper.

In the holding experiment, a gripper without lip-pouches was not able to hold tightly, and most of the objects fall. It fails because of insufficient friction as well as an imperfect condition of force closure. Objects which have convex shapes such as bottle, cup, can, and markerpen slip out easily. Therefore, this 1-DOF hinge style gripper cannot hold convex shape objects well. Likewise, the gripper fails to grasp tape, bowl and dish which have convex and concave sides. Stick-style objects, such as spoon, brush, screw driver, and chopstick are grasped, but when the gripper shakes and rotates itself, the objects move or fall because of low contact force.

With lip-pouches, the gripper can hold and shake various objects with more stability than one without lip-pouches. Grasping performance is enhanced by lip-pouches which generate a passive particle jamming effect. For objects with convex shapes which are hard to grasp with a hinge-style gripper, the passive particle jamming effect occurs near contact surfaces, and an indent occurs according to the contacted shape. For stick-like shape objects, the lip-pouches can hold the objects which are fit into the indent, and they are firmly grasped. Moreover, the results show that objects with similar materials are grasped with different indent heights as discussed in Section II-B. Fig. 6j and Fig. 6l show that the indent of the bowl is deeper than the dish.

In the re-grasping experiment, it was hard to take objects inside straightly as the wire tension distribution system was not set up in this version. Thus, the tension which was applied on each end of the lip-pouches was not equal. Plus, the surface of lip-pouches was not even. Because particles inside the lip-pouches are not perfectly spread, and it is hard to reorganize the particles, the surface is randomly bumpy which makes objects move randomly. Brush and chopstick in Fig. 7 show this result clearly. Furthermore, objects with convex shape roll in and out when the lip-pouches are pulled and released. These kinds of objects are hard to re-grasp because the timing for opening and closing the jaw is unpredictable.

This version of the gripper has limitations for showing perfect results. As the height of the lip-pouches and the friction on the surface of polyurethane are low, the indent from the passive jamming effect is shallow. Plus, as the lip-pouches are fabricated in 2-D, the membrane tends to pull back to the original flattened shape, and this makes the particles jammed a little in the depression state. If the height of the lip-pouch is high enough and the volume is large enough so that particles are not jammed before contact, the effect of passive jamming could be better and the gripper could grasp more objects. Also, the friction coefficient of the membrane should be higher than this polyurethane, because objects like the can are slippery. We will explore materials for the membrane.

V. CONCLUSIONS

In this paper, we proposed lip-inspired soft robotic grippers using a passive particle jamming effect. Firstly, we introduced how we are inspired by lips to design this gripper with an explanation of the lip anatomy and functions. We mimicked functions of the lips, such as holding and re-grasping objects, by using wires and elastic components that imitate the movement of muscles near the lips. By using a heat sealing machine, we could fabricate lip-pouches of particles inside layers of soft material. To generate functions of the lip, we utilized a passive particle jamming effect, which creates rigid contact between the lip-pouches and objects when there is a contact force. For the validation of this capability of the gripper, we conducted experiments. We experimented with various objects which have different shapes and thicknesses. The gripper could hold objects which have convex shapes, such as cup, bottle, and stick-like shapes, such as chopstick, and brush. To show another interesting function of the lip-pouches, the second experiment that was conducted shows the gripper's re-grasping performance to move stick-like shaped objects from the end to inside of the jaws.

In the future, we will work on developing this lip-inspired gripper to have grooves which resemble canine teeth functioning as ones of dogs to carry objects. In the oral structure of dogs, there is a space behind the canine teeth, so dogs can hold sticks or tree branches. Also, we will add patterns on lip-pouch which will act as fingerprints. If a membrane has fingerprint-like patterns on it, grasping performance will be improved. We expect that the next version of the gripper will have abilities of enhanced grasping and re-grasping performance with a patterned lip-pouch and teeth structure.

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