Delicate Grasping by Robotic Gripper with Incompressible Fluid-based Deformable Fingertips

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Abstract— **This paper presents a gripper with fingertips constructed from incompressible fluid covered by rubber with the aim of grasping very fragile objects. Owing to the incompressibility, simply closing the gripper allows the fingertips to approach the target object with low stiffness; after contact, the contact stiffness increases with increasing fingertip deformation, and grasping with high stiffness can be realized. The adaptation of the fingertips to the object shape and a uniform contact pressure are further benefits of the proposed system. Fragile and brittle objects can be grasped by controlling the contact pressure so that it does not exceed the fracture stress/pressure. We found that the initial sign of fracture appears before total fracture when soft and ductile objects are grasped. Based on this phenomenon, we developed a strategy for grasping ductile objects without any advance knowledge of fracture. The proposed fingertips have a rigid layer inside the fluid to grasp objects with normal rigidity. The effectiveness of the fingertips was confirmed experimentally.**

I. INTRODUCTION

Recently, much attention is being given to robots executing everyday tasks in human society. Robotic hands have an important role in completing such tasks. We focused on tasks related with fracture. Human environments have many soft and fragile objects such as foods, glasses, and plastics. This paper proposes a robot hand that can grasp such fragile objects without breaking them.

A number of objects and tools are manufactured for use by human beings in daily life. Thus, robotic hands that resemble human hands are advantageous in human society; many kinds of multi-fingered robotic hands have been developed [1]–[6]. Although multi-fingered hands are versatile, they are not always suitable for equipping specialized functions—for example, fracture control and dealing with complex shapes. Grippers [7]–[11] are suitable for these purposes. Kim and Song developed a gripper with a variable contact stiffness due to hybrid variable stiffness actuators that can grasp an egg [8]. However, they did not consider adaptation to irregularly shaped objects. Hirose and Umetani [7] proposed a robotic hand whose fingers move like a snake to realize a flexible grasp. Brown et al. [9] evaluated a universal gripper constructed from an inflatable rubber bag containing granular materials. By controlling the air pressure inside the bag and utilizing jamming, objects of any shape can be grasped. The original idea was introduced by Schmidt [12] and Perovskii [13]. However, they did not consider fracture and the grasping of fragile and brittle objects. Choi and Koc [10] developed a gripper with inflatable rubber pockets on the gripping areas. By utilizing pneumatic inflation, they were able to grasp objects of different shapes, including eggs, without damaging them. However, the main target objects were not fragile and brittle. Pettersson et al. [11] presented an interesting parallel jaw gripper whose gripping area is covered by magnetorheological (MR) fluid. If the gripper is closed and contact occurs, the MR fluid is molded according to the object shape. An electromagnetic force then changes the viscoelasticity of the MR fluid, and the object is confined inside the MR fluid. They were able to grasp fruits using this method.

The aim of this study was to develop a gripper that can grasp more fragile and brittle objects than those considered in conventional studies. This paper presents a novel robotic gripper whose fingertips (gripping area) are constructed from a rubber bag filled with incompressible fluid; the paper also presents the grasping strategy for the gripper. Details on the contributions of this paper are as follows.

Gripper with incompressible fluid-based deformable and controllable fingertips: Simoga and Goldenberg [14] showed that gel (incompressible fluid) is suitable for fingertips of robotic hands from the viewpoint of impact energy attenuation, surface conformability and strain energy dissipation. The additional/other main benefits of the use of incompressible fluid, which are not presented in [14] but presented in this paper, are a uniform contact pressure profile and automatic stiffness increase. In contrast to compressible fluids like air, increasing the fingertip deformation indicates an increase in fingertip stiffness (if controlling the volume of the fluid to be constant). Both low-contact impact and high-stiffness grasping can be realized by simply closing the gripper. In addition, we attached a pressure sensor for the fluid to control the contact pressure for fracture control.

A low maximum applicable force/pressure is a drawback of the (presented) fingertips. It is hard to grasp normal objects such as a bottle of water. In order to overcome this issue, we constructed a two-layer structure with a rigid component located inside the fluid. If large contact forces are exerted and correspondingly large displacement happens, contact between the rigid component and object occurs. In this case, large contact forces can be applied to the object via the rigid component, and the object can be grasped.

Grasping strategy for delicate grasping: A fracture control method for grasping fragile objects without breaking them is presented. Fracture is not in the force domain but in the stress

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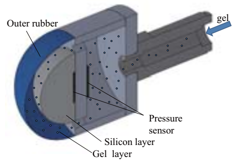


(a) Cross section of the fingertip part

(b) Manufactured fingertip

Fig. 1. Fingertip structure

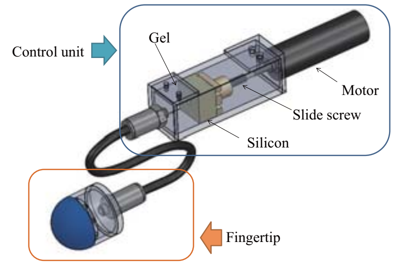


Fig. 2. Fingertip and control unit

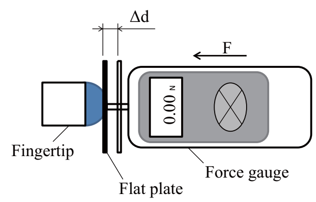


Fig. 3. Experimental set up for compression test

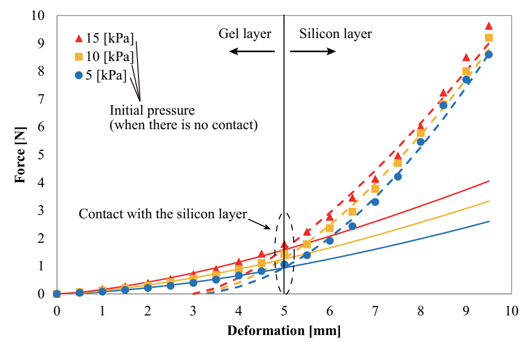


Fig. 4. Force–deformation diagram

or pressure domain. In conventional studies, fracture forces were measured in advance, or only the results (whether or not the grippers could grasp objects without breaking them) were evaluated. Thus, evaluation was indirect, or fracture control was not considered. In this study, we prevented fracture from grasping by controlling the contact pressure so that it is less than the fracture stress/pressure. We demonstrated the efficiency of the approach by having the gripper grasp brittle objects—that is, potato chips. When the gripper grasped ductile objects such as soft tofu, we found that signs of fracture occurred before total fracture. We call this the initial break. Based on the initial break, we developed a strategy for grasping ductile objects without any advance information on fractures.

II. Incompressible Fluid-Based Deformable Fingertips and Gripper Structure

A. *Incompressible fluid-based deformable fingertips and the two-layer system*

The key to a delicate grasp is changing the shape of contact areas according to the object shape and uniform contact pressure. Thus, we developed deformable fingertips filled with an incompressible fluid (gel: Schick SWS-CG180). In order to grasp conventional rigid objects, a silicon layer (made of Shinetsu Silicon KE-1308) was installed inside the gel. Fig. 1 shows the structure of the developed fingertip and a manufactured prototype. Note that we call the contact/gripping area the "fingertip".

Two pressure sensors were installed: one to measure the pressure of the gel and the other (located at the root of the silicon layer) to measure the force applied to the silicon layer. When a large grasping force is not required, only the gel layer is used for grasping. If a large grasping force is required, the silicon layer is mainly utilized with large deformation of the fingertips. In order to achieve compact and lightweight fingertips, the pressure control unit was installed separately and connected to the fingertip by a tube, as shown in Fig. 2. By shaving tubes for the connection, we can control multiple fingertips with one control unit. This approach was used in this study to reduce the number of actuators. The pressure control is based on Pascal's law: if an arbitrary pressure anywhere is applied to the incompressible fluid in a confined container, the pressure is equally transmitted in all directions such that the pressure anywhere is the same. By rotating the slide screw connected with the DC motor (Maxon Amax16 1.2 W), we controlled the position of the piston made of silicon. If the piston moves, the entire volume of the fluid (gel) changes, which causes a change in fluid pressure. According to Pascal's law, the fluid pressure corresponds to the contact pressure when the fingertip comes into contact with something.

B. *Evaluation of fingertips*

We experimentally investigated the variable range of pressure when the fingertips are not contacting anything. The range was 0∼15 [kPa]. We then performed a compression test. Fig. 3 shows the experimental setup for the test. We fixed the fingertip and then pushed and deformed the fingertip surface with a flat plate attached to a force gauge (IMADA DS2-50N) to investigate the relationships of the fluid pressure, applied force, and deformation. Fig. 4 shows the results. The markers show the experimental results, and the curves are the regression curves. Assuming that the presented fingertip is a hemisphere, we applied the model presented by Xydas and Kao [15].

$$f = C\Delta d^{\zeta} \quad (1)$$

where f is the applied force, Δd is the deformation, and C and ζ are the parameters. Table I shows the parameters for the regression curves. The rate of increase suddenly changed

TABLE I
PARAMETERS C AND ζ FOR THE REGRESSION CURVES IN FIG.4

Initial pressure	When contacting with gel layer		When contacting with silicon layer	
	C	ζ	C	ζ
5 [kPa]	0.073	1.59	0.255	1.88
10 [kPa]	0.109	1.52	0.408	1.64
15 [kPa]	0.151	1.46	0.584	1.46

around a deformation of 5 [mm]. This may have been due to contact with the silicon layer. The data were then split into two parts by making a boundary at the deformation of 5 [mm]. The regression was applied to the two parts separately. Fig. 4 shows that the model represented the relationship very well. The stiffness can be regarded as the gradient at each point of the regression curves. Thus, the contact stiffness can be controlled by controlling both the piston of the control unit and the fingertip deformation by contact. In addition, if the deformation is large, the silicon layer can be used to obtain a large stiffness and apply a large force. This is useful for grasping rigid and relatively heavy objects.

C. Structure of gripper

With the aim of developing a simple structure and simple control schema, we developed a gripper-type robotic hand. Note that, with the proposed fingertips, we can construct a multi-fingered hand. Fig. 5 shows the structure of the gripper. Each presented fingertip is attached to every gripping area. Our aim was to realize two grasping modes, as shown in Fig. 6. If the stiffness of the target object is higher than that of the fingertip, the object penetrates the fingertip (Fig. 6(a)); if it is lower than the fingertip, the object is penetrated (Fig. 6(b)). In Fig. 6(a), the object is enveloped by the fingertips, while the fingertips are enveloped by the object in Fig. 6(b). In both cases, if each contact is approximated by a finite number of point contacts with friction, there were at least three points per contact area. In total, there were at least six contact points with friction. This number is sufficient for constructing (passive) force closure [16], [17]. Thus, stable grasp can be achieved.

The main body part has only one degree of freedom for opening and closing the tip parts (gripping area). Table II shows the specifications. We used a parallel crank mechanism such that the gripping surface of every fingertip part can always move parallel to the corresponding opposed surface. We used the Maxon Amax 32 (15 W) actuator to open and close the tip parts. We measured the motor angle using an encoder equipped with the motor and controlled the motor angle corresponding to the distance between the fingertips.

Control of the closing of the gripper indicates control of the fingertip deformation by contact with objects. Thus, the contact stiffness can be controlled by opening and closing the gripper.

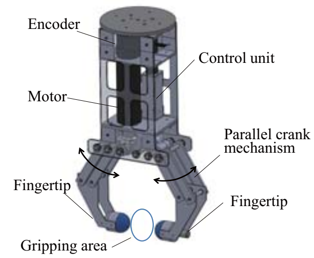


Fig. 5. Structure of gripper

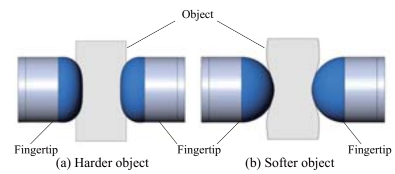


Fig. 6. Grasping mode based on object stiffness

TABLE II
SPECIFICATIONS OF GRIPPER

Maximum height of gripper	300 [mm]
Maximum width of gripper	200 [mm]
Maximum gripping area (length)	90 [mm]
Weight	1.0 (weight for motors: 0.4) [kg]
Maximum joint velocity	75.3 [rpm]
Maximum joint torque	1.43 [Nm]
Maximum grasping force	11.44 [N]

III. INVESTIGATION OF UNIFORMITY OF CONTACT PRESSURE

In conventional fingertips made of silicon, the contact pressure is maximum at the contact center and decreases in the direction of the periphery [15]. In contrast, the contact pressure of the proposed fingertips is expected to be uniform. In order to confirm this characteristic, we investigated the contact pressure distribution. For comparison, we used two types of fingertips: gel layer and silicon fingertips (Fig. 7). To avoid unexpected contact with the silicon layer, the silicon layer was not included in the gel layer fingertip. The silicon fingertip was a hemisphere made of silicon; the size and shape were fitted to be the same as those of the developed fingertip.

Fig. 8 shows the experimental setup. We measured the contact pressure profile using pressure-sensitive paper with Prescale mat (FUJIFILM). In the test, each fingertip pushed the Prescale mat covered with the pressure-sensitive paper from above. The pushing force was kept constant and controlled by a force gauge. When the pressure-sensitive paper was pressed, it became red. The intensity of the red color corresponded to the magnitude of the applied pressure. The Prescale mat was constructed from dot-patterned cones; around the cones, the pressure became concentrated for easy visualization of the pressure profile. Due to the dot pattern of the cones, the obtained red color pattern was also a dot pattern (4×4), as shown in Fig. 9. The other conditions for this experiment are shown in Table III.

(a) Silicon fingertip (b) gel layer fingetip

Fig. 7. Used fingertips

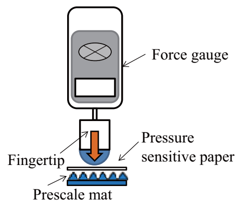
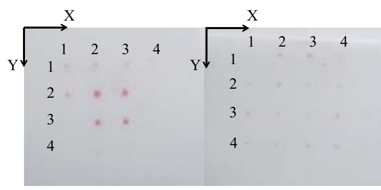


Fig. 8. Investigation of contact pressure profile



Silicon fingertip Gel layer fingertip

Fig. 9. Contact pressure profile for silicon and gel layer fingertips

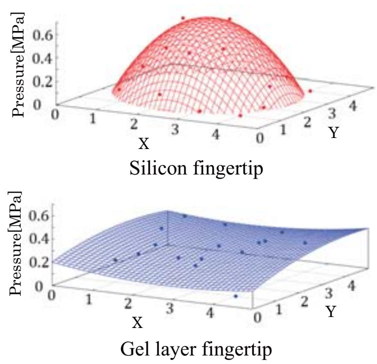


Fig. 10. Contact pressure profile for silicon and gel layer fingertips

We derived the magnitude of the pressure from the intensity of each dot in the obtained patterns and plotted the pressure profile, as shown in Fig. 10. We also showed the regression curved surface using the following model:

$$p = M - \alpha(x - A)^2 - \beta(y - B)^2 + \gamma(x - A)(y - B) \quad (2)$$

where p is the pressure and the values of the parameters are as shown in Table IV. When comparing the results, the silicon fingertip showed high pressure in the area around the center, while the gel layer fingertip had an almost uniform pressure profile. With regard to the maximum pressure value, the maximum pressure for the gel layer fingertip was small compared with that for the silicon fingertip. Thus, the developed fingertip can be used to grasp objects without producing high local pressures, and (large) grasping forces

TABLE III

EXPERIMENTAL CONDITIONS FOR INVESTIGATION OF CONTACT PRESSURE PROFILE

Load weight	Loading time	Temperature	Humidity
10 [N]	2 [min]	24 [°C]	64 [%]

TABLE IV

PARAMETERS FOR REGRESSION CURVED SURFACE

	α	β	γ	A	B	M
Silicon fingertip	0.14	0.15	-0.017	2.2	2.7	0.65
Gel layer fingertip	-0.010	0.011	0.0039	2.2	3.8	0.27

can be generated with small contact pressure.

IV. GRASPING STRATEGY

We present strategies for grasping objects using the developed gripper with incompressible fluid-based deformable fingertips; we experimentally investigated the validity of the presented approach. We considered grasping and picking up objects on a table using the developed gripper.

Since the contact between the fingertip and an object is not a point but an area, a power grasping style is used [18], [19]. In a power grasp, larger grasping internal forces (contact forces which do not affect object motion and whose total sum is zero) mean that a larger external wrench (gravitational force) can be balanced. In addition, a larger contact area means that (large) external wrench (gravitational force) can be balanced in wider directions. However, a large contact force/pressure can damage the grasped object, and it should be avoided for delicate grasping. Since the developed fingertip is very elastic, a large contact area can be easily obtained. Therefore, the key to the success of delicate grasping is setting and controlling the contact pressure (and the corresponding grasping internal (contact) forces). Because fracture occurs due to not force but stress, contact pressure control is essential for delicate grasping.

In the developed gripper, directly controllable factors are the angles of the motor for opening and closing the gripper and for controlling the piston positions inside the control unit to control the fingertip fluid pressure: these are denoted here as q_g and q_p, respectively. The fluid areas for both fingertips are connected, and their pressures are controlled by one control unit. The fluid pressure inside the fingertip when there is no contact (p_{fi}) is expressed by:

$$p_{fi} = p_f = p_f(q_p). \quad (3)$$

p_f is the pressure when contact occurs and should be low to reduce the contact impact. The fluid pressure inside the ith fingertip when there is contact (contact pressure; p_{ci}) is represented by

$$p_{ci} = p_c = p_c(q_p, q_g). \quad (4)$$

If q_p is constant, $p_c(q_p, q_g) = p_c(q_g)$ can be regarded to monotonously increase as the gripper is closed by the control of q_g. We can then take the following simple strategy for control.

1) Let q_p be its desired value; for fixing p_f, keep q_p constant.

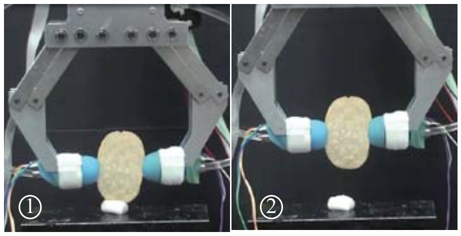


Fig. 11. Grasping of potato chip

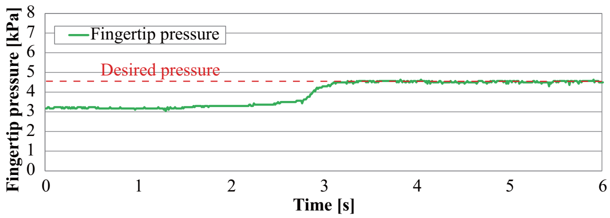


Fig. 12. Pressure profiles when grasping potato chip

2) Close the gripper (by the control of q_g) until $p_c(q_g)$ reaches its desired value.
3) Move the gripper upward to pick up the target object.

We remark that we can increase p_c by increasing q_p when there is contact, but we do not take the way in order to get relatively larger contact area and make the control strategy easy. The role of the control of q_p is the control of initial pressure (the pressure when there is no contact) such that the gripper can always contact objects with desired stiffness.

A. Grasping fragile and brittle object (potato chip)

We investigated the efficiency of the developed gripper when grasping a potato chip (1.89 [g]) to represent fragile and brittle objects. When brittle objects are grasped, fracture suddenly occurs when the stress applied to the object is over a certain value (fracture stress). In order to determine the fracture stress, we conducted an experiment of closing the gripper and breaking the potato chip. We set the initial fluid pressure to $p_f = 3$ [kPa]. Let p_{cf} be the contact pressure (p_c) when fracture occurs. We set the desired contact pressure (p_{cd}) such that $p_{cd} = s(p_{cf} - p_f) + p_f$. Note that the controllable part is $p_{cf} - p_f$; we then multiplied it by the safety ratio s and derived p_{cd}. We selected $s = 0.5$ so that we could obtain a sufficiently large contact pressure to compensate for the object weight while avoiding fracture.

We grasped potato chips using the control method. Fig. 11 is a photo of a potato chip being grasped. Fig. 12 shows the results for the fluid pressure transition inside the fingertip (p_c). These figures show that the pressure can be controlled to its desired value, and the potato chip was successfully grasped. We repeated the same experiment five times; in every case, we succeeded at grasping the potato chip without breaking it.

In general, it is hard to grasp potato chips with the posture shown in Fig. 11, and there were individual differences in shapes and weights. We used the same desired contact pressure p_{cd} in all cases. Nonetheless, we succeeded in grasping the potato chips in every case.

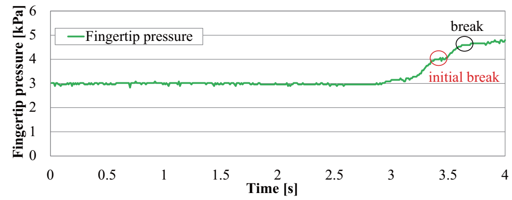


Fig. 13. Initial break when grasping soft tofu

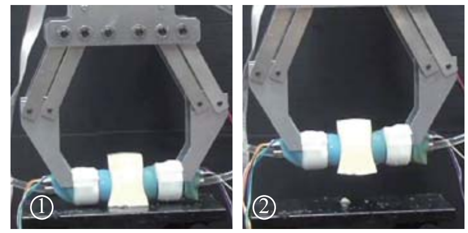


Fig. 14. Grasping of soft tofu

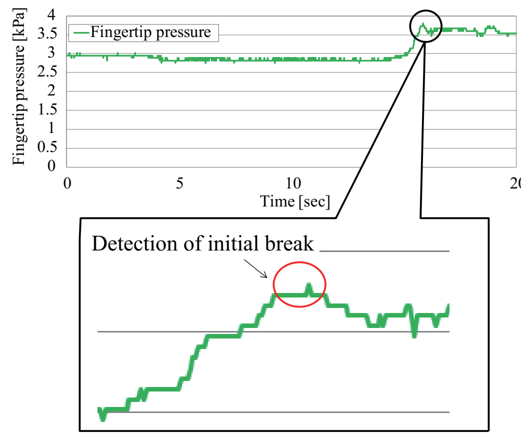


Fig. 15. Pressure profiles when grasping soft tofu

B. Grasping fragile and ductile object (soft tofu)

Fig. 13 shows the result when grasping and breaking soft tofu. In contrast to grasping brittle objects, fracture does not occur suddenly but gradually. The important point is around the red-circled area in Fig. 13. A flat line can be seen before the final fracture. Around the flat area, there is no change in appearance. We call this the initial break. If we can detect the initial break and control the contact pressure p_c such that p_c is lower than the pressure at the initial break, grasping the soft tofu without knowing the fracture stress/pressure in advance should be possible. Note that the grasping force corresponding to the contact pressure at the initial break is considered to be the maximum grasping force that can be applied without breaking the object. We thus considered the following approach to grasping soft tofu without any advance knowledge about fracture.

1) Closing the gripper until the initial break (flat area) is detected.

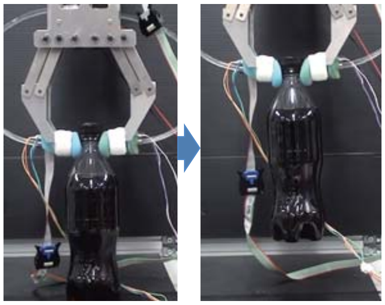


Fig. 16. Grasping of heavy object

2) If the initial break is detected, we stop closing the gripper and control the contact pressure (p_c) to its desired value.

We detected the initial break by investigating whether or not the following condition held:

$$|p_c(t) - p_c(t - t_b)| \leq \epsilon \quad (t_b = 0, \cdots, T) \tag{5}$$

where t is time, $p_c(t)$ is the contact pressure at time t, $T = 0.1$ [s] is the parameter related to how long the flat area should continue at the initial break, and ϵ is a small positive constant. We supposed that the initial break should have a sufficiently long flat line. If the flat area is short (for example, see the several flat regions before the initial break in Fig. 15), we do not regard it as the initial break. Note that breaking was allowed a few times (2 in this case) to take noise into consideration. We set the desired contact pressure p_{cd} such that $p_{cd} = p_{cI}$, where p_{cI} is the contact pressure p_c at the initial break.

Fig. 14 shows the photo of soft tofu being grasped. Fig. 15 shows the results for the transition of the contact pressure (p_c). We succeeded at grasping soft tofu without breaking it and without any advance knowledge about fracture. We repeated the same experiment five times. We succeeded at grasping the soft tofu without breaking it four times. The one failure was due to a failure to detect the initial break.

C. Grasping heavy object

To confirm the effectiveness of the two-layer structure, we conducted an experiment of grasping heavy objects using the developed gripper. The target object was a bottle of juice with a weight of 535 [g]. Fig. 16 shows the result, which demonstrated the effectiveness of the silicon layer and the grasping success.

V. Conclusion

This paper presented a novel gripper with fingertips constructed from a rubber bag filled with gel, an incompressible fluid. A silicon layer was also installed inside the gel so that not only fragile objects (special objects) but also relatively heavy, normal, and rigid objects can be grasped. Owing to the incompressibility of the fluid, simply closing the gripper allowed it to approach the target object with low stiffness; after contact, the contact stiffness increased with fingertip deformation, and grasping with high stiffness was realized. The fingertips have uniform contact pressure and can provide a contact force with a small maximum contact pressure.

We presented strategies for grasping fragile objects with the gripper. We were able to grasp potato chips (brittle object) by controlling the contact pressure such that the pressure did not exceed the fracture stress/pressure. The same strategy was valid for grasping soft tofu (ductile object). We also demonstrated another method. When grasping soft tofu, we found that invisible local fracture occurred before total fracture. Based on this characteristic, we presented a strategy for grasping soft tofu (ductile object) without any advance knowledge of fracture. Finally, we confirmed the effectiveness of the silicon layer for grasping normal heavy objects with the proposed fingertips.

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