New condition for tofu stable grasping with fluid fingertips

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***Abstract*— Tofu shows the following compression behavior. First, the behavior is non-linear; subsequently, the behavior becomes elastic/linear, followed by yielding and fracture. A linear behavior indicates that there is no fracture, but further increase of compression can cause yielding or fracture. The compression in the region of linear behavior then can be regarded as maximum. With this in mind, this paper presented a grasping condition of controlling the amount of compression so that the compression behavior can be linear. This condition is applied to the previously proposed fluid fingertip that utilizes a rubber bag filled with a viscoelastic fluid and having a rigid layer inside the fluid. In addition, this paper presents a methodology for checking whether the grasping condition is held, based on our previously developed phase change detection method of comparing the fitting accuracies of different approximation models. Additionally, this paper presents the reason behind the behavioral change of fluid pressure. Before phase change, the fluid fingertip behaves like a rigid fingertip, while after phase change, the contact pressure is transmitted to the fluid pressure and can be observed by the fluid pressure. The validity of the approach was shown through experiments.**

I. INTRODUCTION

Robotic systems that can work in a human environment are required. Robotic hands play an important role as end-effectors for such robotic systems, and many types of robotic hands have been developed [1]–[16]. In a human environment, a collision between humans and robots cannot be avoided, and thus, the surfaces of robots should be soft. With this in mind, we previously developed a robotic hand with a soft surface by filling a rubber bag with a viscoelastic fluid, and showed that the hand can grasp a wide variety of fragile objects [1]–[3]. Because of incompressibility, a uniform contact pressure distribution is obtained. Uncertainties in object shape can be absorbed by fluid deformation. These are benefits for delicate grasping of fragile objects. Additionally, a rigid layer was set inside of fluid that helped in grasping heavy rigid objects. We presented a methodology especially for grasping (Kinugoshi) tofu, which is one of the softest and most fragile objects, without using any advanced knowledge related to fracture stress. We focused on the pressure profile of the filled fluid because it corresponds to stress. If the pushing distance is increased, the rate of increase of fluid pressure decreases just before fracture. By detecting this decrease, a tofu can be grasped without fracture [1], [2]. The success rate was 4/5. The problem was too close to total fracture, and local fracture could not be avoided. We then performed a detailed investigation of the pressure profile, and presented a new method was presented [3]. We showed that tofu could be grasped without fracturing at the point where the behavior of fluid pressure changed. The drawbacks of the method are as follows.

1) Which change should be the grasping point was unclear. The strategy varied based on the filling rate of fluid in the fingertips.

2) Why the behavioral change of fluid pressure happened was unclear.

Therefore, it was not a reasonable grasping strategy, although the tofu could be grasped.

In order to overcome these drawbacks, this paper provides a novel condition for stable grasping of soft and fragile objects whose compression behavior is qualitatively similar to that of tofu. Tofu shows the following compression behavior. At the first stage of compression, the pressure exponentially increases. Subsequently the behavior becomes elastic/linear. Finally, yielding and total fracture occurs. Elastic/linear behavior indicates that the contact between an object and the fingertip can be modeled using a linear spring, and the applied force can be transmitted to the object without any loss. Fracture does not occur in the region of linear behavior. The applied force is large because linear behavior is observed before yielding, and nominal grasping conditions of frictional and equilibrium conditions can be satisfied with high possibility. The failure in the region of linear behavior indicates impossibility of grasping; required force for grasping cannot be applied. Larger grasping force causes yielding or fracture. Therefore, the grasping in this region (alternatively saying, to control the amount of compression so that the compression behavior can be elastic/linear) is a condition for tofu grasping. The condition remains the same irrespective of the filling rate of fluid. This paper also presents a methodology for detecting the elastic behavior of compressed objects. The proposed methodology is based on the phase change detection method [3] of comparing fitting accuracies of different approximation models. Additionally, this paper presents the reason behind the behavioral change of fluid pressure.

The rest of this paper is arranged as follows. The next subsection provides related works. Section 2 presents the

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basic concept of grasping conditions and applicable objects. Section 3 presents the methodology for detecting whether the grasping condition can be held. Section 4 presents the experimental results for observing the working of the grasping condition.

A. *Related works*

Anthropoid robotic hands have been developed in consideration of human affinity [4]–[10]. Normally, the surface of a finger is rigid at factories and not suitable for adaptation to human environment. Simoga and Goldenberg claimed that gel is effective for constructing the surfaces of fingertips because it can reduce contact impact and strain energy, and fit according to the shape of the object [17]. In addition to these advantages, we observed other benefits in our previous studies, i.e., a uniform contact pressure distribution and an automatic stiffness increase [1], [2]. The main drawback of using gel for fingertips is the limitation on the maximum applicable forces. Thus, a two-layer structure where a rigid component was installed inside the gel was presented in[1], [2].

To fit the target object is key for obtaining universal grasping (a wide variety of objects can be grasped by one robotic hand). A pioneer work in this regard might be the snake like gripper presented by Hirose and Umetani [11]. Kim and Song developed a gripper that included hybrid variable stiffness actuators [12]. The actuators could control contact stiffness. Brown et al. [13] developed a universal gripper for grasping objects having a wide variety of shapes. It was based on the jamming phenomenon [18], [19]. Choi and Koc developed a design of inflatable rubber pockets on the gripping sides [14] for the same purpose of grasping objects having a wide variety of shapes. Pettersson et al. utilized magnetorheological (MR) fluid for constructing a gripper that can fit to the shape of the object and provide a space for confining objects [15]. The space was formed by molding the MR fluid. Kim et al. [16] presented a soft skin for safe interaction between children and robots. The research showed that a robotic hand with soft skin could grasp several objects, including a plastic cup and a roll of paper. In the above studies, several fragile objects, including eggs and fruits, were successfully grasped. However, studies on grasping soft and fragile objects, such as tofu, are still limited.

The next step in enhancing the function of robotic hands from the viewpoint of universal grasping would be to grasp soft and fragile objects. Thus, this paper focuses on grasping soft and fragile objects, and presents a grasping strategy for such objects.

II. BASIC CONCEPT FOR GRASPING CONDITION AND APPLICABLE OBJECTS

Soft (Kinugoshi) tofu, which is a typical example of a fragile and soft object in a human environment, was used as the target object. In order to observe the compression behavior of tofu, a compression test was conducted. Fig. 1 shows the experimental setup. An indenter was attached to an automatic poisoning stage. The tofu (Topvalue, Silken tofu, size: $25 \times 25 \times 30$ [mm^3]) was pushed against a duralumin plate at a low speed of 1.0 [mm/s] to minimize the influence of speed.

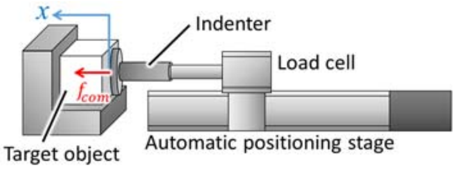

Figure 1. Experimental setup for compression test of soft (Kinugoshi) tofu

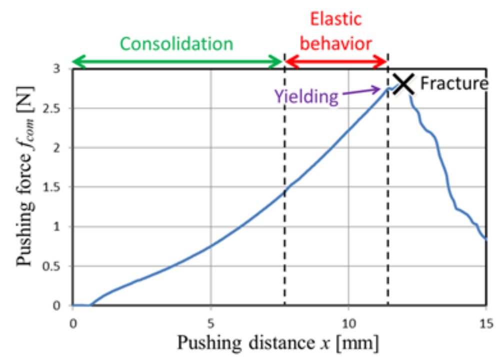

Figure 2. Results of compression test; pushing distance x [mm] versus compression force

Fig. 2 shows the result of the compression test. At first, the tofu showed a curve behavior; subsequently, a linear behavior was observed with the increase of pushing distance, followed by yielding and fracture. The curve behavior is considered to be due to the increase of density. The increase of density in tofu corresponds to consolidation [20] which is a process of decrease in volume with the decrease of water inside the object (tofu). Consolidation indicates the increase in filling rate of the solid part. An evidence that supports this assumption is the existence of water around the tofu after the compression test. The process of increase of density is non-linear. Therefore, linear behavior is not considered as the process, i.e., the increase of density stops in the region of linear behavior. Linear behavior is helpful for grasping because it indicates that the contact can be modeled using a linear spring, and compliance control can be obtained. The force applied by the robot/finger can be transmitted to the tofu without any loss in the region of linear behavior. In addition, it should be noted that linear behavior is observed before yielding and subsequent fracture. Forces in the region can be regarded as maximum applicable grasping forces without fracture. Hence, if stable grasping of tofu cannot be realized in the region of linear behavior, tofu cannot be grasped without fracture. Grasping when the compression behavior is linear is then the proposed grasping condition. Then, the only problem that remains to be solved is detecting the region of linear behavior It should be noted that frictional and equilibrium conditions (balancing of object weight) are additionally required for realizing grasping [21]. If the weight of an object is small, it is expected that these conditions can be satisfied because of the large grasping force in the region of linear behavior.

Although the target object is tofu, the grasping strategy can be applied to all objects whose compression behavior is qualitatively similar tofu (i.e., linear behavior after non-linear behavior). It should be noted that the presented condition does not depend on size or weight of objects because it is associated with not gravity compensation but fracture/yielding avoidance.

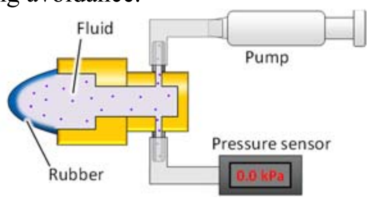

Figure 3. Schematic view of fluid fingertip

III. Methodology for Detecting Whether Grasping Condition Can Be Held

A. Fluid fingertips

We developed deformable fingertips having a two-layer structure, i.e., a fluid layer and a rigid layer. Fragile objects can be handled using the fluid layer, and normal rigid objects can be handled using the rigid layer [1], [2]. For realizing universal grasping, we will try to grasp tofu with the fingertips. Because this study focuses on grasping soft and fragile objects (tofu), we will consider only the fluid layer. For this purpose, we constructed deformable fingertips by using a rubber bag filled with a viscoelastic fluid, as shown in Fig. 3. The structure, sensors, and materials are similar to those used to fabricate the fluid fingertip in our previous study [3].

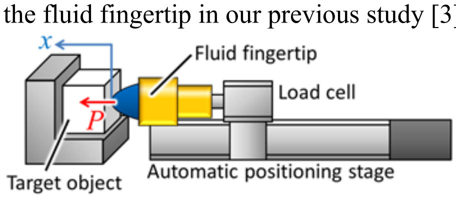

Figure 4. Experimental setup for compression test of tofu using fluid fingertip

B. Overview of methodology

The area where the grasping condition can be held corresponds to the area where the compression behavior of the object is linear. An overview of the methodology for detecting the area is presented below.

Step 1. Detect the point where the fluid pressure inside the fingertip corresponds to the contact pressure of the object. After detecting the point, the contact pressure of the object can be observed via the fluid pressure.

Step 2. Detect points where the compression behavior is linear through the fluid pressure.

As described later, at the first stage of compressing the tofu, the fluid pressure does not correspond to the contact pressure of the object, and we cannot observe the state of tofu via the fluid pressure. This is the reason why step 1 is conducted before step 2.

The detection method is based on the phase change detection method [3] of comparing the fitting accuracies of different approximation models.

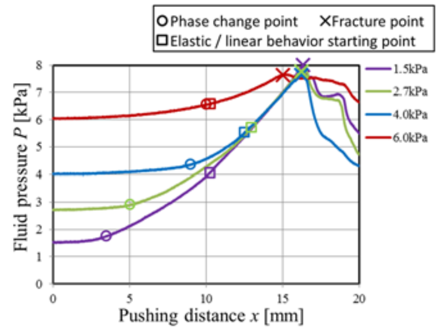

Figure 5. Pushing distance x versus fluid pressure P in compression test of tofu using fluid fingertip (initial fluid pressures (the pressure when there is no contact) were 1.5, 2.7, 4.0, and 6.0 [kPa])

C. Compression test of tofu by fluid fingertips

Fig. 4 shows the experimental setup. The fluid fingertip was attached to a handmade load cell (allowable load: 20 [N]; resolution: 0.01 [N]) that was fixed on an automatic positioning stage. The tofu was pushed by the fluid fingertip at a low speed of 1.0 [mm/s] to minimize the influence of speed. The experiment was conducted until the tofu was completely broken. The experiment was conducted at initial fluid pressures (the pressure when there is no contact) of 1.5, 2.7, 4.0, and 6.0 [kPa]. The initial pressures were chosen by considering allowable maximum and minimum tensions of rubber surface. It should be noted that the filling rate of the fluid was 1.5, 2.7, 4.0, and 6.0 [kPa]. The experiments were conducted three times for each condition.

Fig. 5 shows the results where mean values are displayed for convenience. When the initial fluid pressure was 1.5, 2.7, and 4.0 [kPa], the curve converged to one line. When the initial fluid pressure was 6.0 [kPa], linear behavior was observed, but it was different from those observed under other conditions. The presented methodology is to detect the region of linear behavior.

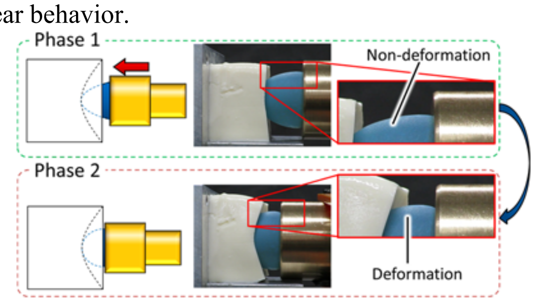

Figure 6. Schematic views of phase 1 (fluid fingertip behaves like rigid fingertip) and phase 2 (Contact pressure of the object can be transmitted to the fluid in the fingertip)

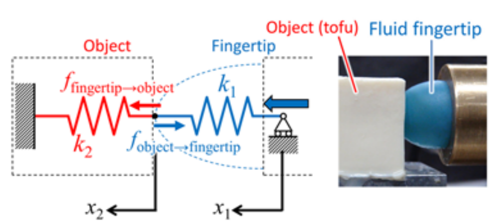

Figure 7. Model of interaction between the fluid fingertip and soft object (tofu).

D. *Step 1: detection of the point where the fluid pressure inside the fingertips becomes to correspond to the contact pressure of the object*

As shown in Fig. 5, if the pushing distance x is small, the value of the fluid pressure does not change significantly. Here, we focused on the interaction between the fluid fingertip and the tofu, and defined two phases, as shown in Fig. 6. At phase 1, the fluid fingertip does not deform while the object deforms. The fluid fingertip behaves like a rigid fingertip. Phase 1 can be observed when the pushing distance x is small. If the pushing distance x is increased, phase 2 can be observed. At phase 2, both the fluid fingertip and object deform; this phenomenon is called phase change. Note that here, only two phases were used for explanation, but there could be more than two phases. In that case, there could be more than one phase change.

Here, we constructed a simple model for describing the phenomenon (Fig. 7). For easy understanding, a spring model was used, and viscosity was neglected (because of the low speed of the test). Let k_1 and k_2 be the stiffnesses of the fingertip and the object, respectively; x_1 and x_2 denote the displacements of the fingertip and the object, $f_{\text{object}\rightarrow\text{fingertip}}$ be the force applied to the fingertip by the object, and $f_{\text{fingertip}\rightarrow\text{object}}$ be the force applied to the object by the fingertip. Then, we obtain

$$f_{\text{object}\rightarrow\text{fingertip}} = k_1(x_1 - x_2) \tag{1}$$

$$f_{\text{fingertip}\rightarrow\text{object}} = k_2 x_2 \tag{2}$$

From $f_{\text{object}\rightarrow\text{fingertip}} = f_{\text{fingertip}\rightarrow\text{object}}$, we have

$$x_1 = \left(1 + \frac{k_2}{k_1}\right) x_2 \tag{3}$$

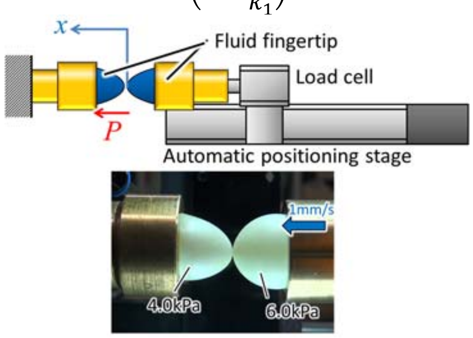

Figure 8. Experimental setup for pushing the fluid fingertip with an initial fluid pressure of 4.0 [kPa] by the fluid fingertip with an initial fluid pressure of 6.0 [kPa]

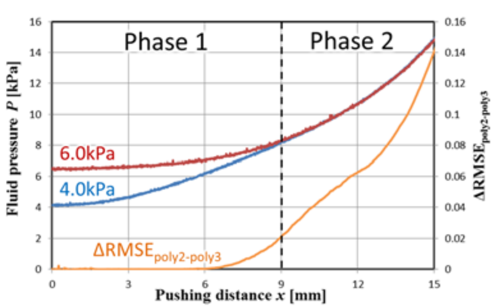

Figure 9. Results of the experiment shown in Fig. 8; pushing distance x [mm] versus fluid pressures with the $\Delta\text{RMSE}_{\text{poly2}-\text{poly3}}$ for the fluid fingertip with the an initial fluid pressure of 6.0 [kPa]

It should be noted that k_1 and k_2 changes with the change in displacements x_1 and x_2, as shown in Figs. 2, 5. Here, we suppose the case when the stiffness of the fluid fingertip is greater than that of the object initially (when there is no contact). In this case, $k_1 \gg k_2$. Then, (3) becomes

$$x_1 = \left(1 + \frac{k_2}{k_1}\right) x_2 \cong x_2 \tag{4}$$

It indicates that the fingertip displacement x_1 corresponds to the deformation of the tofu x_2, i.e., there is no deformation in the fingertip, and the fingertip behaves like a rigid fingertip. This state corresponds to phase 1. We observed the captured image at phase 1, and found that there was no deformation of the fingertip at phase 1 (Note that only visible parts were examined), as shown in Fig. 6. A slight increase in fluid pressure (see Fig. 5) is also an evidence. It should be noted that at phase 1, the fluid pressure does not correspond to the contact pressure of the object. Therefore, the fluid pressure cannot be used for observing the contact pressure at phase 1.

At phase 2, the deformation of the fingertip was observed, as shown in Fig. 6, although the deformation was small. Thus, the contact pressure can be observed via the fluid pressure at the fingertip in phase 2.

In order to verify it, we conducted experiments where a fluid fingertip was used instead of the tofu, as shown in Fig. 8. A direct measurement of the internal pressure of the tofu was not possible; thus, we conducted this experiment to simulate the pushing of tofu by the fluid fingertip. For the simulation, the fluid fingertip having an initial fluid pressure of 4.0 [kPa] was pushed by the fluid fingertip having an initial fluid pressure of 6.0 [kPa]. Fig. 9 shows the results of the experiment; the behavior of fluid pressure of the fingertip with an initial fluid pressure of 6.0 [kPa] was very close to the case when the tofu was pushed, as shown in Fig. 5. At first, the fluid pressure of the fluid fingertip with an initial fluid pressure of 4.0 [kPa] increased. When the pushing distance was increased, phase change occurred, and the fluid pressure of both the fingertips increased. The value of fluid pressure for both the fingertips became similar. Phase 2 corresponds to the state where the fluid pressure of both the fingertips increased, while phase 1 corresponds to the state when the fluid pressure of the fluid fingertip with a larger initial fluid pressure of 6.0 [kPa] did not increase. It should be noted that phase change was detected by checking whether $\Delta\text{RMSE}_{\text{poly2}-\text{poly3}}$ exceeded the threshold value (more detail will be described later). Although the structure of the fluid fingertip was different from that of the tofu, the results support the findings; the fluid fingertip behaves like a rigid fingertip at phase 1, while the contact pressure can be transmitted to the fluid and can be observed via the fluid pressure at phase 2. Therefore, in order to detect the area where the presented grasping condition can be held via fluid pressure, we need to stay at phase 2. Hence, as a first step, we need to detect (first) phase change (Recall that there could be more than one phase change).

The methodology is based on our previous one [3], which compared the fitting accuracies of different approximation models. Simple and complex fitting models were prepared for the approximation. For easy understanding, two- and three-dimensional polynomial functions were assumed to represent simple and complex fitting models, respectively. The regression started from the point where the pushing distance x was 0.1 [mm] (the number of data points was 10). Regression was performed each time new data were available, and the root mean squared error (RMSE) was calculated for each model. Let $\mathrm{RMSE_{poly2}}$ and $\mathrm{RMSE_{poly3}}$ be the RMSE for two- (simple) and three-dimensional (complex) polynomial functions. Then, the RMSE difference was computed as follows:

$$\Delta\mathrm{RMSE_{poly2-poly3}} = \mathrm{RMSE_{poly2}} - \mathrm{RMSE_{poly3}} \qquad (5)$$

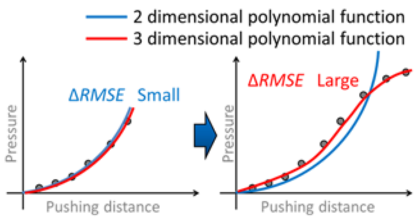

Figure 10. Phase change detection method

Suppose the simple and complex models describe data well before phase change, because of a simple data arrangement. In this case, $\Delta\mathrm{RMSE_{poly2-poly3}}$ is small (see Fig. 10 left). During phase change, the data is rearranged, and new data deviates from the original data arrangement. In this case, the simple model might not be able to describe the data adequately, while the complex model can do so. Then, the $\Delta\mathrm{RMSE_{poly2-poly3}}$ could become large (see Fig. 10 right). Hence, by checking whether the value of $\Delta\mathrm{RMSE_{poly2-poly3}}$ exceeds a threshold value (0.001), phase change can be detected. It should be noted that in our previous paper, $\Delta\mathrm{RMSE_{poly2-poly3}}$ was continuously calculated after (first) phase change, and an attempt was made to obtain another phase change. However, the change of $\Delta\mathrm{RMSE_{poly2-poly3}}$ after (first) phase change lost physical meaning. Thus, we stopped the regression after (first) phase change in this paper. The regression was restarted, and the starting point was selected as the point just after phase change.

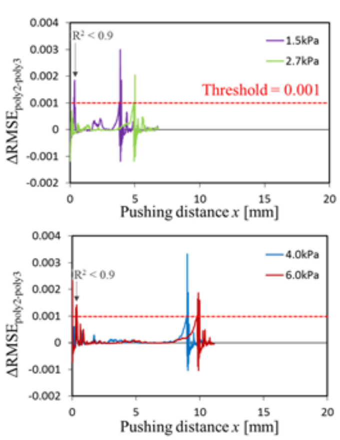

Figure 11. Pushing distance x [mm] versus $\Delta\mathrm{RMSE_{poly2-poly3}}$

Fig. 11 shows the calculated $\Delta\mathrm{RMSE_{poly2-poly3}}$ for detecting the first phase change for the data shown in Fig. 5. It can be seen that phase change was successfully detected. It should be noted that when the number of data is small, RMSE does not work well. We then ignored cases when $\mathrm{R}^2 < 0.9$ (R is coefficient of determination), which corresponds to the case when the pushing distance x was close to zero.

E. *Step2: Detect the points where compression behavior is linear.*

Suppose the number of data is increased in increments of one when conducting linear regression. The keys for detecting linear/elastic behavior are determining a method to continuously obtain the same slope of the regression line, and appropriate setting of the starting point for regression.

A one-dimensional polynomial function was prepared for regression. Regression was performed each time new data were available, and the coefficient of determination (R^2) and the slope (a of $P = ax + b$) of the regression line were derived. The coefficient of determination (R^2) and the deviation of the slope were evaluated. The deviation of the slope (a_d) was determined using

$$a_\mathrm{d}(x_k) = \frac{1}{10}\sum_{i=1}^{10} \frac{|a(x_{k-i}) - a(x_k)|}{a(x_k)} \qquad (6)$$

where x_k is the kth point of x, and $a_\mathrm{d}(x_k)$ is the a_d at x_k. If the deviation of the slope (a_d) was less than the threshold value (0.92), and the coefficient of determination (R^2) exceeded the threshold value (0.9), we judged that the data arrangement showed a linear/elastic behavior.

For setting the starting point for regression, we used the phase change detection method. We subsequently checked phase change after the first phase change was detected, and the data were split into several phases. Linear regression was applied to split phases. The point just after phase change was set as the starting point for regression. Phase change indicates the change of the fitting model. Therefore, this strategy was suitable for detecting linear behavior.

Table 1 shows the points where linear behavior was observed, and grasping condition was satisfied. Recall that the compression test was conducted three times for each condition. Small deviations showed the stability of the proposed detection methodology. The points are also shown in Fig. 5, where it can be seen that the detection method worked well.

Fig. 12 summarizes the procedure for detecting points where linear behavior was observed, and grasping condition was satisfied.

TABLE I. THE POINTS WHERE LINEAR BEHAVIOR WAS OBSERVED, AND GRASPING CONDITION WAS SATISFIED

Initial fluid pressure [kPa]	**1.5**	**2.7**	**4.0**	**6.0**
The (grasping) points x_g [mm]	11.6	13.8	12.6	10.4
Standard deviation of x_g [mm]	0.5	0.3	0.1	0.4

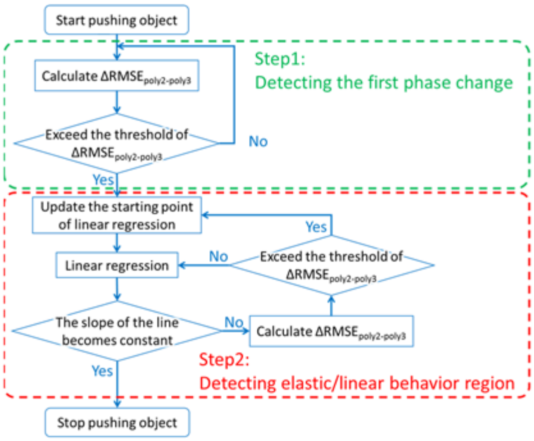

Figure 12. Procedure for detecting the points where linear behavior was observed, and grasping condition was satisfied

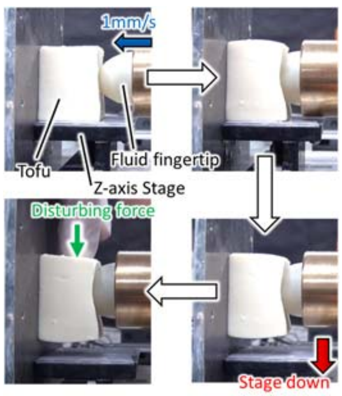

Figure 13. Experimental procedure for grasping soft (Kinugoshi) tofu

IV. Experimental Confirmation of How the Proposed Grasping Condition Worked

In order to observe how the proposed grasping strategy works, we conducted experiments for grasping a tofu. The experimental setup is shown in Fig. 4. The procedure of performing the experiments is shown in Fig. 13. The dimensions and weight (22.7 [g]) of all the tofus were same. The fluid fingertip was pushed against the tofu at a speed of 1.0 mm/s. We stopped when the pushing distance was $x_l = 4$, 6, 8, 10, 12, and 14 [mm], and the Z-axis of the stage on which the tofu was placed was moved in the lower direction for grasping. After checking whether the tofu was grasped (fall down), a disturbing force was exerted in the direction of gravitational force manually, in order to observe the stability of grasping. If the tofu did not fall down, the grasping was judged to be stable. If the tofu fell down, the grasping was judged to be unstable. The manual disturbance was not quantitative. Then, we measured the amplitude of fluid pressure in the fingertip when the disturbing force was applied, as shown in Fig. 14. Table 2 lists the measured mean amplitude for each condition. The magnitude of the disturbing force when the grasping was stable was lower than or equal to that when the grasping was unstable, except for one or two cases. Thus, it can be concluded that the evaluation/judgment was valid. The initial fluid pressure in the fingertip (when there is no contact) was set as 1.5, 2.7, 4.0, and 6.0 [kPa]. The experiments were conducted three times for each condition.

Table 2 summarizes the results of the experiment. It can be seen that if the pushing distance during the experiment (x_l) is larger than the pushing distance at the point where the compression behavior becomes linear (Table 1), the grasping was successful for each case and the grasping was stable. It indicates that the proposed grasping condition is valid. It should be noted that the proposed condition is not a necessary condition, but a sufficient and conservative condition. Linear behavior is observed before yielding, and corresponds to the case when a relatively large grasping force is applied to the object. If the weight of an object is small, the magnitudes of the grasping force is sufficient to satisfy frictional and equilibrium conditions. In this case, grasping is guaranteed to succeed if only the proposed condition is satisfied. This is the reason why grasping succeeded for each case listed in Table 2. If the proposed condition is not satisfied, it cannot be confirmed whether grasping was successful (therefore, there could be cases when grasping succeeded even if the proposed condition is not satisfied).

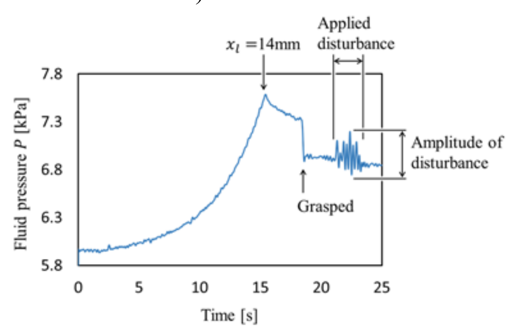

Figure 14. Time series data of the fluid pressure P (initial fluid pressure: 6 kPa, pushing distance x_l: 14 mm). The first peak (indicated by the arrow) denote the point when the pushing distance x_l was 14mm. The second peak denotes the point when the tofu was grasped.

V. Conclusion

This paper presented a novel condition for grasping objects whose compression behavior is qualitatively similar to that of tofu. We applied the condition to the fluid fingertip that utilizes a rubber bag filled with a viscoelastic fluid [1]–[3]. The compression behavior of tofu shows the following trend: at first, the behavior is non-linear, followed by linear behavior. Finally, yielding and fracture occurs. The grasping condition is to control the amount of compression so that the compression behavior can be elastic/linear. When the grasping condition is satisfied, it indicates that there is no fracture, and the contact between the fluid fingertips and the object can be modeled using a liner spring, and contact force by the fingertip can be transmitted without any loss. Therefore, stable grasping can be easily obtained (by a simple controller). Contact pressure can be observed through the fluid pressure of the fingertips (because linear behavior is observed in phase 2, as shown in Figs. 7 and 10). Linear behavior is observed before yielding, and corresponds to the case when the grasping force is relatively large. Thus, if the weight of an object small, the grasping force is sufficient to satisfy frictional and equilibrium conditions. In this case, grasping succeeds only if the proposed condition is satisfied.

TABLE II. EXPERIMENTAL RESULTS FOR GRASPING TOFU AT AN INITIAL FLUID PRESSURE OF 1.5, 2.7, 4.0, AND 6.0 [KPA]. THE CONDITIONS WHEN THE PUSHING DISTANCE EXCEED THE GRASPING POINTS ARE INDICATED IN BOLD.

Initial fluid pressure [kPa]	Pushing distace x_l [mm]	Success rate $(\frac{\text{Number of successes}}{\text{Number of trials}})$	Stability	Measured mean amplitude of disturbance [kPa]
1.5	4 [mm]	0/3	-	-
	6 [mm]	0/3	-	-
	8 [mm]	3/3	Unstable	0.633
	10 [mm]	3/3	Stable	0.674
	12 [mm]	**3/3**	**Stable**	**0.502**
	14[mm]	**3/3**	**Stable**	**0.477**
2.7	4 [mm]	0/3	-	-
	6 [mm]	3/3	Unstable	0.207
	8 [mm]	3/3	Unstable	0.439
	10 [mm]	3/3	Unstable	0.518
	12 [mm]	3/3	Stable	0.514
	14[mm]	**3/3**	**Stable**	**0.456**
4.0	4 [mm]	0/3	-	-
	6 [mm]	0/3	-	-
	8 [mm]	3/3	Unstable	0.351
	10 [mm]	3/3	Unstable	0.600
	12 [mm]	**3/3**	**Stable**	**0.822**
	14[mm]	**3/3**	**Stable**	**0.658**
6.0	4 [mm]	0/3	-	-
	6 [mm]	0/3	-	-
	8 [mm]	3/3	Unstable	0.165
	10 [mm]	**3/3**	**Stable**	**0.307**
	12 [mm]	**3/3**	**Stable**	**0.581**
	14[mm]	**3/3**	**Stable**	**0.497**

This paper also presented a methodology for detecting whether the proposed grasping condition was satisfied. The methodology was based on the phase change detection method [3] of comparing the fitting accuracies of different approximation models. Phase change indicates the change of fitting/approximation model. By using the phase change detection method, the starting point of each phase was detected. By applying linear regression to the data from the obtained starting point, we determined the points where the slope of the regression line was constant under the condition of good fitting accuracy. The obtained points correspond to points where the compression behavior is linear.

We also presented the reason behind (first) phase change, which was unclear in the previous study [3]. In the phase just before phase change, there was a slight increase in fluid pressure, and the fingertip behaves like a rigid fingertip. In the phase after phase change, the internal pressure of the object (contact pressure) is transmitted to the fluid pressure, and the contact pressure can be observed through the fluid pressure.

The linear behavior of compression suggests the possibility of construction of a controller for (tofu) manipulation. This will be discussed in a future study.

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