Identification of Danger State for Grasping Delicate Tofu with Fingertips Containing Viscoelastic Fluid

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Identification of danger state for grasping delicate tofu with fingertips containing viscoelastic fluid

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***Abstract*— In this study, we experimentally investigated the process leading to fracture in tofu grasping by deformable fingertips filled with a fluid. In our previous papers [1, 2], we developed deformable fingertips using a rubber bag filled with a viscoelastic fluid, and presented a strategy for delicate tofu grasping without any advance knowledge about fracture. However, the predication point was close to fracture, and the prediction was then still a gamble. In order to realize fracture prediction at an earlier stage, we examined the process leading to fracture when pushing tofu by the deformable fingertips. The stiffness of the fingertips can be controlled with the pressure of the fluid inside the fingertips. The pushing force and fluid pressure were examined for different levels of stiffness of the fingertips. The main findings and contributions are as follows. 1) The convergence of the ratio of the contact force to fluid pressure gives an indication of dent occurrence. This convergence could be seen when fingertip rubber bag was not filled (low stiffness). 2) It was easier for a dent to occur when the fingertip rubber bag was not filled than when it was filled (high stiffness). 3) Changes in the rate of increase of the fluid pressure as the tofu was pushed were repeatedly observed. We defined this as a phase change and present a method for detecting such changes. The phase change points were detected by comparing the fitting accuracies of different approximation models. 4) The last and second to the last phase changes before fracture were detected by detecting the first phase change (after the convergence of the rate of the contact force to fluid pressure if the fingertip bag was not completely filled). The detected points can be regarded as alert points indicating a fracture risk that is not close to the fracture point.**

I. INTRODUCTION

Everyday tasks must be performed by robots in order to support humans. Robotic hands [1–13] have essential roles as end-effectors to complete such tasks. In order to substitute for the hands of a human, robotic hands must be able to perform a wide variety of functions to grasp and manipulate objects. Most of the developed robotic hands have targeted rigid object grasping [3-9], with only a few targeting delicate grasping [1, 2, 10–13]. In the human environment, there are many fragile and soft objects such as foods and living tissues. If a robot could deal with such fragile and soft objects, it is expected that autonomous humanlike cooking and safe medical operations could be realized by robots. One of the softest and most fragile objects is (soft) tofu, which can be used as phantom objects simulating brain tumors [14]. With this in mind, this study targeted tofu grasping without breaking.

We previously presented [1, 2] a robotic gripper whose fingertips (contact area) consisted of a rubber bag filled with a viscoelastic fluid or gel (Fig. 1). The fluid pressure can be measured with a pressure sensor inside the fingertips. The main benefits of this hand for delicate grasping are as follows. 1) A uniform contact pressure distribution is obtained thanks to its viscoelasticity and incompressibility. 2) A rigid object can be grasped by using the rigid layer of the fingertip. 3) Fracture can be predicted before total fracture when grasping a fragile and soft object such as tofu. Fracture is in the pressure or stress domain, and the fluid pressure profile has the potential to show the fracture characteristic of a ductile material: the increasing rate of stress decreases in the stress–strain diagram just before breaking. In real situations, a decrease in the increasing rate of fluid pressure was observed. We called this the initial break. We then formulated a strategy for grasping delicate ductile objects (tofu) without any advance knowledge about fracture. If the initial break was detected, the robot gripper stopped closing and picked up the object. We succeeded in grasping the object four out of five times. However, there were still serious problems. As the name initial break indicates, the detection point was very close to the total fracture. The decrease in the increasing rate of fluid pressure was sometimes unclear. Therefore, avoiding a fracture was still close to a gamble. In addition, local/partial fracture could not be avoided. If the prediction could be done at an earlier stage, safer delicate grasping could be realized. In addition, the characteristics of the developed viscoelastic fluid fingertips were still unclear.

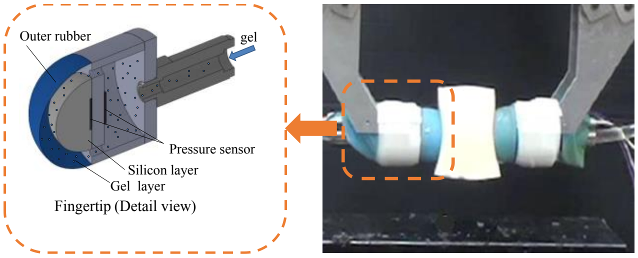

Figure 1. Structure of deformable fingertip and tofu grasping in [1, 2]

With this in mind, this study experimentally investigated the phenomenon when pushing tofu using the viscoelastic fluid fingertips. The main findings and contributions are as follows.

1) The convergence of the ratio of the contact force to fluid pressure gave an indication of dent occurrence. This convergence could be seen when the fingertips were not completely filled with the fluid.

2) It was easier for a dent to occur when the fingertip rubber bag was not filled than when it was filled.

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3) A change in the increasing rate of the fluid pressure gave an indication of an alternation of the material (tofu) related to a preliminary step/stage toward the yielding and fracture of the tofu. This paper presents a method to detect/estimate this indication: the phase change points. The phase change points were detected by comparing the fitting accuracies of different approximation models.

4) By detecting the first phase change when the fingertip rubber bag was filled and the first phase change after the convergence of the rate of the contact force to fluid pressure when the fingertip rubber bag was not filled, the last and second to the last phase change points before fracture could be detected. We called these points the danger area starting points, and used them as a warning of the fracture risk. The pushing force at the danger area starting points could be regarded as the maximum grasping force free of the risk of fracture. We investigated tofu grasping with the pushing forces and showed that safe tofu grasping could be realized. Note that the danger area starting points were not close to the initial break points presented in our previous paper [1, 2].

The remaining parts of this paper are as follows. The subsequent subsection describes the related works. In section 2, we introduce the developed fingertip system for delicate grasping. In section 3, we describe the investigation of the phenomenon when pushing tofu using the viscoelastic fluid fingertips. We also discuss the method for detecting the phase change points. In section 4, we discuss danger area starting points, and show the experimental results of tofu grasping with the pushing force at the danger area starting points.

A. *Related works*

The efficiency of using gel for fingertips was discussed by Simoga and Goldenberg [15]. They claimed that gel is effective at reducing the contact impact and strain energy and fitting the object shape. We found other benefits from using gel in our previous studies: a uniform contact pressure profile and an automatic stiffness increase [1, 2]. The main drawback of using gel for fingertips is the limitation of the maximum applicable forces. Thus, we constructed a two-layer structure where a rigid component was installed inside the gel for grasping relatively heavy objects.

Kim and Song developed a gripper that included hybrid variable stiffness actuators that could control the contact stiffness [10]. Brown et al. [11] developed a gripper that utilized a jamming phenomenon based on the ideas presented in [16] and [17]. Choi and Koc developed a gripper with inflatable rubber pockets on the gripping sides [12]. Their pneumatic inflation made it possible to grasp objects with a wide variety of shapes. Pettersson et al. presented a gripper with a gripping area covered by a magnetorheological (MR) fluid [13]. The area with the MR fluid was molded according to the object shape, and the object was confined inside the space formed by the molded MR fluid. In the above studies, eggs or fruits were successfully grasped. However, the main targets were not fracture control, and none of these studies considered fragile and soft objects such as tofu.

II. VISCOELASTIC FLUID FINGERTIPS

A. *Structure*

In the previous studies [1, 2], we developed deformable fingertips with a two-layer structure. Its purpose was to make it possible to handle both fragile objects using the fluid layer and normal rigid objects using the rigid layer. Because this study focuses on grasping fragile objects (tofu), we will consider only the fluid layer here. For this purpose, we constructed deformable fingertips using a rubber bag filled with a viscoelastic fluid, as shown in Fig. 2. The radius of each fingertip was 11 [mm]. The outer rubber material was made of nitrile, and the fluid was oil (chainsaw oil, ISO VG 100 (International Organization for Standard Viscosity Grade)). In contrast to previous fingertips, a screw clamp was used to improve the sealing performance. Thus, a fluid with a low viscosity could be used. A pressure sensor (KEYENCE, AP-12s) was connected using a tube. A piston was also connected using a tube to control the fluid pressure. According to Pascal's law, if a fluid is incompressible, the pressure is the same everywhere, even when an external pressure/force is applied to the container used to confine the fluid. Additionally, a change in the fluid volume indicates a change in the fluid pressure. Therefore, by controlling the piston, we could control the fluid pressure. The main body was made of brass to prevent corrode.

Because of the deformability of the fingertip, the fingertip shape conformed to the object shape. As we showed in the previous papers [1, 2], the contact pressure distribution was uniform. These two features made it very effective for grasping fragile objects. The fingertip stiffness increased with an increase in the deformation, as we also showed in the previous papers [1, 2]. However, we did not previously investigate the contact force. Here, we experimentally investigated the behaviors of the contact force and fluid pressure at the same time.

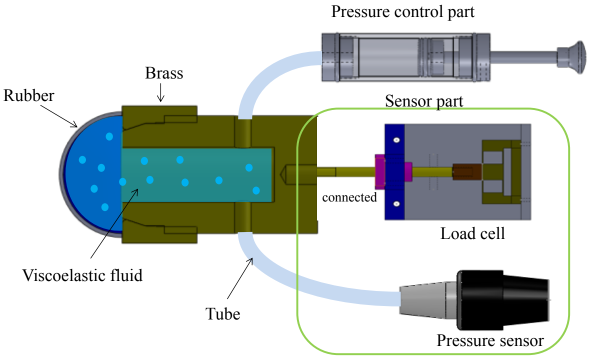


Figure 2. Structture of deformable fingertip constructed from rubber bag filled with viscoelastic fluid

B. *Behaviors of applied load and fluid pressure of fingertip when pushing against flat plate*

Fig. 3 shows the experimental setup for investigating the behaviors of the fluid pressure and pushing force, and determining the stiffness of the fingertip. The fingertip was attached to a handmade load cell (allowable load: 20 [N]; resolution: 0.01[N]) fixed on an automatic positioning stage so that the fingertip position and speed could be controlled. We pushed the fingertip against a duralumin plate a slow speed of

1.0 [mm/s] to minimize the influence of the speed. We conducted the investigation with initial fluid pressure (the pressure when there is no contact) values of 1.5, 2.7, 4.0, and 6.0 [kPa]. The ascending filling rate order for the fluid was 1.5, 2.7, 4.0, and 6.0 [kPa].

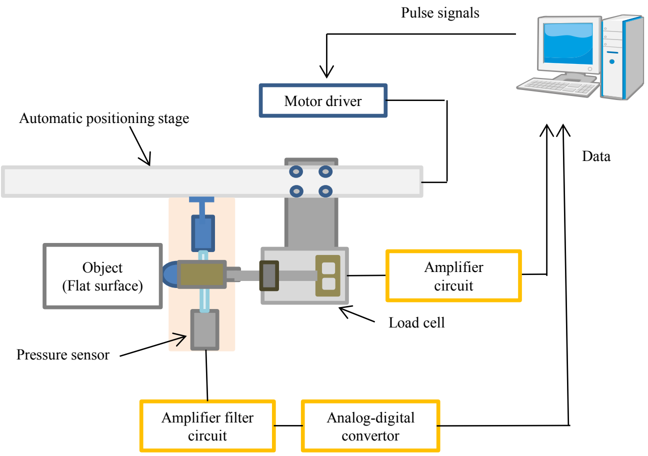
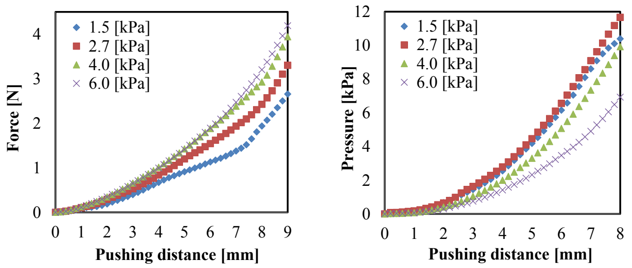


Figure 3. Schematic view of experimental setup when fingertip pushed duralumin plate at speed of 1.0 [mm/s]



(a) Applied force

(b) Fluid pressure

Figure 4. Results when fingertip pushed duralumin plate at speed of 1.0 [mm/s]: (a) Pushing distance versus applied force, (b) Pushing distance versus fluid pressure

Fig. 4 shows the results. Note that the pressure shown is the differential pressure compared to the initial pressure. Hereafter, we simply call this differential pressure "pressure" except for special cases. The horizontal axis shows the moving/pushing distance (pushing amount) of the fingertip. It can be seen that the order of the initial pressure corresponds to the order of the fingertip stiffness. There is little difference in the applied force between the cases when the internal fluid pressure (p_{in}) is 4.0 and 6.0 [kPa], while there is little difference in the fluid pressure between the cases when the internal fluid pressure (p_{in}) is 1.5 and 2.7 [kPa]. However, the behavior of the force curves is complex/nonlinear when p_{in} is 1.5 and 2.7 [kPa]. One reason is that the fingertip rubber bag was not filled with fluid when there was no contact at p_{in} = 1.5 and 2.7 [kPa], while it was filled at p_{in} = 4.0 and 6.0 [kPa]. Therefore, from the force and pressure profiles when pushing against a flat plate, we can determine whether the fingertip rubber bag is filled.

III. COMPRESSION TEST OF TOFU BY VISCOELASTIC FLUID FINGERTIPS

We investigated the phenomena when breaking tofu. The experimental setup was the same as the previous one shown in Fig. 3, except for the object being contacted. Instead of the flat surface, a fragile object, tofu (Topvalue, Silken tofu, size: 25 × 25 × 30 [mm^3]), was used. The tofu and fingertip were in contact with each other at the initial state without any contact pressure or contact force. Then, by moving the automatic positioning stage, the tofu was pressed by the fingertip at a speed of 1 [mm/s] until the tofu completely broke, as shown in Fig. 5. The experiment was conducted with initial internal fluid pressures (p_{in}) of 1.5, 2.7, 4.0, and 6.0 [kPa]. In order to determine the repeatability, the experiments were conducted three times for every condition. Note that pushing an object against a flat plate with one fingertip produces the same physical conditions as pushing an object from both sides with two fingertips.

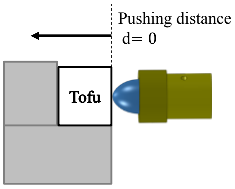
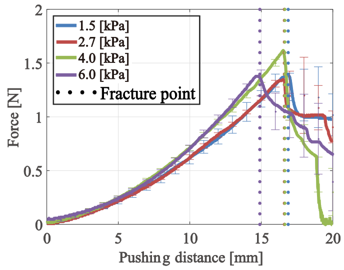
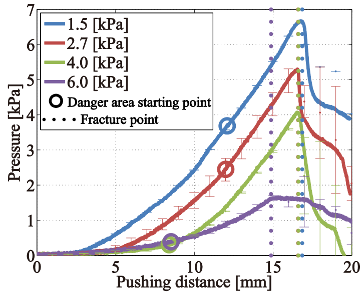


Figure 5. Close-up of fingertip area in experimental setup for breaking tofu



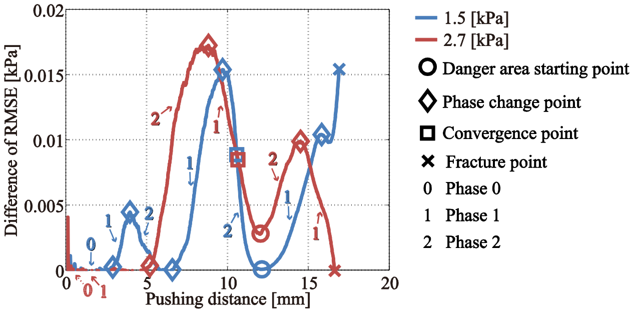
(a) Pushing distance versus applied force, where dotted lines show fracture points



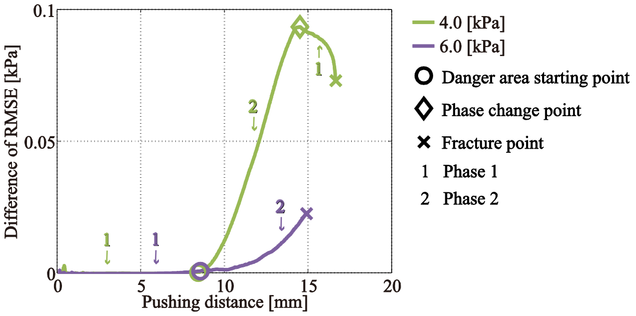
(b) Pushing distance versus differential fluid pressure, where dotted lines show fracture points and circles show detected danger area starting points

Figure 6. Results of breaking tofu by pushing it at speed of 1.0 [mm/s]

Fig. 6 shows the results. One case for every condition (rigid line) and the mean value with the standard deviation (point and error bar) are shown for easy visualization. Fig. 6 (a) shows the applied force profile. There is no significant difference if these values are separated into two cases: a small initial pressure (at p_{in} = 1.5 or 2.7 [kPa] (not-filled fingertip)) and large initial pressure (at p_{in} = 4.0 or 6.0 [kPa] (filled fingertip)). Fig. 6 (b) shows the fluid pressure profile. Note that this pressure is the differential pressure, and a relatively larger differential pressure was obtained when p_{in} was smaller. The dotted line is the point where the tofu broke. The broken points were determined to be the points just before which the fluid pressure had decreased for 0.1 [sec]. We focused on the decrease in pressure, because the fracture is in the pressure or stress domain and there was no clear difference of the decrease between using force and pressure. Note also that a relatively flat area can be seen just before the tofu broke (although it is not easy to see especially at $p_{\mathrm{in}} = 4.0$ [kPa]). This is the initial break area discussed in our previous papers [1, 2]. The purpose of this study was to detect the danger area for breaking before this area. The pressure profile is nonlinear, and both an area where the increasing rate is rapid and an area where the increasing rate is slow can be seen. Thus, the profile is divided into several phases.



(a) Pushing distance versus ΔRMSE when initial pressure was low ($p_{\mathrm{in}} = 1.5$ and 2.7 [kPa]), where circles show danger area starting points, squares show convergence points, diamonds show other phase change points, and X-marks show fracture points



(b) Pushing distance versus ΔRMSE when initial pressure was high ($p_{\mathrm{in}} = 4.0$ and 6.0 [kPa]), where circles show danger area starting points, diamonds show other phase change points, and X-marks show fracture points

Figure 7. Results for phase change detection

A. Phase change detection

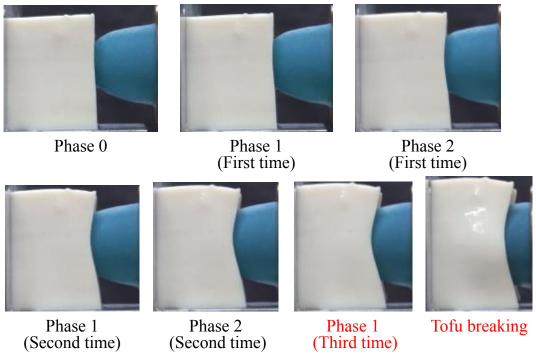
A change in phase appeared with an increasing rate of fluid pressure (see Fig. 6 (b)). However, this change was not easy to see. Therefore, a method to make the change clearer was needed. This paper presents a method based on the difference in the fitting accuracies of different approximation models. When the phase changed, the arrangement of data also changed. If new data deviated from the original data, a more complex model would be required for good fitting accuracy. In this case, the difference in the fitting accuracies of complex and simple models would be large. If new data decreased the effect of the deviation/variation of the original data, a simpler model would be sufficient to describe the data. In this case, the difference in the fitting accuracies of complex and simple models would be small. Namely, the difference in the fitting accuracies of complex and simple models could be used to predict the phase change. Based on this concept, the following method was developed.

Method: Two (simple) and three (complex) dimensional polynomial functions were prepared for approximation models. The regression started from the case when the pushing distance was 0.1 (the number of data points was 10). Every time new data became available, regression was performed, and the root mean squared error (RMSE) was calculated for every model. The RMSE difference was computed. The local minimum and maximum points and the initial rise point were taken as the phase change points.

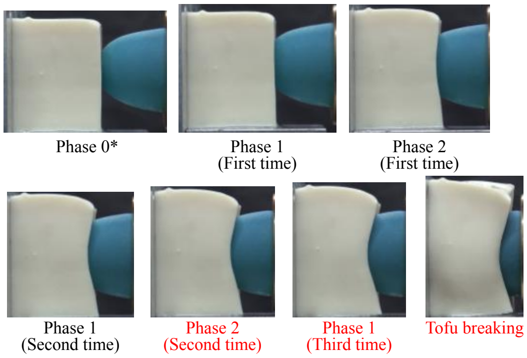
Let $\mathrm{RMSE}_{\mathrm{poly2}}$ and $\mathrm{RMSE}_{\mathrm{poly3}}$ be the RMSE values for two (simple) and three (complex) dimensional polynomial functions. Then, the RMSE difference can be written as follows:

$$\Delta\mathrm{RMSE} = \mathrm{RMSE}_{\mathrm{poly2}} - \mathrm{RMSE}_{\mathrm{poly3}}$$

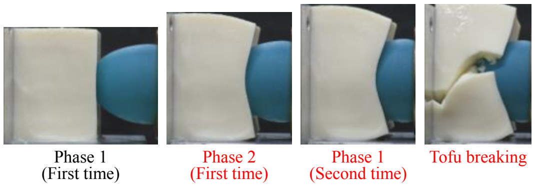
Fig. 7 shows the calculated ΔRMSE for each case. Note that to make it easy to see, one case for every condition is shown, but the qualitatively same profiles (same number of waves) were obtained for every condition. The local minimum and maximum points and the initial rise point are the phase change points (circles and diamond shapes in Fig. 7). It can be seen that the phases, which are not easy to detect in Fig. 6 (b), can be clearly distinguished. According to the results and from observing the movies, the following phases were defined.



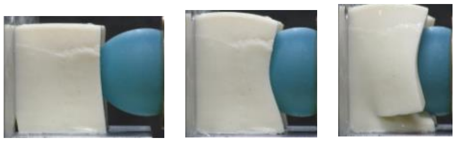
p_{in} **(Initial pressure)=1.5 [kPa]**



p_{in} **(Initial pressure)=2.7 [kPa]**



p_{in} **(Initial pressure)=4.0 [kPa]**



Phase 1 Phase 2 Tofu breaking

p_{in} **(Initial pressure)=6.0 [kPa]**

Figure 8. Photos of each phase when pushing tofu, with the red colored phases corresponding to danger areas (*Note that Phase 0 at p_{in} = 2.7 [kPa] was derived manually because it was not detected by the phase change point analysis)

Phase 0: The fingertip (internal fluid) pressed against the tofu because the rubber bag of the fingertip was not filled. This phase is basically the same as phase 2. The difference is when it occurs (before phase 1) and the tofu does not stretch.

Phase 1: The fingertip dented the tofu

Phase 2: The denting by the fingertip decreased due to the increase in the tofu stiffness. The fingertip swelled while the tofu stretched.

Fig. 8 shows a photo at every phase. Note that Phase 0 was not detected by the method at p_{in} = 2.7 [kPa] because its period/term was short. It was observed that phase 1 and phase 2 were alternately repeated, especially when p_{in} was low (p_{in} = 1.5 or 2.7 [kPa]). The phase change is considered to be the result of the change in relative stiffness between the tofu and the fingertip. If the fingertip was stiffer than the tofu, the fingertip dents the tofu (Phase 1), whereas if the tofu was stiffer than the fingertip, denting by the fingertip decreased (Phase 2). A dent/yielding could occur in the change from Phase 2 to Phase 1, because at Phase 2, the tofu stores a large strain energy preventing the penetration of fingertip, whereas the phase change indicates that the stiffness of the fingertip overcomes that of the tofu. A change from Phase 1 to Phase 2 indicates that the tofu becomes hard. This alternation also means that a large strain energy is stored and the risk of breaking increases. Therefore, the key for preventing the tofu from breaking might be to detect the point where the last or second to the last phase change occurs before breaking. The detection point is defined as the starting point for the danger area. When p_{in} is high (p_{in} = 4.0 or 6.0 [kPa]), the first phase change corresponds to the last or second to the last phase change. Therefore, it is sufficient to detect the first phase change. However, this is not true when p_{in} is low (p_{in} = 1.5 or 2.7 [kPa]). In this case, which phase change point to consider becomes the issue. In order to resolve this issue, we focused on the rate of the applied force to the fluid pressure, as shown in Fig. 9. In order to avoid dividing by zero, the following rate was used:

$$\frac{f}{p+\epsilon_0}$$

where f denotes the applied force, p denotes the differential fluid pressure, and ϵ_0 (= 0.001) denotes a small constant.

In order to see the state of yielding, we also observed the appearance of the contact surface of the tofu with pushing distances (d) of 5, 10, and 15 [mm], as shown in Fig. 10.

When p_{in} was low (p_{in} = 1.5 or 2.7 [kPa]), the rate converged to a certain value (see square marks). At the convergence point, the rate of increase for the applied force was the same as that for the fluid pressure. This meant the applied force was directly transferred to the fingertip fluid. It was believed that a kind of assimilation between the tofu and fingertip could have occurred. Based on the phase change point analysis shown in Fig. 7 (a), multiple phase changes were considered to have occurred before the convergence. Especially the change from Phase 2 to Phase 1 is important because it could cause a dent/yielding. When the fingertip rubber bag was not filled, the rubber bag could have wrinkles in this situation. Because of capillarity, a high-pressure area could occur at a wrinkle, which could cause a partial dent in the tofu. It could proceed especially at a phase change from Phase 2 to Phase 1. In practice, a small dent of tofu could be seen around this convergence point, as shown in Fig. 10 (10 mm). However, the dent was small and far from the complete fracture. It can be said that at the convergence point, the tofu changed and a dent could be seen, but the complete fracture could be avoided if the application of the force stopped. The phase at the convergence point was safe from the viewpoint of complete fracture. Inversely, there was at least one phase change after the convergence with a high possibility for fracture. Therefore, we devised a way to detect the first phase change point after the convergence, and defined this phase change point as the starting point for the danger area.

It is also interesting to note that a smaller initial pressure resulted in a clearer/larger dent. One reason might be the large number of phase changes. If a small dent is not desired, a larger initial pressure (the fingertip rubber bag is filled) should be used for grasping.

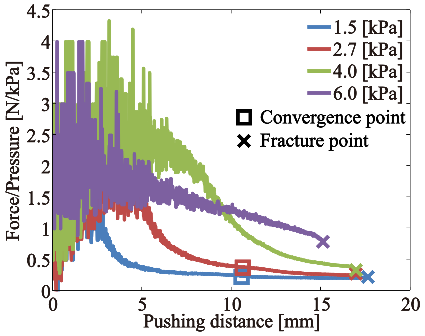
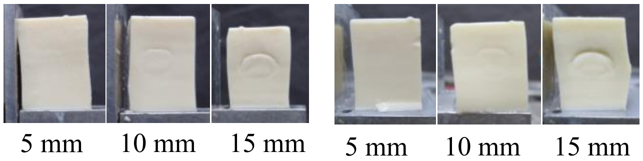
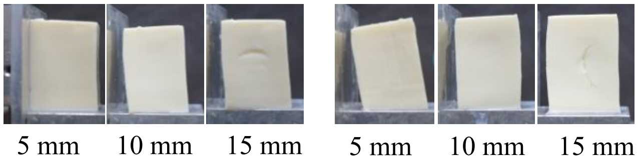


Figure 9. Pushing distance versus ratio of applied force to fluid pressure, with squares showing convergence points and X-marks showing fracture points



p_{in} **(Initial pressure) = 1.5 [kPa]** p_{in} **(Initial pressure) = 2.7 [kPa]**



p_{in} **(Initial pressure) = 4.0 [kPa]** p_{in} **(Initial pressure) = 6.0 [kPa]**

Figure 10. Photos of contact surfaces after pushing tofu when pushing distances were 5, 10, and 15 [mm]

IV. DANGER AREA STARTING POINT FOR AVOIDING FRACTURE AND DELICATE TOFU GRASPING

Based on the definition mentioned above, the danger area starting points were detected as follows.

Step 1) If fingertip rubber bag is filled, go to step 3, letting $d_\mathrm{s} = 0$. Otherwise go to step 2.
Step 2) Detect the convergence point for the rate of applied force to fluid pressure. Let $d_\mathrm{s}$be the pushing distance at the convergence point.
Step 3) Detect the first phase change point, counting from d_s.

The obtained danger area starting points (circle marks) are shown in Fig. 7. These danger area starting points are also shown in Fig. 6 (b). It can be seen that the danger area starting points are the last or second to the last phase change points before breaking if we ignore the phase changes very close to the breaking points, and are not very close to nor far away from the breaking points. Thus, it can be said that the points can be used as warnings of the potential for fracture.

On the other hand, the danger area starting points can be regarded as grasping points. The danger area starting point indicates that increasing the pushing distance/force from this point presents a risk of fracture, whereas fracture can be avoided if the pushing distance (applied force) is not increased any further. In other words, the pushing distance/force at the danger area starting point is the guaranteed maximum (grasping) force that can avoid fracture. In addition, a phase change from Phase 1 to Phase 2 indicated an alteration in the tofu (it became hard), and there have been reports that a harder contact area can produce larger frictional forces when contacting soft materials [18, 19]. Therefore, easier grasping can be expected compared to previous phases. In this regard, a simple grasping strategy is to grasp an object with the force at the danger area starting point. This is preferable if the grasping succeeds, because the grasping force has the guaranteed maximum value. If the grasping fails, there is no other choice but gradually increasing the grasping force (so that breaking does not occur). With this in mind, we attempted to grasp tofu using the pushing amount (force) at the danger area starting point. The nominal method is to calculate ΔRMSE step by step and detect the danger area starting point. However, here, in order to verify the repeatability of the methodologies, the mean of the pushing distances (forces) at the danger area starting points obtained in the experiments described in the previous section was calculated and used (Table 1).

The experimental setup was the same as the one shown in Fig. 5, except the table for the tofu was removed. First, by moving the automatic positioning stage, we pressed on the tofu with the fingertip using the mean pushing distance/force at the danger area starting points. Subsequently, the table for tofu was removed to determine whether grasping could be realized. Three trials were conducted for every condition (p_{in}).

Fig. 11 shows the results. The grasping succeeded under all the conditions and in all the trials, which showed the validity of our approach. It can be said that the danger area starting points could work as grasping points for delicate tofu grasping, although to be precise, whether grasping could be performed also depended on the weight of the object. When the fingertip rubber bag was not filled (p_{in} = 1.5 and 2.7 [kPa]), the grasping points came after the convergence of the rate of the applied force to fluid pressure, and the occurrence of dents could not be avoided. On the other hand, when the fingertip rubber bag was filled (p_{in} = 4.0 and 6.0 [kPa]), only a small dent could be seen.

TABLE I. MEAN VALUE OF DERIVED PUSHING DISTANCE AT DANGER AREA STARTING POINTS

Initial pressure p_{in} [kPa]	1.5	2.7	4.0	6.0
Mean pushing distance [mm]	12.6	12.4	8.8	9.1


Grasping tofu
Tofu's surface after grasping
Grasping tofu
Tofu's surface after grasping

p_{in} (Initial pressure) = 1.5 [kPa] **p_{in} (Initial pressure) = 2.7 [kPa]**


Grasping tofu
Tofu's surface after grasping
Grasping tofu
Tofu's surface after grasping

p_{in} (Initial pressure) = 4.0 [kPa] **p_{in} (Initial pressure) = 6.0 [kPa]**

Figure 11. Results when grasping tofu using mean pushing distance/force at danger area starting points and Tofu's surface after grasping

V. CONCLUSION

In this study, we experimentally investigated the process leading to fracture in tofu grasping using a deformable fingertip fabricated with a rubber bag filled with a fluid. In our previous papers [1, 2], we developed deformable fingertips using a rubber bag filled with a viscoelastic fluid, and presented a strategy for delicate tofu grasping without any advance knowledge about fracture. A decrease in the increasing rate of fluid pressure was observed just before the complete facture. By detecting this decrease, we succeeded in grasping tofu without breaking. However, the detection point was close to the complete fracture. It is definitely preferable for fracture prediction to be done at an earlier stage. Aiming at the realization of early fracture prediction, we investigated the phenomena that occurred when a deformable fingertip fabricated with a rubber bag filled with a fluid was pushed against tofu. The main findings and contributions are as follows (see also Table 2 for the major differences between the cases using fingertips with low and high initial pressures).

- **The convergence of the ratio of the contact force to fluid pressure caused the occurrence of dents in the tofu**. The convergence occurred only when the fingertip rubber bag was not filled (p_{in} = 1.5 or 2.7 [kPa]).
- **A higher initial pressure for the fluid in the fingertip rubber bag made it less likely for dents to occur.**

- **Phase changes were observed**. There were mainly two phases: the fingertip dented the tofu and the fingertip denting decreased when the fingertip swelled. These two phases were alternately repeated until breakage occurred.
- **Phase change detection method**: The phase change points were detected by comparing the fitting accuracies of different approximation models.
- **Danger area starting point detection**: By detecting the first phase change when the fingertip rubber bag was filled and the first phase change after the convergence of the rate of the applied force to fluid pressure when the fingertip rubber bag was not filled, the last or second to the last phase change point before fracture could be detected. If the applied force was increased from that point, a risk of breaking was considered to occur. We called these points the danger area starting points, and used them as warnings of fracture risk. The danger area starting points were not close to the initial break points presented in our previous papers [1, 2].
- **Tofu delicate grasping without breaking**: We showed that tofu grasping using the (pushing) force at the danger area starting points succeeded under all conditions of initial fingertip fluid pressure. This means the danger area starting points could work as grasping points for delicate grasping without breaking.

There appears to be no merit in using fingertips with a low filling rate of the fluid. However, if much softer objects are targeted, convergence may not occur and breaking may easily occur with filled fingertips. In that case, the strategy for filled fingertips can be applied to grasping with non-filled fingertips. In summary, this study provided multiple fundamental methodologies for dealing with soft and fragile objects. Which method should be taken depends on the materials of object and fingertips. More detailed investigation for this issue is beyond of scope of this paper and might be topics for future works.

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TABLE II. MAJOR DIFFERENCES BETWEEN CASES USING FINGERTIPS WITH LOW AND HIGH INITIAL PRESSURES

Initial pressure of fingertip p_{in} [kPa]	High (4.0, 6.0)	Low (1.5, 2.7)
Stiffness of fingertip	High	Low
Convergence speed of $\frac{f}{p+\epsilon_0}$	Slow	Fast
Dent risk	Low	High
Number of phase changes	Low frequency	High frequency
Prediction of danger area	Easy	Complex