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Bent Sheet Grasping Stability for Sheet Manipulation

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***Abstract*— In this study, we focused on sheet manipulation with robotic hands. This manipulation involves grasping the sides of the sheet and utilizing the convex area resulting from bending the sheet. This sheet manipulation requires the development of a model of a bent sheet grasped with fingertips. We investigated the relationship between the grasping force and bending of the sheet and developed a bent sheet model. We also performed experiments on the sheet grasping stability with a focus on the resistible force, which is defined as the maximum external force at which a fingertip can maintain contact when applying an external force. The main findings and contributions are as follows: 1) After the sheet buckles, the grasping force only increases slightly even if the fingertip pressure is increased. 2) The range of the applicable grasping forces depends on the stiffness of the fingertips. Stiffer fingertips cannot provide a small grasping force but can resist large external forces. Softer fingertips can provide a small grasping force but cannot resist large external forces. 3) A grasping strategy for sheet manipulation is presented that is based on controlling the stiffness of the fingertips.**

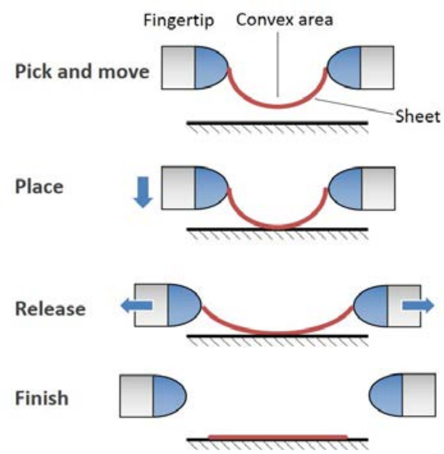

Fig. 1. Example of sheet manipulation.

I. INTRODUCTION

Sheet manipulation is widely used in factories, medicine, and daily life. Examples include bonding a sheet-shaped film to a plate in factories, bonding a cell sheet on heart/organs or in a petri dish, and bonding a protective sheet on smartphones. Conventionally, specialized machines are used for sheet manipulation. If a multi-fingered robotic hand could be used, the functions of robotic hands may be expanded.

Fig.1 shows a typical example of sheet manipulation, which is considered as a manipulation that a multi-fingered robotic hand can deal with. For the sake of convenience, the simplest and the most fundamental mode of grasping, i.e., with two opposing fingertips, was considered here. The manipulation is conducted by grasping the sides of sheet. It is assumed that one face of the sheet has a bonding agent. The manipulation includes bending of the sheet not only for preventing bonding of the sheet to fingertips but also for precise placement of the sheet. Without bending, the whole area of the sheet face would need to be positioned at the same time. Bending allows the (initial) contact area to be small by utilizing the convex area resulted from bending, which makes precise positioning and bonding easy. Planning the fingertip motions also becomes easier. In the concrete case of bonding a protective sheet to a smartphone, additional entrained air between the sheet and smartphone should be prevented. Our final goal in this study was to conduct such a sheet manipulation. It should be noted that some parts of this manipulation can correspond to steps for pinching sheet objects such as envelops, papers, and cards. The manipulation methods can also be applied to the task of conveying large metal sheets with mobile robots. Thus, target manipulation is considered as one of the fundamental tasks in order to realize widely varying sheet manipulations. We focused on manipulation without external sensors such as a camera. Manipulation with external sensors would be expected to be more precise. The other assumptions are that the target objects are not bent by its own gravity and that the manipulation is quasi-static. These assumptions indicate the applicable types of sheets in this paper.

The merits of the sheet manipulation proposed here comparing to the conventional method utilizing suction systems are as follows. First, the conventional method cannot always deal with the shape and condition of the surface. Suction requires a smooth surface and cannot be used when there is a liquid such as a bonding agent on the surface. However, such a case can be handled with the proposed sheet manipulation. Second, manipulation with suction requires a specific machine structure, and only specialized tasks can be carried out. The proposed method can be conducted with many kinds of robotic hands such as grippers and multi-fingered hands. In order to realize the proposed sheet manipulation (without

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external sensors), methods for estimating the sheet bending state from internal sensors such as force sensors embedded in fingertips are required. This paper presents a sheet model for an estimation based on the Euler-Bernoulli beam theory. The sheet model can also give the characteristics of the sheet manipulation. The design of appropriate fingertips and grasping stability analysis are also important issues. Softer fingertips can envelop the sides of the sheet and should easily grasp the sheet even when bending occurs. On the other hand, stiffer fingertips can apply large grasping forces and resist large external forces. In sum, there may be an appropriate fingertip stiffness depending on each step of the proposed sheet manipulation. As a first step, we investigated the relationship between the grasping force and the bending of a sheet in order to construct a bent sheet model. We also performed an experiment on the sheet grasping stability to consider the maximum resistible force, which is defined as the maximum external force at which the fingertip can maintain contact when applying an external force. Based on the results, we developed a design of appropriate fingertips and a grasping strategy for the proposed sheet manipulation. The main contributions and findings are as follows:

1) After buckling, the grasping force increases only slightly even as the fingertip pressure is increased. A bent sheet model representing this phenomenon is presented.
2) The range of the applicable grasping force depends on the stiffness of the fingertips. A stiffer fingertip cannot provide a small grasping force but can resist large external forces. A softer fingertip can provide a small grasping force and grasping with small forces. However, large external forces cannot be resisted.
3) A grasping strategy for sheet manipulation is presented that is based on controlling the stiffness of the fingertips.

A. Related works

To the best of our knowledge, there has been no research that dealt with sheet manipulation by explicitly utilizing bending. Belts are similar objects to sheet, and a model and manipulation strategy were presented by Hirai et al. [1], [2]. Ueda et al. [3] conducted the method of acquisition of a page turning skill. M. Moll and L. E. Kavraki [4] introduced a method of path planning for deformable linear object (e.g. flexible wire). T. Bretl and Z. McCarthy [5] reported mechanics and manipulation planning of chain with a fixed base in which each joint is an elastic element. L. Sun et al. [6] developed a system which can flatten garments by accurate surface analysis using RGB-D images. Odhner [7] proposed a model of robots having planar elastic flexure joints by using the Euler-Bernoulli beam theory.

In the material mechanics field, different research groups have presented buckling models. Amirbayat and Hearle [8] presented the buckling theory of flexible sheet materials. Byklum [9] derived a computational model for buckling analysis of stiffened panels. However, the relation between the grasping force and sheet deformation is unclear.

Watanabe et al. [10], [11], [12] investigated the effects of fingertip stiffness on the grasping stability by performing experiments. These studies focused on the contact between rigid objects and soft fingers. In the sheet manipulation considered here, the elasticity of the bent sheet needs to be considered, and its phenomena are still unclear.

II. MECHANICS OF BENT SHEET

The grasping-style compression test of the sheet was used to understand the mechanics of the sheet. Three types of fingertips was used to investigate the effect of the stiffness around the contact area: rigid material, elastic material, and fluid fingertips. These were respectively made from ABS plastic, silicon, and a rubber bag filled with machine oil. Based on the experimental results, the sheet model is presented with the Euler model for buckling and elastica theory. The theoretical and experimental results were compared for validation.

A. Grasping-style compression test of sheet

Fig. 2 shows the experimental setup for the grasping-style compression test of the sheet. The fingertip on one side was fixed, while the fingertip on the other side could be moved by the automatic positioning stage. The configuration was the same as the gripper with two fingertips. Initially the sheet located between the fingertips was on the stand. By closing the fingertips, the sheet was compressed. The sheet was always deflected upward because of the stand. The movable fingertip was attached to a handmade load cell fixed on an automatic positioning stage, and the grasping force (in the pushing direction) was measured. A camera was used to observe the deformation of the sheet. Fig. 3 shows photos of the sheet and fingertips. The sheet was made of PET and had dimensions of 70 mm $\times$ 100 mm $\times$ 0.41 mm, which are equivalent to the size of a screen for a smartphone. The rigid material, elastic material, and fluid fingertips were respectively made of ABS plastic, silicon, and a rubber bag filled with machine oil (ISO VG 100). The surface of each fingertip was covered with nitrile rubber to ensure the same friction conditions. The fluid fingertip was the same as the one used for grasping fragile objects in our previous studies [13]. The stiffness of the fluid fingertip can be controlled by adjusting the fluid pressure inside the rubber bag. In this experiment, the initial fluid pressures of the fluid fingertips were set to 3 and 6 kPa. The moveable and fixed

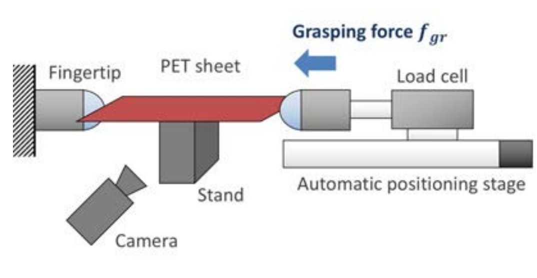

Fig. 2. Schematic illustration of the experimental setup for the grasping-style compression test of the sheet.

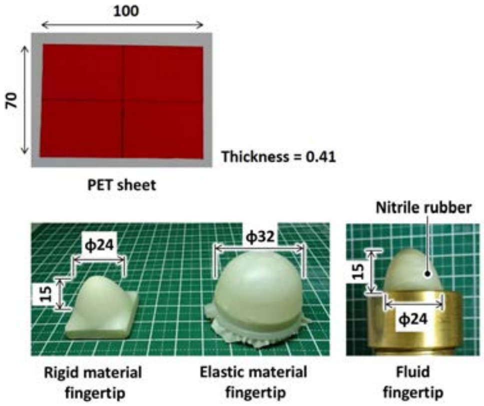

Fig. 3. Photo of the sheet and fingertips used in the experiments.

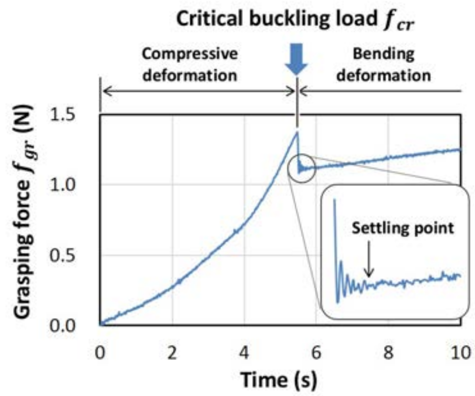

Fig. 4. Time series data of the grasping force f_{gr} for a fluid fingertip (initial pressure: 3 kPa). The peak (indicated by the arrow) is the critical buckling load.

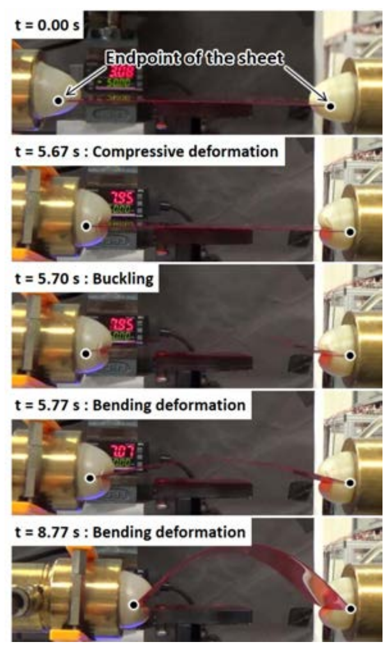

Fig. 5. Photos of side views when the sheet was grasped with the fluid fingertips (initial pressure: 3 kPa): t = 0.00 s the fingertips contact the sheet; t = 5.67 s the fingertips deform; t = 5.70 s the sheet buckles; t = 5.77 s the sheet vibrations settle; t $>$ 5.77 s the sheet is bent.The circles show the (derived) endpoints of the sheet.

fingertips were the same type. The movable fingertip was pushed against the sheet at a speed of 3.0 mm/s to minimize the influence of the deforming speed. The test was conducted three times for each fingertip.

Fig. 4 shows the time series data of the grasping force for the fluid fingertip with an initial fluid pressure of 3 kPa to clarify the behavior. Fig. 5 shows the corresponding photos. The fingertip surface deformed until the force reached its peak (t = 5.67 s). The deformation mode changed due to buckling, and the grasping force suddenly greatly decreased. A small vibration was observed. After that, the grasping force slightly increased thanks to the stiffness resulting from the bending deformation of the sheet. Based on the experimental results, we derived the relationship between the sheet deformation and grasping force.

If totally considering, success rates for grasping sheet using rigid material, elastic material, fluid (initial pressure: 6 kPa) and fluid (initial pressure: 3 kPa) fingertips are 54.5%, 37.5%, 100% and 100% respectively. It should be noted that no statistically significant difference is observed between the success rates for grasping sheets, using rigid material and elastic material. It can be seen that softer (fluid) fingertips have the advantage for realizing grasping. Note that if taking into account rigid material fingertips got better results than elastic material fingertips, there might be a threshold of stiffness of fingertips to increase the success rate of grasping.

Fig. 6 shows the time series data for all cases when the direction of initial small deformation was upward. After buckling, the rate of increase in the grasping force was very little. We present the model of this phenomenon in the next subsection. The ascending order of the required time to reach buckling was as follows: rigid material, elastic material, fluid (initial pressure: 6 kPa), and fluid (initial pressure: 3 kPa) fingertips. This corresponded to the order of stiffness. A softer fingertip decreased the rate of increase in the grasping force.

This indicates that, if a fingertip is stiff like the rigid material, the grasping force can easily reach the buckling force just after contact. Therefore, it is difficult to control the grasping force just after contact. Additional small perturbations in the contact position can make the grasping force exit the friction cone because the sheet has a small contact area. Thus, slip can easily occur and make it hard to keep grasping the sheet. If the fingertips are softer like the fluid fingertip, the rate of increase in the grasping force is small, and the sheet around the contact area is enveloped by the fingertips. Deviations in the contact position can be absorbed. Therefore, the grasping force can be located inside friction cone, and the grasping can be easily maintained.

Fig. 7 shows the displacement of the endpoint of the sheet δ in each case when the vibration by buckling settled. The endpoint was defined as the endpoint of the sheet when viewing from the side (see Fig. 5). The displacement of the

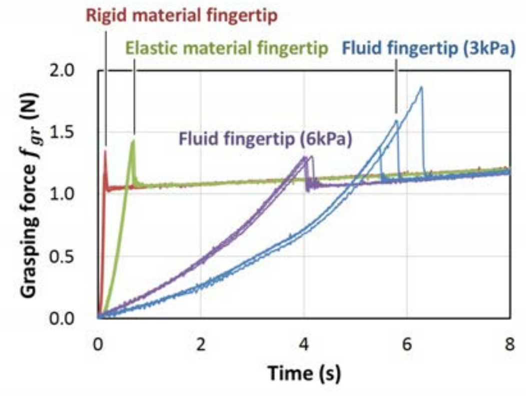

Fig. 6. Time series data for the grasping force f_{gr} of each fingertip. The ascending order for the required time to reach buckling was as follows: rigid material, elastic material, fluid (initial pressure: 6 kPa), and fluid (initial pressure: 3 kPa) fingertips.

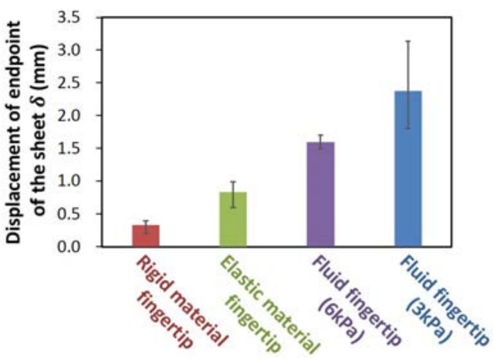

Fig. 7. Displacement of the endpoint of the sheet δ when the vibration from buckling settled. The ascending order of the displacement was as follows: rigid material, elastic material, fluid (initial pressure: 6 kPa) and fluid (initial pressure: 3 kPa) fingertips.

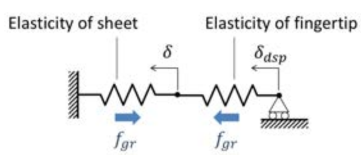

Fig. 8. Relationship between the displacement of the endpoint of the sheet δ related with the grasping force f_{gr} and the displacement of the fingertip δ_{dsp}.

endpoint of the sheet δ was acquired from the photos of side views when the sheet was grasped. It should be noted that $\delta = \delta_{dsp} - \delta_{dfm}$ where δ_{dsp} is the displacement of the fingertip and δ_{dfm} is the deformation of the fingertip at the endpoints. Fig. 8 shows the relationship between the displacement of the endpoint of the sheet δ and the displacement of the fingertip δ_{dsp}. Softer fingertips produced larger sheet deformations. The required time for buckling increased for softer fingertips. This indicates that the distance between fingertips was small for buckling and that the distance between the extreme points of the sheet are small. If a small deformation of the sheet is required after buckling, stiffer fingertips are preferable.

B. Mechanics of bent sheet

We considered a two-dimensional model with symmetric properties. First, we considered the critical buckling load f_{cr} at which sheet deformation mode changes (see Fig. 4). As the grasping force increases, the deformation mode changes when the load reaches a certain value (critical buckling load f_{cr}), and buckling occurs (see Fig. 5). By utilizing Euler's column formula [14], the critical buckling load f_{cr} can be represented by

$$f_{cr} = \frac{\pi^2}{l_0^2} EI \tag{1}$$

where l_0 is the length of the sheet, I is the second moment of the area of the sheet, and E is Young's modulus of the sheet.

Next, we focused on the bending deformation of the sheet after buckling in order to model bending. The contact between the fingertip and the sheet can be regarded as rotationally free, because rotations at the contact point can be observed, as seen in the photo of the experiment (see Fig. 5). We then assumed the bent beam model shown in Fig. 9 for the sheet. Bending moment $M(x)$ at x can be represented by

$$M(x) = f_{gr} y(x) \tag{2}$$

where $y(x)$ is the deflection of the sheet at x. The bending moment $M(x)$ causes the bending deformation of the sheet. The relationship between the bending moment $M(x)$ and the deflection of the sheet $y(x)$ is represented by

$$EI \frac{d^2 y(x)}{dx^2} = -M(x) \tag{3}$$

This equation is the beam bending equation based on the Euler-Bernoulli beam theory [14]. From (2) and (3), we obtain

$$EI \frac{d^2 y(x)}{dx^2} + f_{gr} y(x) = 0 \tag{4}$$

Let A be the deflection at the center of sheet. Let l be the distance between the endpoints of the sheet. Note that, if the sheet bends, l does not always equal l_0. From (4) and the boundary conditions at both endpoints of the sheet ($y(0) = y(l) = 0$), we obtain

$$y(x) = A \sin \frac{\pi}{l} x \tag{5}$$

Next, we derived the deflection at the center of the sheet A. The deflection of the sheet is considered to mainly be caused by bending (compressive deformation in the direction along the curve of the bent sheet is negligible). The length of the curve for the bent sheet S is then the same as the length of the sheet l_0, and we get

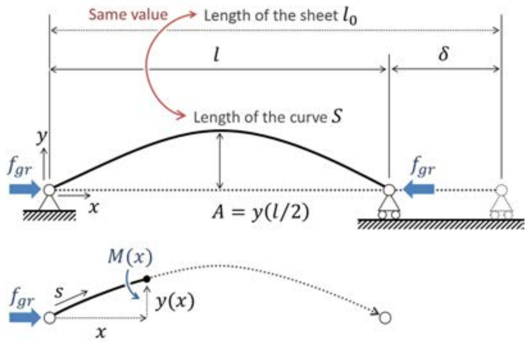

Fig. 9. Schematic illustration of the bent sheet model.

$$l_0 = S = \int_0^l \sqrt{1 + \left(\frac{dy(x)}{dx}\right)^2} dx = \int_0^l \sqrt{1 + \left(\frac{A\pi}{l}\right)^2 \cos^2 \frac{\pi}{l} x dx} \quad (6)$$

Here the deviation of S is based on differential geometry [15]. By utilizing this equation, A can be numerically obtained.

Finally, we derived the relation between the grasping force f_{gr} and the displacement of the endpoint of the sheet δ based on the potential energy. Assuming that the sheet can be represented by simply-supported Euler's column (see Fig. 9), from elastica theory [16], the potential energy of the sheet U is represented by

$$U = \frac{EI}{2} \int_0^{l_0} \left(\frac{d\theta}{ds}\right)^2 ds - f_{gr}\delta \quad (7)$$

where s denotes the coordinate along the curve of the bent sheet, and θ is the rotation of the column cross section (the deflection angle) of the bent sheet at s. The first term corresponds to the strain energy and the second term corresponds to the work done by f_{gr}. In Fig.6, the energy dissipation was observed at buckling. Letting f_{dis} be the corresponding dissipative force, the potential energy of the sheet after buckling $U_{after\ buckling}$ can be represented by

$$U_{after\ buckling} = \frac{EI}{2} \int_0^{l_0} \left(\frac{d\theta}{ds}\right)^2 ds - f_{gr}\left(l_0 - \int_0^{l_0} \cos\theta ds\right) + f_{dis}\left(l_0 - \int_0^{l_0} \cos\theta ds\right) \quad (8)$$

where $\delta = l_0 - \int_0^{l_0} \cos\theta ds$ was used. The third term corresponds to the work done by f_{dis}, namely the dissipated energy. A perturbation method [16] was applied to obtain the relation between f_{gr} and δ. By perturbing the potential energy U around the buckling point ($f_{gr} = f_{cr}$ and $\theta = 0$), we get

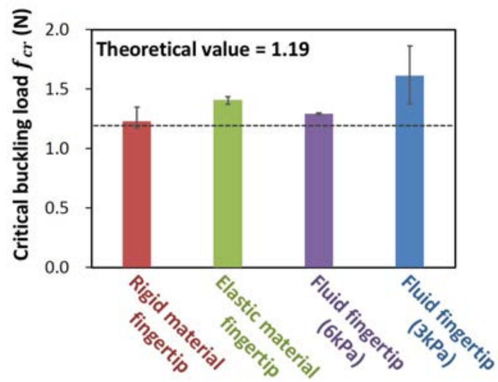

Fig. 10. Comparison of the experimental critical buckling loads f_{cr} and the theoretical value from (1).

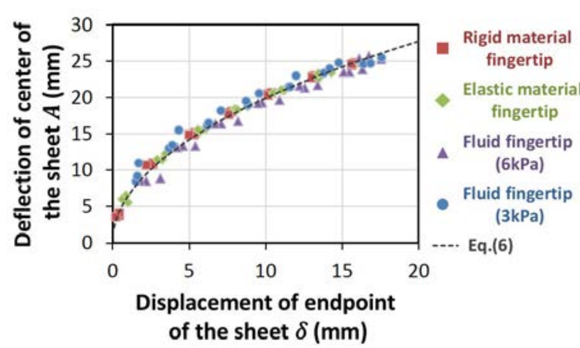

Fig. 11. Displacement of the endpoint of the sheet δ versus the deflection of the center of the sheet A. The dashed line is the theoretical value from (6).

$$\frac{f_{gr}}{f_{cr} - f_{dis}} = 1 + \frac{1}{8}\left(\frac{\pi A(\delta)}{l_0}\right)^2 \quad (9)$$

C. Comparison between theory and experimental results

We numerically calculated the relations between the grasping force f_{gr}, the displacement of the endpoint of the sheet in the x direction δ, and the deflection at the center of the sheet A. We set the Young's modulus of the sheet to $E = 3$ GPa. The integral terms in (6) was integrated numerically, and (6) was solved by being formulated as an optimization problem with constraints with respect to A. f_{gr} was calculated utilizing (9), A derived from (6), and $f_{cr} - f_{dis}$ obtained from experimental results. $f_{cr} - f_{dis}$ was set to be the mean grasping force when $A = 0$ after buckling in the experiments shown in Fig. 6. The calculation was performed by using MATLAB® (Mathworks).

Fig. 10 shows the critical buckling loads obtained experimentally and derived from (1). The theoretically derived value was close to the experimental results. No statistically significant difference is observed between the buckling loads for the type or stiffness of the fingertips.

Fig. 11 shows the relation between the displacement of the endpoint of the sheet in the x direction δ and the deformation

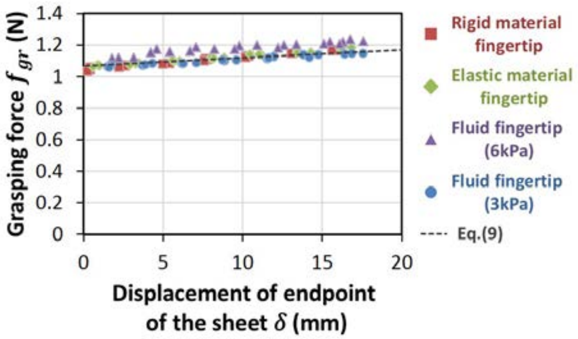

Fig. 12. Displacement of the endpoints of the sheet δ versus the grasping force f_{gr}. The dashed line is the theoretical value from (9).

at the center of the sheet A. Note that the data is the one after buckling and in the range of bending deformation (see Fig. 4). The theoretical value derived from (6) was very close to the experimental results. As we assumed, the length of the sheet did not change, and the sheet deformation was mainly dominated by bending. The deflection of sheet A is determined by the displacement of the endpoint of the sheet δ, irrespective of the stiffness or deformation of fingertips. The stiffness or deformation of the fingertips is indirectly related with A through δ.

Fig. 12 shows the relation between the displacement of the endpoint of the sheet in the x direction δ and the grasping force f_{gr}. Note that the data is the one after buckling and in the range of bending deformation (see Fig. 4). Even as δ increased, f_{gr} did not increase very much. This indicates that the normal way of grasping by increasing the pressure on the object does not work well for grasping a sheet. Conventional grasping methods (for example, see [17], [18]) may not work for sheet grasping. In the comparison of the theoretical and experimental results, the theoretical results were close to the experimental results.

III. GRASPING STABILITY ANALYSIS

The balancing of a large external force is one metric for evaluating the grasping stability (e.g., see [17], [18]). In our situation of sheet grasping, the external force in the direction of the gravitational force is critical, as the effect of gravity is maximum in this direction. The direction of the gravitational force is orthogonal to the grasping force, and during the processes of picking and placing, the external force can be applied mainly in this direction. Thus, the resistible force can be considered to be minimum in the critical direction. We investigated how a large external force in that direction can be applied to the sheet while maintaining a grasp with three types of fingertips: rigid material, elastic material, and fluid.

A. Set up of experiment

Fig. 13 shows a schematic view of the experimental setup. It is based on the experimental setup shown in Fig. 1, but a device for providing an external force was added. The device was constructed by attaching a force gauge to the automatic positioning stage. By moving the stage in the vertical direction, an external force in the direction of the gravitational force could be applied, and its value could be measured by the force gauge. The fingertips and sheet were the same as in the previous experiment. The initial pressure of the fluid inside the fluid fingertip was set to 3 kPa. Supposing the position for the movable fingertip is zero when the grasping force f_{gr} is zero, we moved the movable fingertip by δ_{dsp} and grasped the sheet. After that, the external force in the direction of the gravitational force was applied to the center of the sheet. We considered the cases of δ_{dsp} = 5, 10, 15, 20, and 25 mm. The speed of the automatic positioning stage for applying the external force was set to 1.0 mm/s. We repeated the experiments three times for each setting.

B. Results and discussion

Fig. 14 shows the time series data for the grasping force of the elastic fingertip and δ_{dsp} = 5 mm. We denote the force with no external force as the initial grasping force and the force with the maximum external force (corresponding to the maximum balanced external force) as the critical grasping force. The grasping force decreased when the external force was increased because the deformation/deflection of the sheet was increased by the external force, and the endpoints of the sheet were displaced toward the center of the sheet.

Fig. 15 shows the initial grasping force versus the resistible force by the grasp, which is defined as the maximum external force at which the fingertip can maintain contact with the application of an increasing external force. For the fluid fingertip, the resistible force was small even when the initial grasping force was increased. For the rigid material fingertip, the resistible force was greatly increased as the initial grasping force was increased. As shown in Fig. 6, buckling occurred when the pushing amount was 15 mm with a fluid fingertip (3 kPa). Therefore, the results for the fluid fingertips include the cases of before and after buckling. Including the previous experimental results (see Fig. 6), the rigid material

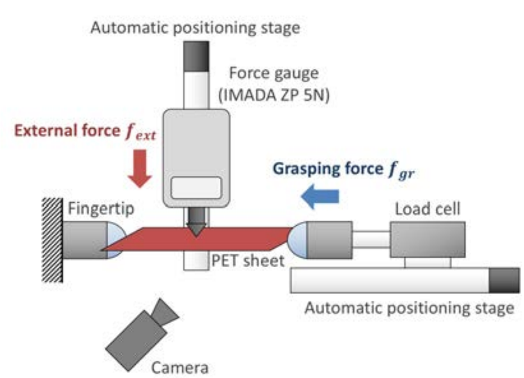

Fig. 13. Schematic illustration of the experimental setup for the grasping stability test focusing on the resistible force, which is defined as the maximum external force at which the fingertip can maintain contact when applying an increasing external force.

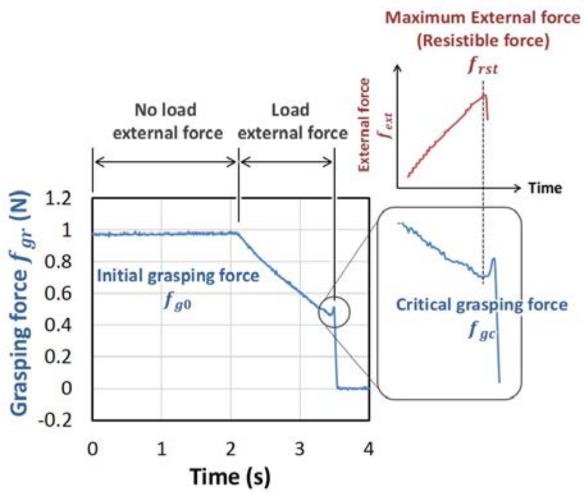

Fig. 14. Time series data for grasping force f_{gr} for elastic fingertip and the displacement of the movable fingertip δ_{dsp} = 5 mm.

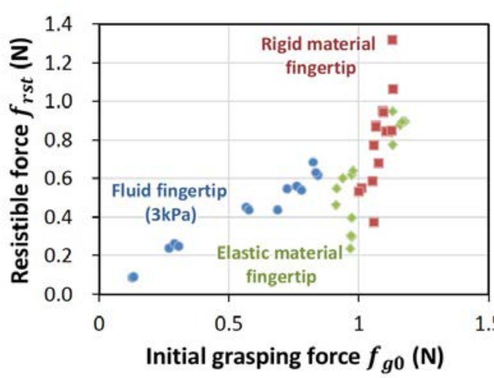

Fig. 15. Initial grasping force f_{g0} versus resistible force f_{rst}.

fingertip required large grasping forces but could resist large external forces. The fluid fingertips required small grasping forces but could not resist large external forces. In sum, various levels of softness for the fingertips have both merits and demerits, and the type of fingertip should be selected according to the task. The conventional metric evaluating grasping (for example, see [17], [18]) evaluates based on convex theory. Therefore, if the magnitude of grasping forces was set to be twice, the magnitude of resistible force also got to be twice, irrespective of stiffness of fingertips. However, this way is not applicable to sheet manipulation, because the range applicable grasping force varies with stiffness of fingertips as it can be seen from Fig. 15. These results correspond to our previous results, which showed that stiffer fingertips have a higher resistible force (frictional force) [11], [12].

IV. Ideal Grasping Strategy for Sheet Manipulation

The results of the two experiments showed that stiff and soft fingertips provide different advantages. Ideally, we should control the stiffness of the fingertip according to the task. Then, for a case where the stiffness is controllable, an ideal grasping strategy for sheet manipulation can be constructed as shown in Fig. 16. When making contact with a sheet, a softer fingertip like the fluid fingertip is desirable. Softer fingertips can easily grasp the sheet with a small force and are also robust against perturbations of the contact position. When picking up or transferring a sheet, external forces such as inertia are applied. In that case, stiffer fingertips are preferable because they can resist large external forces. When placing a sheet, stiffer fingertips are preferable until contact in order to resist the impulsive force at contact. After contact, the bending of the sheet should be released while the sheet is placed precisely. Softer fingertips are preferable in this case. The rate of increase in the displacement of the endpoint of the sheet in the pushing direction (δ) with respect to the pressing amount is small, as shown in Fig. 6. Then, softer fingertips can precisely control the bending and positioning while providing grasping ability with a small grasping force. Therefore, stiffness-variable fingertips [19], [20] are preferable for sheet manipulation. In particular, fingertips with a two-layer structure where a rigid component is located inside the fluid (as presented in [20]) may be good idea.

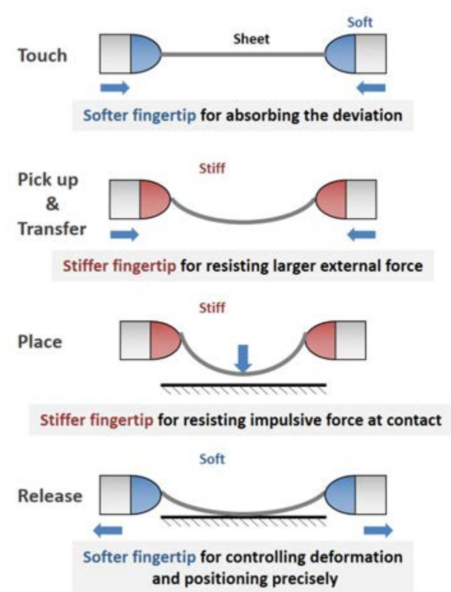

Fig. 16. Grasping strategy for sheet manipulation.

V. Conclusion

In order to realize sheet manipulation (see Fig. 1), we considered grasping by bending the sheet and evaluated the grasping stability in terms of resistance to a large external force. The main results are as follows:

1) We theoretically and experimentally showed that the rate of increase in the grasping/pushing force with respect to the displacement of the endpoint of the sheet in the pushing direction (δ) is small after buckling. The conventional method of displacing the fingertip toward

the object to increase the grasping force is not available for bent sheet grasping.

2) The available range of the grasping force varies with the fingertip stiffness. Stiffer fingertips can only provide a large grasping force while resisting a large maximum resistible force. Softer fingertips provide a small grasping force with a small maximum resistible force.
3) An ideal grasping strategy for sheet manipulation where the stiffness of the fingertips changes according to the task is presented based on the above analysis. A suitable fingertip may be a two-layer structure with a rigid component located inside the fluid, as presented in [**?**].

The other findings and contributions are as follows:

- The buckling load was the same regardless of the type/stiffness of fingertip.
- Softer fingertip can grasp the endpoints of the sheet easily, while stiffer fingertips cannot.
- Sheet models (1), (6), (9), which represent the above phenomenon and provide the estimation of sheet bending, were presented.
- In stiffer fingertips, the maximum resistible force can be greatly increased by increasing the (initial) grasping force. For softer fingertips, this approach is not available.

In the future, we plan to develop suitable fingertips for sheet manipulation.

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