

Piercing Based Grasping by Using Self-Tightening Effect

Naoki Sakamoto, Mitsuru Higashimori, Toshio Tsuji and Makoto Kaneko

Abstract—This paper proposes a piercing based grasping by using the self-tightening effect of objects with elasticity. We suppose a piercing hand with palm where the piercing motion by needles can be independently achieved irrespective of the palm motion. The palm first approaches and touches with the object, with a slight pushing motion. This motion produces an increase of potential energy of object. After the motion, the needles pierce the object. When the object is lifted up, the accumulated potential energy is released and the object tries to recover the original shape under the piercing condition. We found a particular mechanical configuration between the object and the needle, under which the constraint of object is tightened due to the object deformation during the release of the potential energy. In order to confirm the robustness of the proposed method, we have done a couple of experiments. The results show that the proposed method keeps an extremely high robustness compared with the other piercing methods.

I. INTRODUCTION

Currently, dishing up food into a box lunch sold at convenience store is done manually by workers standing at both sides of a belt conveyor. Since most of them are part time workers, it is hard to keep a pace for dishing and a constant man power through the year. Also, from the viewpoint of maintaining safety of food, it is desirable to touch food as less as possible by human hand. Based on these backgrounds, several research projects have been launched for developing a robot system capable of handling foods instead of human. The most different point between food handling robots and conventional industrial robots is the characteristics of objects to be manipulated. Generally, a food has the visco-elasticity, adhesiveness, and non-homogeneity. While the gripping hand as shown in Fig.1(a) is a typical approach for food handling, we focus on piercing based grasping of foods by considering the advantages of easy matching with different size of box to be packed and different size of foods as shown in Fig.1(b). Fig.2 shows an example of piercing hand and its procedure for handling a food, where (a), (b), (c), and (d) denote the initial phase, the pressing phase by using a palm, the piercing phase by using needles, and the lifting phase by using a robot, respectively. The role of palm is to avoid dropping the object and to assist the easy pulling out the needle from the object by pressing the object. Through the basic experiments of piercing grasp, we found by chance a particular needle arrangement for enhancing the robustness of grasping by

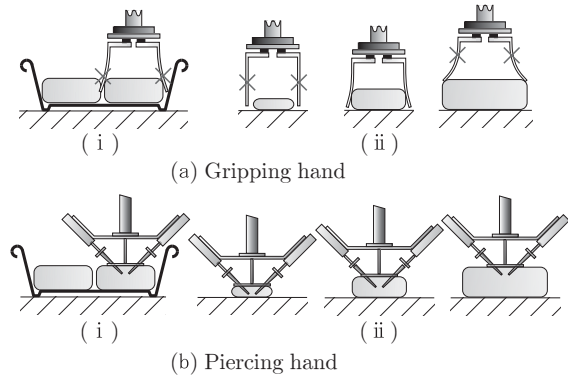


Fig. 1. Advantages of piercing hand

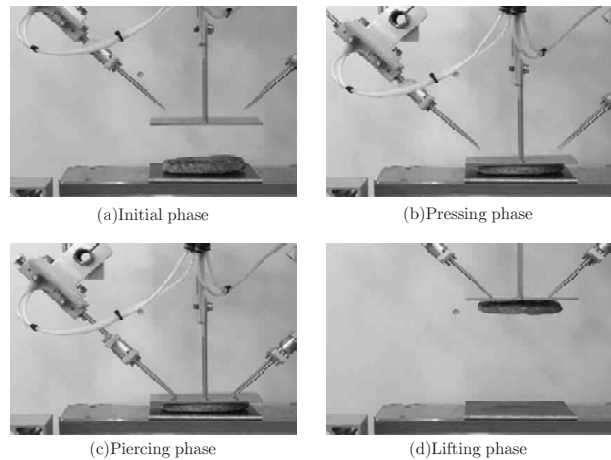


Fig. 2. A procedure for food handling by a piercing hand

piercing. When the palm presses an object with elasticity, the potential energy of food increases according to how much it is pressed. When the object is lifted after piercing by the needles under a particular geometrical relationship, the internal force between the needle and the palm increases as the potential energy is released. This is what we call the self-tightening effect. In this paper, we precisely explain why such an effect appears and under what conditions we can expect the effect. We confirm experimentally that the piercing grasping based on the self-tightening effect keeps surprisingly high robustness, compared with other piercing based grasping, in terms of avoiding dropping the object under disturbance. This paper is organized as follows: After reviewing related works in Section II, we show in Section III the physics of the self-tightening effect and the structural condition leading to the effect. In Section IV, we confirm experimentally the robustness of the piercing grasp based

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on the self-tightening effect, compared with other types of piercing methods, before concluding in Section V.

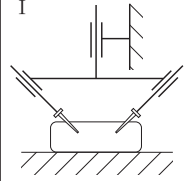
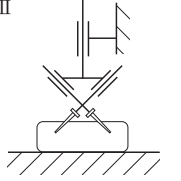
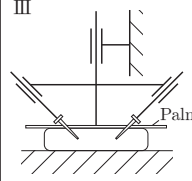
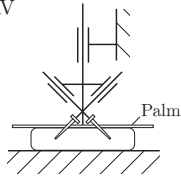
II. RELATED WORKS

In general, a food has the characteristics of visco-elasticity, adhesiveness, and non-homogeneity, respectively. As for deformations of food, Tokumoto et al. [1] have focused on the rheological characteristics of food, and simulated the deformation of object by using the model with non-linear viscous elements. Zhou et al. [2] have proposed a model of food, especially by focusing on the behavior during cutting so that they can formulate an algorithm for controlling the cutting force. As for parameter estimation of food, Sakamoto et al. [3] have successfully estimated a viscoelastic parameter of food, and shown an optimum design for controlling robot hand from the viewpoint of avoiding plastic deformation and speeding up the operational time. Silsoe Research Institute [4] has developed a robot hand so that it can handle handling for a food with adhesion. The hand is composed of a pair of gripping fingers and a film such as belt conveyor, can release the adhesion object successfully. Li and Lee [5] have developed a visually guided robotic system for handling food. They have shown that the hand grasps robustly an object with non-homogeneity by visual information. The handling robot capable of applying a food production line was developed. Davis et al. [6] have developed an automation system for making a sandwich, where the machine can dish up ingredients and manipulate a completed sandwich. As examples of piercing based grasping for food, there is a carrier machine for deep-fried food [7]. The needles arranged vertically downward pierce deep-fried foods on the belt conveyor, and carry them to a prescheduled position. Also, the piercing hand has been designed for dishing up ingredients on the pizza [8], where it is composed of a number of needles attached vertically downward at the palm. The hand approaches and pierces ingredients, and catches them by needles. During releasing motion, the needles are pulled up under that the palm is stationary. Ingredients are dished up on a pizza crust, as the palm is away from the ingredients. However, these systems have not strongly considered the rheological characteristic of food for the handling procedure. As far as we know, it seems that there are no piercing type hands based on rheological characteristics of food, especially the elastic one.

III. PIERCING BASED GRASPING BY USING SELF-TIGHTENING EFFECT

The piercing based hand can be classified into four groups with the arrangements of needles and the existence of palm, as shown in Table I, where I and II are without the palm, and III and IV are with the palm, respectively. As mentioned in Section I, the function of palm is important for pressing the object at the contact phase and pulling the needles from the object. From now on, we focus on the hands with the palm by taking this advantage into consideration.

TABLE I
CLASSIFICATION OF THE PIERCING HAND

	Inner direction	Outer direction
Without palm	I 	II 
With palm	III 	IV 

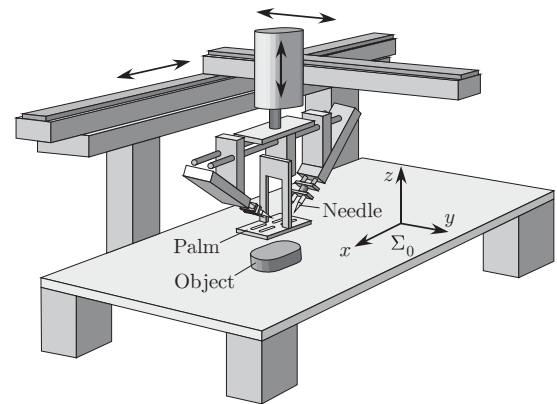


Fig. 3. An overview of the system

A. Assumptions and Outline of Robot System

For simplifying discussions, we set several assumptions as follows.

- 1 The object contains an elastic characteristic. (Elastic object)
- 2 The object has a rectangular parallelepiped. (Symmetrical shape of object)
- 3 The piercing hand is attached at the end of a three-axis cartesian robot. The palm is always kept horizontal and the object is placed on a horizontal table. (Keeping horizontal state)
- 4 The center of palm approaches to the geometrical center of the object. (Keeping symmetry during contact phase)
- 5 After the palm contacts the object, it presses with additional displacement of s from the initial contact. (Increasing potential energy)
- 6 The palm is even larger than the contact area of the object. (Pressing evenly)

Fig.3 shows an overview of the system including the robot, the piercing hand, the table, and the coordinate system of the reference frame.

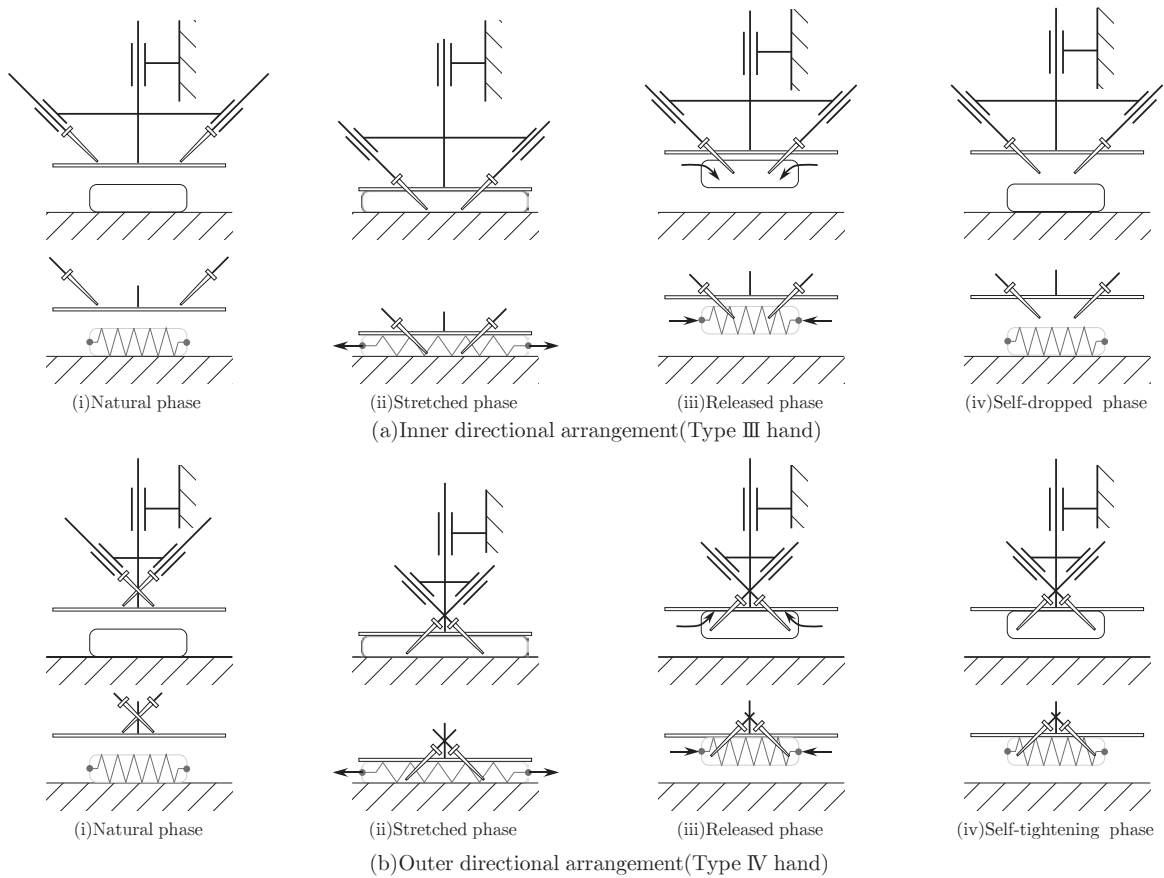


Fig. 4. Self-tightening effect

B. What is the Self-Tightening Effect?

Fig.4 shows a series of procedure where the hands with the type III and IV are approaching to the object, respectively. In phase (ii), while the object is pressed by the palm, the object is deformed by stretching toward the outer direction as shown in phase (ii) Fig.4 (a). We would note that the potential energy increases inside the object during pressing. An increase of potential energy is caused by equivalent springs of the object existing in both thickness and longitudinal directions. Hereafter, we focus on an effect caused by one equivalent spring existing along the longitudinal direction. We can suppose that the spring with longitudinal direction is stretched enough in phase (ii). Next, as shown in phase (iii) in Fig.4 (a), the needles pierce the object, and the hand lifts up the object. Immediately when the object is lifted, the stretched spring starts to recover to the original length due to the release of contact force between the palm and the table. Let us now focus on how the spring recovers. As shown in the hand with the type III, the direction where the spring recovers is corresponding to the one where the object drops from the needles. As shown in the hand with the type IV hand, on the other hand, the direction where the spring recovers is corresponding to the one where the object is pierced more than the type III hand by needles. Thus, by arranging the direction of needles where the tips of needles direct the outside of object from the center, the hand can

utilize previously accumulated potential energy for an effect where the internal force between the palm and the needles increases. We can regard that this effect tries to generate the force to tighten the object itself firmly through the release of the accumulated potential energy. This is what we call the self-tightening effect and the key effect for increasing the grasping robustness. We would note that a piercing based hand where the self-tightening effect can be expected belongs to the one categorized in type IV.

C. The Condition Leading to the Self-Tightening Effect

We now consider the condition by which the self-tightening effect is expected between a piercing hand and an object as shown in Fig.5, where the piercing angle, the piercing length, the piercing starting position by the needle, the pressing depth, the thickness of object, and the length of object after pressed by the palm are q ($0 < q < \pi$ [rad]), d , l ($0 < l$), s , h ($s < h$), and $2L$, respectively. The self-tightening effect is produced when the following condition is satisfied,

$$(l < L) \cap (\pi/2 < q < \pi[\text{rad}]). \quad (1)$$

In addition, the conditions for avoiding for the tip of needle not to penetrate through the object are given by

$$l - d \cos q < L, \quad (2)$$

$$d \sin q < h - s. \quad (3)$$

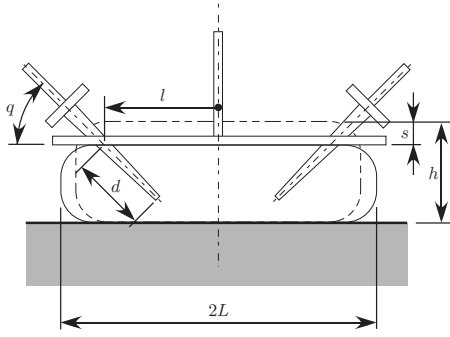


Fig. 5. Design parameters for a piercing hand

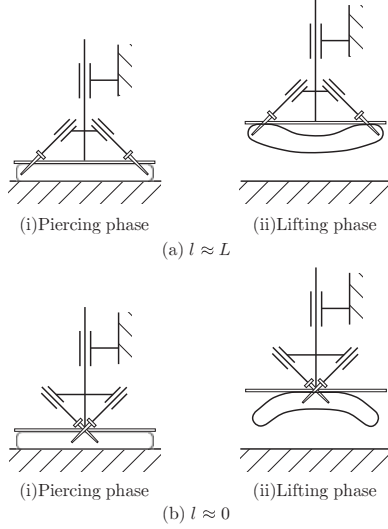


Fig. 6. Two examples where the object may be broken due to the gravitational force

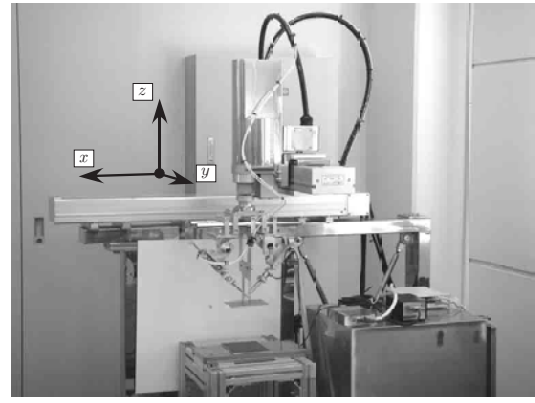
Namely, when (1)–(3) are satisfied, the tip of needle never penetrates through the object and the self-tightening effect is ensured. However, we would note that satisfying these conditions are not always equivalent to guaranteeing for the object to be lifted up. For example, when the object whose length L is extremely large, the object deforms by its own weight as shown in Fig.6, under the condition that l is nearly equal to L (a), or l is extremely small (b). These are cases where we can see some possibilities in which the hand drops the object eventually due to the heavy deformation of object. In this paper, however, we do not discuss this issue further deeply.

IV. EXPERIMENT

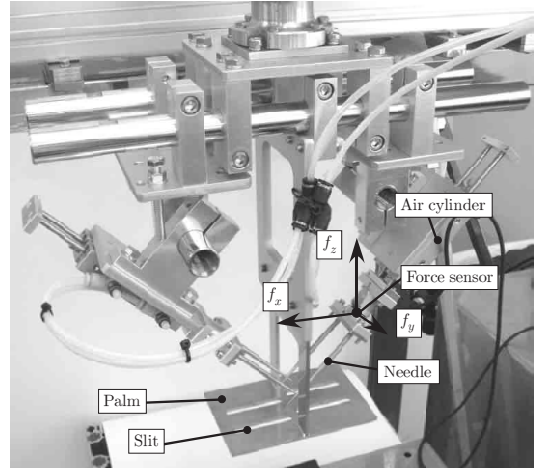
In this section, we experimentally confirm the effect of self-tightening characteristic for all types of hand as shown in Table I. Further, we observe the force applied to the needles by utilizing a six-axis force sensor implemented at the base of needles, so that we can observe how the force is related with the robustness against an external disturbance.

A. Experimental System

Fig.7 shows an overview of the experimental system where it is composed of the three-axis cartesian robot and the



(a) Arm/hand system



(b) The developed hand

Fig. 7. An overview of experiment system

piercing hand attached at the end of the cartesian robot. The piercing hand is composed of two needle units where each unit is arranged as right and left units as shown in Fig.7. Each unit is further decomposed into two needles parallelly arranged with the interval of 24[mm]. Both the piercing and the pulling out motions are produced by the air cylinders. The piercing angle q , the piercing distance l , and the piercing length d can be changed according to the items of experiments. Also, we can remove the palm for changing the type of hand as shown in Table I. The needle units can be shifted 3[mm] along the y -direction each other for avoiding collision of piercing motion. Also, the six-axis force sensor is mounted at the base of one-side of needle unit so that we can observe the force between the needles and the object, as shown in Fig. 7(b) where f_x , f_y , and f_z denote the axis of each force. We utilize hamburger with the size of $97 \times 70 \times 17$ [mm] as an object for the experiments. The hamburger is set on the table, where the longitudinal direction coincides with the x -direction.

B. Experimental Method

The parameters for experiments are shown in Table II. The hand with the type IV satisfies the conditions for producing the self-tightening effect. The three force components of f_x , f_y , and f_z are measured while the needles pierce and

TABLE II
PARAMETERS FOR EXPERIMENT

q	Piercing angle in Type I, III	45 [deg]
	Piercing angle in Type II, IV	135 [deg]
l	Piercing distance in Type I, III	28 [mm]
	Piercing distance in Type II, IV	22 [mm]
d	Piercing length	8.5 [mm]
s	Pressing depth	6 [mm]
a	Acceleration of disturbance	30 [m/s ²]
m	Mass of object	0.078 [kg]
h	Thickness of object	17 [mm]
$2L_0$	Initial length of object	97 [mm]

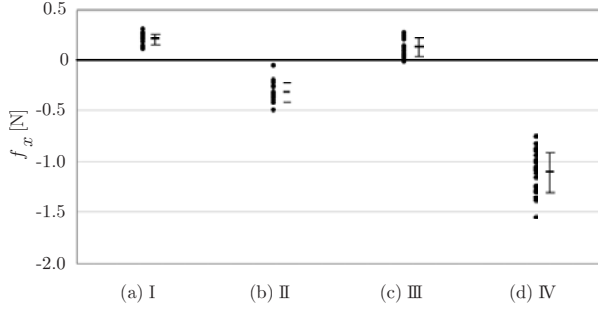


Fig. 8. x -directional force f_x

lift up the object. We take the force data with sampling rate of 1[ms] and feed them into a computer through the A/D converter. The robustness of piercing grasp is evaluated while the acceleration disturbance is given to the hand. The hand is swung with the distance of 100[mm] under acceleration and deceleration of 30[m/s²]. We choose the directions of disturbance with x , y , and z , respectively, as shown in Fig.7(a). Let a and n be the concerned directions and the number of measurements, respectively. We count the number of reciprocating motion N_{ai} ($a = x, y, z$) ($i = 1, 2, \dots, n$) until the object is dropped from the hand. We define that this is the robustness index where N_{ai} is the number of acceleration disturbance. The maximum number of disturbance is set to 100, so the number of disturbance for all experiments never exceeds 100. This experiment is done for all types of hand as shown in Table I.

C. Experimental Results

1) *Results of Force*: Fig.8–10 show the force f_x , f_y , and f_z , respectively where the data are obtained while the needles pierce the object, and (a), (b), (c), and (d) are results by using the hand with the type I, II, III, and IV, respectively. One point in this figure shows the average force during one experiment while the hand completes both piercing and lifting motions, where the average and the standard deviation for all data are also indicated in the figure. We would note that these figures do not include the data when the hand drops the object before finishing the lifting motion. From Fig.8, we can compare the absolute value of the average of forces f_x for every hand. We would note that the hand with the type IV shows 3~8 times as large as other hands. Thus, we see from

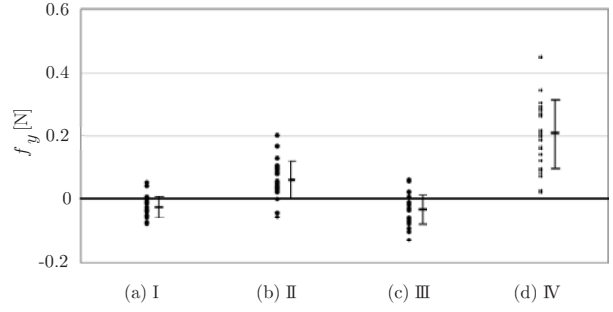


Fig. 9. y -directional force f_y

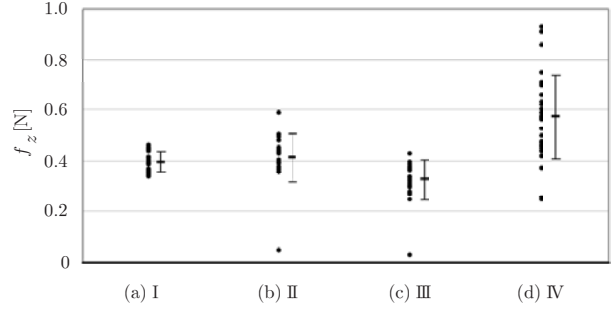


Fig. 10. z -directional force f_z

these figures that a large internal force is produced by the hand with the type IV. This may be due to the self-tightening effect. By comparing the average forces f_y for all types of hand in Fig.9, we can see that the hand with the type IV shows 3~7 times as large as other hands. We can again see that while the force f_y is less than f_x , we can observe a large force for the hand with the type IV. From Fig.10, we can see that the average of forces f_z for the hand with the type I, II, and III are roughly half (0.38[N]) of the force corresponding to the gravity force ($mg = 0.76$ [N]). This means that both right and left needles share the total weight evenly, respectively. On the other hand, the average of force f_z in the hand with the type IV shows 1.5 times more than half (0.38[N]) of the gravity force. This result means that an internal force is generated between the needles and the palm by self-tightening effect. We could experimentally confirm that a large internal force is generated with both horizontal and vertical directions by the self-tightening effect especially for the hand with the type IV.

2) *Evaluation of Robustness under Acceleration Disturbance*: Fig.11 shows the experimental results for evaluating the robustness for acceleration disturbance, where (a), (b), (c), and (d) are corresponding to the results for the hand with the type I, II, III, and IV, respectively. In this figure, x , y , and z mean the directions indicating the acceleration disturbance, respectively. This figure shows the average $\overline{N_a} = (\sum_{i=1}^n N_{ai})/n$ ($a = x, y, z$, $n = 10$) and the standard deviation of the robustness index N_{ai} with each direction, respectively. The average $\overline{N} = (\overline{N_x} + \overline{N_y} + \overline{N_z})/3$ and the standard deviation on each hand are also computed for the hand with the type I, II, III, and IV. They are 2.4 ± 4.5 , 9.4 ± 19.1 , 3.4 ± 6.3 , 88.7 ± 27.6 , respectively. From

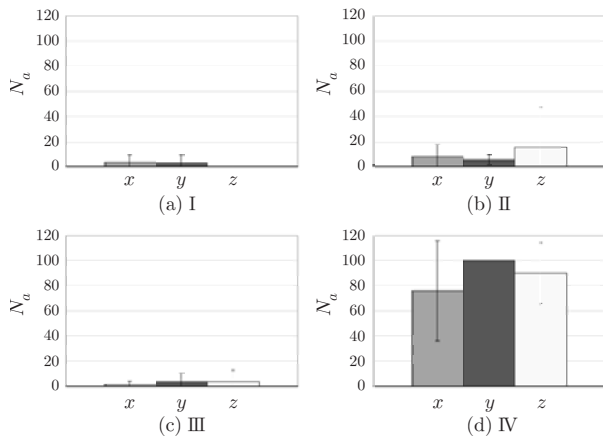


Fig. 11. Robustness index

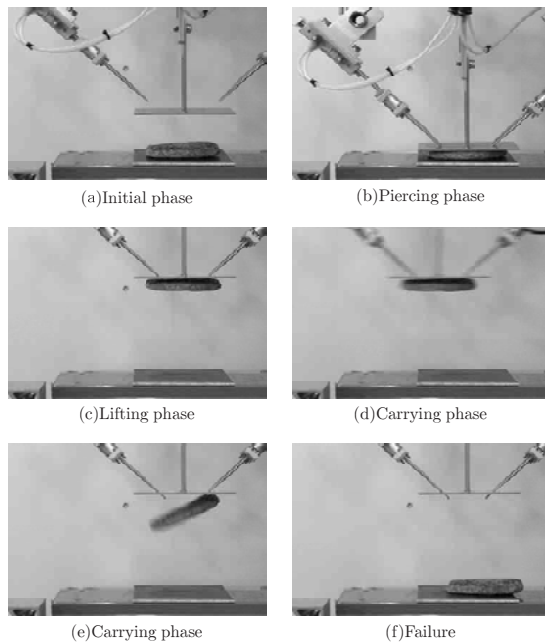


Fig. 12. An overview of test by using the type III hand

these data, we can see that the robustness for acceleration disturbance for the hand with the type IV is even higher than those of the other hands. In addition, it is interesting to note that the robustness is invariant irrespective of the direction for all types of hands for acceleration disturbance. Fig.12 and Fig.13 show experiments by using hand with the type III and IV, respectively. Fig.12 and Fig.13 are corresponding to those cases where the self-tightening effect is not expected and can be expected, respectively. Fig.12 shows an example where the hand failed in continuous grasping for acceleration disturbance, and eventually dropped the object. Fig.13 shows that the hand is continuously achieving a firm grasping due to the self-tightening effect¹.

V. CONCLUSION

This paper discusses the food handling method based on piercing. The main results are summarized as follows:

¹The video attachment media file for this paper shows experiments.

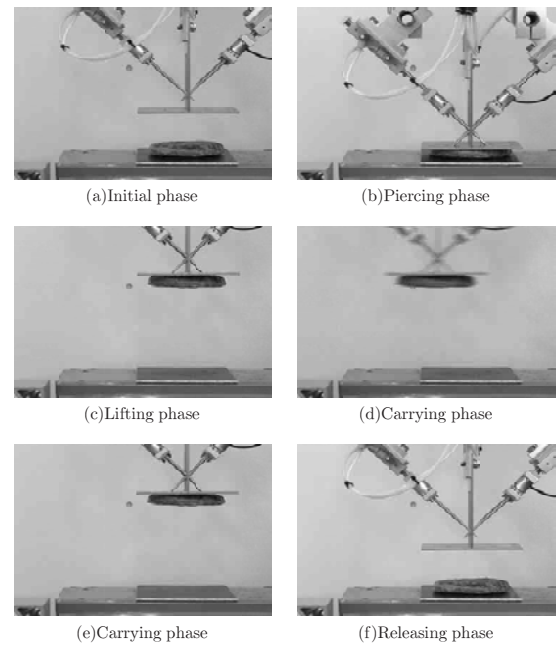


Fig. 13. An overview of test by using the type IV hand

- 1) We proposed the piercing hand based on the self-tightening effect.
- 2) We showed the geometric condition of piercing hand for producing the self-tightening effect.
- 3) We evaluated the robustness under piercing for acceleration disturbance for four types of hand. Through the experiments, we confirmed that the robustness of piercing hand based on the self-tightening effect is even higher than those of the other hands.

VI. ACKNOWLEDGMENTS

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