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A Wrapping Gripper for Packaging Chopped and Granular Food Materials

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***Abstract*— Pneumatic driven soft robotic gripper has been studied intensively in recent years for grasping various types of objects including food materials. However, grasping of finely chopped and granular food materials has not been investigated frequently. This paper presents a pneumatic soft gripper capable of forming an approximately closed cavity to wrap the chapped and granular food materials. The gripper consists of four soft fingers and each finger was constructed by multiple horizontal and vertical air chambers. When the chambers were inflated, the finger bends towards two perpendicular directions. Finite element (FE) model of the soft finger was developed to predict the desired deformation behaviors. A robotic gripper was assembled with four soft fingers in a circular configuration. Experimental tests were conducted on grasping granular kernel corn, chopped green onion, and boiled hijiki. Results showed that the proposed gripper is able to wrap the food materials and the averaged weight of the grasped materials can be controlled by varying the insertion depth. However, the variations in grasped weight among trials are relatively large.**

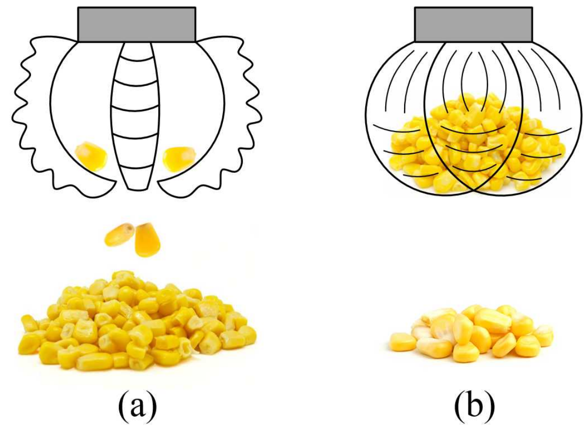

Fig. 1. Grasping kernel corn with (a) the traditional soft gripper and (b) the proposed wrapping gripper.

I. INTRODUCTION

Soft robotics, as an emerging research field, has been receiving massive attentions in the last decade. Many soft robots were proposed for various applications. Polygerinos *et al.* proposed a soft robotic glove driven by pneumatic actuators for combined assistance and at-home rehabilitation [1]. The Jamming gripper has been used for handling various types of daily objects [2]. Galloway *et al.* presented two soft grippers for biological sampling on deep reefs [3]. A very thin soft gripper was proposed by Shintake *et al.* utilizing intrinsic electroadhesion to handle various objects [4]. Deng *et al.* developed a soft machine table for manipulation of delicate objects [5]. Zhou *et al.* proposed several soft grippers for dexterous grasping of daily object and in-hand manipulations [6], [7], [8]. The advantages of using soft grippers to handle objects are the adaptabilities to object variations in dimensions and physical properties without damaging the target objects thanks to the soft nature of the grippers [9]. These abilities are extremely important and demanded in food, agriculture, and fishery industries. In our current work, we are particularly focusing on the applications in food industry.

Despite the rapid development of robot and automation, food industry is still labor-intensive and under-automated. However, countries like Japan with aging societies are having problems of labor lack and highly demanding automation in such labor-intensive industries [10]. The most difficult task in automating food production is the handling of food materials, which have great variations in dimension or shape and physical property. Attentions have to be paid to fulfill these tasks.

For handling food products especially the bagged food, vacuum pad was widely used in food industry. Because of the surface texture and hygience issues, vacuum pad is hard to be adopted for handling raw food materials. Instead, robotic grippers are more preferable in such situations. Pettersson *et al.* proposed a soft gripper utilizing the effects of a magnetorheological fluid for gripping delicate food products [11]. Davis *et al.* proposed an end effector based on the Bernoulli principle for handling sliced fruit and vegetables [12]. Endo *et al.* presented a rigid multi-fingered gripper for grasping simmered food materials considering appetizing presentation [13]. A binding hand was also presented by Iwamasa *et al.* for handing food materials filled in a paper container [14]. In our previous studies, we proposed 3D printed soft grippers with different designs for packaging Japanese boxed meals [15]. A prestressed soft gripper was also presented for realizing gentle grasping [16]. These multi-fingered grippers can handle a range of different sized targets, such as a fried chicken, a raw egg, a baked salmon, and so on. However, due to the gap between neighboring fingers, these grippers have difficulties to grasp finely chopped and granular food materials, as shown in Fig. 1(a). Such chopped and granular food materials often appear in Japanese boxed meals and they are currently packaged by human labors. Therefore, in

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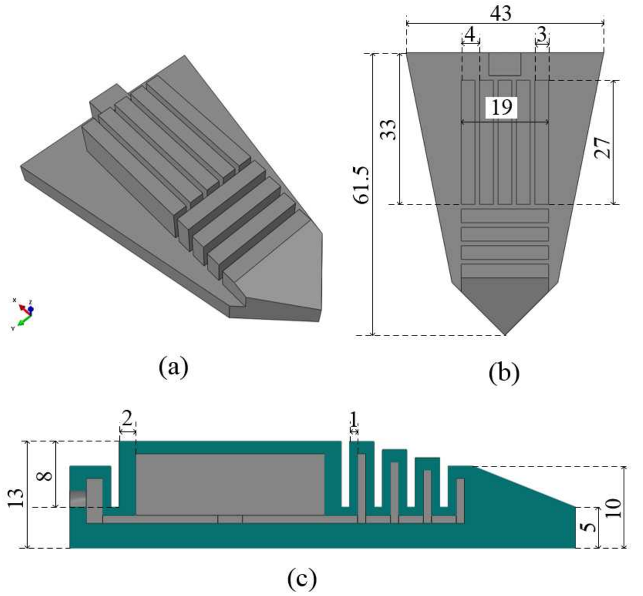

Fig. 2. The soft finger design in (a) an isometric view, (b) a top view, and (c) a side section view.

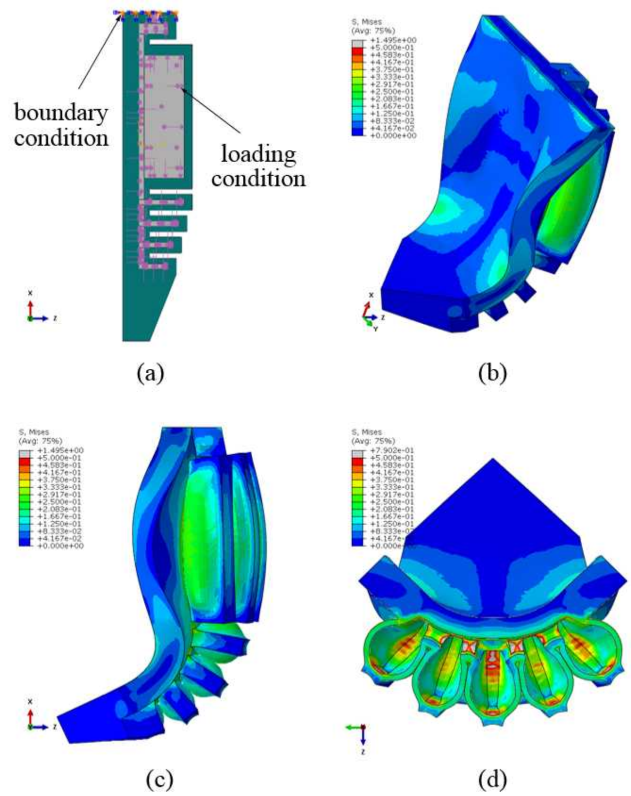

Fig. 3. FE model and simulation of the soft finger: (a) the boundary and loading conditions, results of deformation with Mises stresses in (b) an isometric view, (c) a vertical side view, and (d) a horizontal section view.

this study, we choose these materials as our grasping targets. For grasping these targets, a gripper being able to form an closed cavity is preferable, as shown in Fig. 1(b). In this paper, we proposed such a gripper for grasping chopped and granular food materials.

The rest of the paper is organized as follows. The soft finger design and finite element (FE) simulation are presented in Section II. The finger fabrication and gripper assembly are introduced in Section III, followed by experimental tests on three food materials and the test results in Section IV and V, respectively. Section VI concludes the paper and suggests some future work.

II. Finger Design and FE Simulation

A. Finger Design

The soft finger design adopted the principle of pneumatic bellow-type actuator [17]. The soft finger was designed to have a triangular shape with a tip angle of 90°, as shown in Fig. 2a. The overall size of the finger depends on the desired amount of the grasping target. Once the overall size of the finger is determined, the volume of the cavity formed by the gripper can be approximately calculated as a cylinder plus a hemisphere. In this design, the finger has an overall size of 43 mm×61.5 mm (Fig. 2b) and the four-fingered gripper can theoretically form a cavity volume of about $1.64 \times 10^5\,\mathrm{mm}^3$. The soft finger consists of five vertical and four horizontal air chambers and it has a 90° tip to ensure a complete closure by four fingers. The external width of one air chamber is designed as 3 mm and the gap between neighboring chambers is set to 1 mm (Fig. 2b). The thickness of the chamber wall is set to 1 mm and 2 mm for the preferable and non-preferable inflation direction, respectively, as shown in Fig. 2c. The height of the horizontal chambers is gradually reduced towards the finger tip from 8 mm to 5 mm (Fig. 2c). A thinner tip (5 mm in height) was designed for easy insertion into the food materials.

B. FE Simulation

To predict the deformation behaviors of the soft finger, FE simulation was performed. The 3D geometry of the soft finger was imported into Abaqus/Standard (Simulia, Dassault System, MA) for FE simulation. Referring to [18], the soft material was described by a hyperelastic incompressible Yeoh model with two parameters of $C_1 = 0.11\,\mathrm{MPa}$ and $C_2 = 0.02\,\mathrm{MPa}$, which corresponding to a Shore hardness of A28. The model was meshed using solid tetrahedral quadratic hybrid elements (Abaqus element type C3D10H) with a global seed size of approximately 1 mm. The interaction among neighboring chambers was modeled as 'tangential behavior' (Penalty method) with a friction coefficient of 1.16 as rubber to rubber friction [19]. The 'ENCASTRE' boundary condition was defined at the finger proximal to fix the finger in space and a pressure loading condition was applied on the chamber internal surfaces to inflate the chambers, as shown in Fig. 3a. An one-second implicit simulation was implemented with geometrical nonlinearity turning on. Simulation results at a pressure of 50 kPa were given in Figs. 3b-d, in which a two directional bending was confirmed. The vertical deformation generated a bending angle of 75.6° (Fig. 3c) and horizontal bending angle achieved at 90.6° (Fig. 3d). Accordingly, it is possible to form an approximately closed

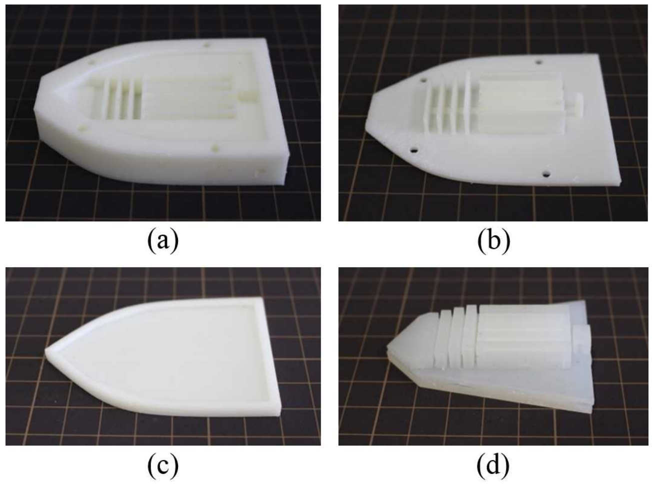

Fig. 4. 3D printed molds for casting process: (a) the chamber female mold, (b) the chamber male mold, (c) the cover mold, and (d) an example of the fabricated soft finger.

cavity by assembling four such soft fingers in a circular configuration.

III. Finger Fabrication and Gripper Assembly

A. Soft Finger Fabrication

The soft finger was fabricated using the traditional casting process. Three casting molds (Figs. 4a-c) were 3D printed using Zortrax M200 printer (Zortrax, Olsztyn, Poland). Two sets of soft fingers were fabricated using Dragon Skin 10 and 20 (Smooth-on Inc., PA). The liquid rubber material was degassed for 1 minute at a pressure of $-85\,\text{kPa}$, and then poured into the chamber female mold (Fig. 4a) and the cover mold (Fig. 4c). They were degassed for another 1 minute at the same negative pressure. After degassing, the cover mold was sealed using an acrylic plate. The chamber male mold (Fig. 4b) was then fitted into the female mold and fixed with screws. After curing at room temperature, the chamber and cover were carefully released from the molds and glued together using the same rubber material. The fabricated soft finger was shown in Fig. 4d as an example.

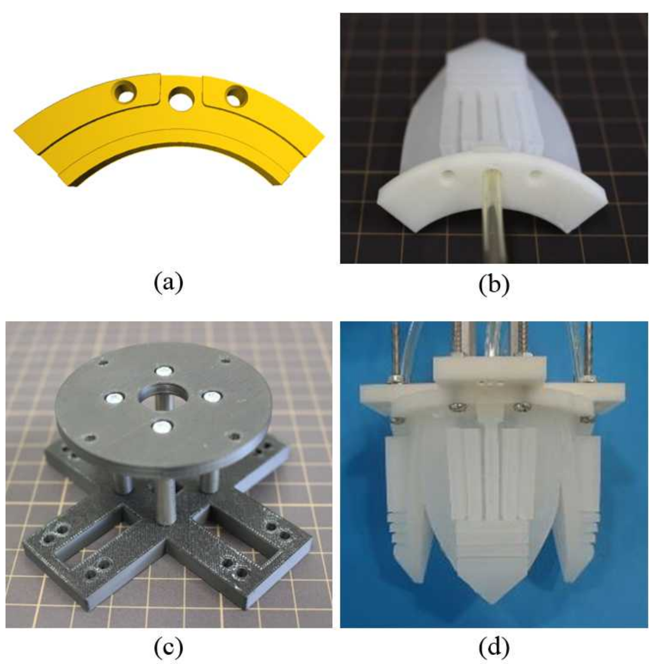

Fig. 5. Gripper assembly: (a) the rigid circular connector, (b) the assembled soft finger, (c) the gripper base, and (d) the assembled four-fingered gripper.

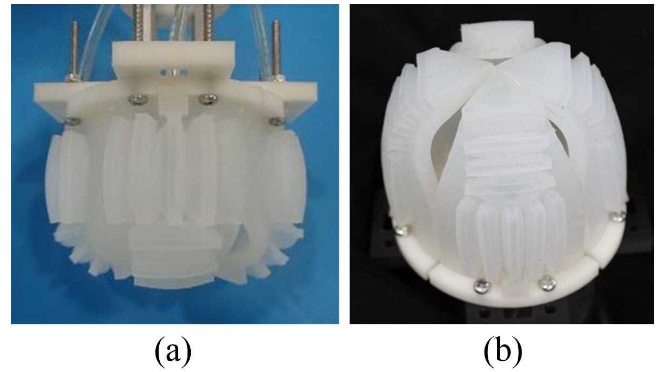

Fig. 6. Inflated gripper in (a) a side view and (b) a bottom view.

B. Gripper Assembly

To realize a circular configuration of the gripper, a circular connector (Fig. 5a) was designed and 3D printed using ABS filament. A tube with a diameter of 4 mm was inserted into the soft finger and then glued onto the circular connector using an instant adhesive (Cemedine Co., Ltd., Tokyo). The assembled soft finger is shown in Fig. 5b. To assemble the gripper and mount the gripper onto a robot arm, a gripper base was 3D printed and assembled as shown in Fig. 5c. Finally, a four-fingered soft gripper was assembled (Fig. 5d). Applying a pressure, the gripper was inflated and able to form an approximately closed cavity as shown in Fig. 6.

IV. Grasping Tests

A. Experimental System

The experimental system is shown in Fig. 7. The soft gripper was mounted onto a robot arm (Denso VS-050, Denso, Tokyo) and a pick-and-place motion was programmed. The inflation of the gripper was on-off controlled by a solenoid valve (VQ110-5M-M5, SMC, Tokyo) and programmed using a Nucleo board (STM32F303K8T6, STMicroelectronics, Geneva) on the control board. An electronic balance (UX6200H, SHIMADZU, Kyoto) was used to automatically record the target weight of every grasping trial. Two cameras were fixed on the workspace frame to record the grasping performance and the releasing appearance. The entire system was constructed based on robot operating system (ROS) and it can continuously iterate the grasping tasks for a desired number of trials. The experimental data of the target weights and releasing appearances were logged for further analysis.

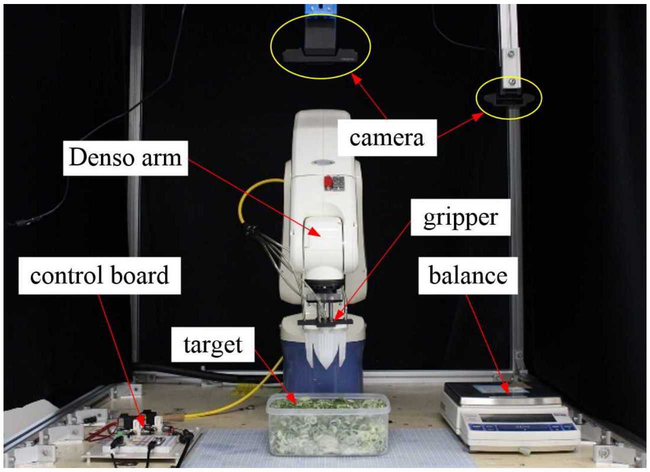

Fig. 7. Experimental system for grasping tests.

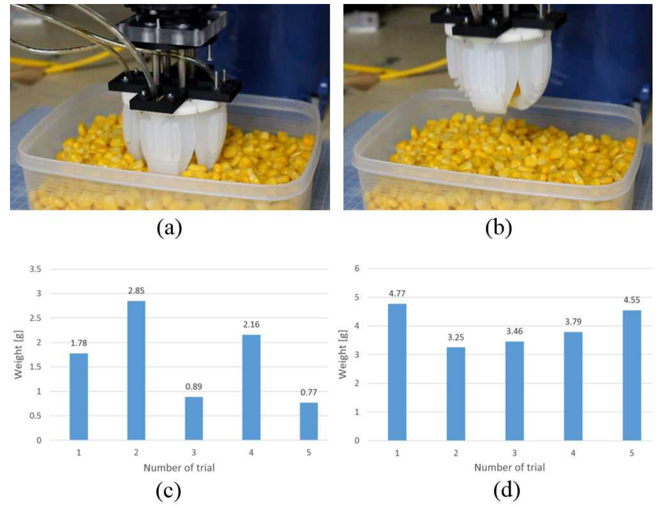

Fig. 9. Results of grasping experiments on kernel corn: (a) snapshot upon insertion, (b) snapshot after grasping, (c) weight distribution among different trials at an insertion depth of 10 mm, and (d) weight distribution among different trials at an insertion depth of 20 mm.

B. Grasping Experiments

The grasping experiments were conducted on three food materials: granular kernel corn, chopped green onion, and boiled hijiki, which often appear in Japanese boxed meals. The boiled hijiki is one kind of Japanese side dishes which often consists of boiled seaweed, sliced carrot, and fried tofu. The materials were randomly scattered in a container and the surface was manually flattened, as shown in Fig. 8. The surface height was considered as a known parameter and input into the arm control program. The soft gripper was then positioned based on this height value. One control parameter is the insertion depth which indicates how much the finger distal should be inserted below the material surface. Different depths were tested and compared.

The chopped green onion and kernel corn were defrosted before testing. The tests on kernel corn and chopped green onion with 10 mm insertion were conducted in Ritsumeikan University using a soft gripper fabricated using Dragon Skin 10 material. A pressure of 20 kPa was used to inflate the gripper. On the other hand, the tests on chopped green onion with 30 mm insertion and boiled hijiki were conducted at Nippon Flour Mills Co., Ltd, which is a major manufacturer of Japanese boxed meals. This soft gripper was fabricated using Dragon Skin 20 material and inflated with a pressure of 45 kPa while grasping. Pick-and-place test was repeated five times under each experimental condition. The weights of grasped food materials were recorded and results are discussed in the following section.

Fig. 8. Examples of grasping targets before defrosting: (a) granular kernel corn and (b) chopped green onion.

V. Results and Discussions

A. Grasping of Kernel Corn

Two insertion depths of 10 mm and 20 mm were tested on kernel corn and results were summarized in Fig. 9. Upon insertion, the tips of the soft fingers were bent a little, but they were still able to insert inside the corn (Fig. 9a). Once the fingers were inflated, the gripper formed an approximately close cavity and it was able to wrap the corns inside as shown in Fig. 9b. With an 10 mm insertion, the averaged corn weight grasped by the gripper is 1.69 g with a standard deviation of 0.78 g. The weight distribution among five trials was shown in Fig. 9c. On the other hand, with a 20 mm insertion, the averaged weight was increased to 3.96 g with a standard deviation of 0.60 g. The weight distribution among five trials is given in Fig. 9d for 20 mm insertion.

B. Grasping of Green Onion

Two insertion depths of 10 mm and 30 mm were tested for grasping green onion. Two experimental snapshots with 30 mm insertion were shown in Figs. 10a and 10b. The gripper was able to form an approximately close cavity while grasping and no material drops were found along the way to place and release for most of the trials. With a 10 mm insertion, the gripper could grasp an average weight of 3.27 g with a standard deviation of 1.38 g. The weight distribution among five trials were shown in Fig. 10c. When the insertion depth was increased to 30 mm, the average weight increased to 5.8 g with a standard deviation of 1.42 g. The weight distribution among five trials is given in Fig. 10d.

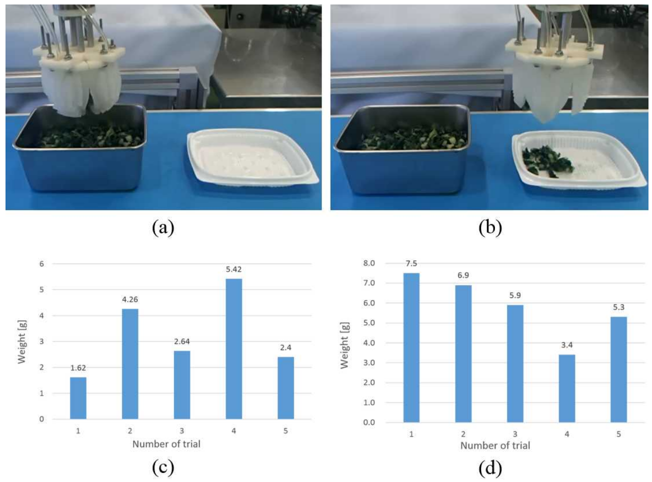

Fig. 10. Results of grasping experiments on chopped green onion: (a) snapshot upon grasping, (b) snapshot after release, (c) weight distribution among different trials at an insertion depth of 10 mm, and (d) weight distribution among different trials at an insertion depth of 30 mm.

C. Grasping of Boiled Hijiki

These experiments were performed at Nippon Flour Mills Co., Ltd. and only a 30 mm insertion was tested. The grasping snapshots and weight results on boiled hijiki were given in Fig. 11. Based on the experimental results, the insertion was easier comparing to the tests on kernel corn and green onion. Therefore, the grasped weight of boiled hijiki was much larger than that of corn and green onion as shown in Fig. 11c. Even though some higiki was caught in the gap between neighboring fingers, no material dropping was found through the experiments. The gripper could grasp an average weight of 16.6 g with a standard deviation of 6.20 g for an insertion of 30 mm. The weight distribution among five trials is shown in Fig. 11d.

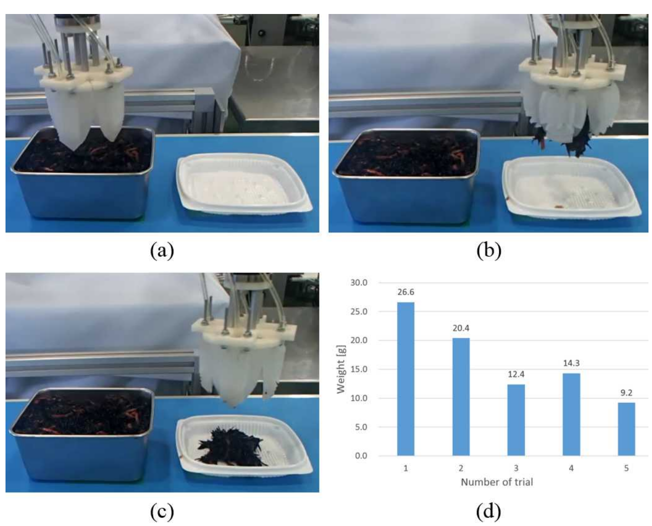

Fig. 11. Results of grasping experiments on boiled hijiki: (a) snapshot before grasping, (b) snapshot upon grasping, (c) snapshot after release, and (d) weight distribution among different trials at an insertion depth of 30 mm.

D. Discussions

With the proposed wrapping gripper, it is possible to wrap chopped and granular food materials. By varying the insertion depth, the averaged grasping weight can be controlled. However, the individual differences in grasping weight among different trials are relatively large. The main reason is because the current grippers were fabricated with Dragon Skin 10 and 20, which are relatively soft rubber materials. During insertion, the soft fingers were bent and could not be inserted into the desired depth. The insertion situation changes at every trial, therefore, the individual differences in grasping weight varied among trials. In the case of grasping chopped green onion, the fingertip sometimes stuck inside or blocked by an onion piece and the gripper could not be inserted properly. On the other hand, boiled hijiki was easier to be grasped comparing to kernel corn and green onion because of the smaller pieces and wet-and-soft properties of the hijiki material.

VI. CONCLUSIONS

This paper presented a soft robotic gripper capable of forming an approximately closed cavity for wrapping finely chopped and granular food materials. Such food materials often appear in Japanese boxed meals and the packaging operations of such materials are currently performed by human labors. The soft gripper presented in this paper is a preliminary attempt towards automating such operations by a robot. The soft finger design adopted the principle of pneumatic bellow-type actuator. It consists of multiple vertical and horizontal air chambers. Once inflated, the soft finger can bend in two perpendicular directions. FE simulation was performed and the deformation behavior of the soft finger was predicted. The soft finger was fabricated using Dragon Skin 10 and 20 materials and followed the traditional casting process. A circular rigid connector was designed and 3D printed to assemble a four-fingered soft gripper. Applying a pressure, the gripper can form an approximately closed cavity. Grasping experiments were conducted on three food materials: granular kernel corn, chopped green onion, and boiled hijiki. Pick-and-place tests with different insertion depths were performed and the grasped material weights were recorded by an electrical balance. Experimental results showed that the proposed soft gripper could wrap granular and chopped food materials and the grasped food weight in average can be controlled by varying the insertion depth. However, the individual differences in the grasped weight among different experimental trials are relatively large due to the difficulties of reaching the desired insertion depth. In addition, we found that the food materials were safely wrapped by the gripper and material dropping was infrequent.

In future, soft grippers fabricated with harder materials will be tested and the performances will be compared. The soft finger design will be further improved to form a better closed cavity with less gap between neighboring fingers. Last but not least, insertion with rotation motion will be investigated to achieve a better insertion even with softer fingers.

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