Multi-fingered Robotic Hand based on Hybrid Mechanism of Tendon-Driven and Jamming Transition

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***Abstract*— This study presents a novel four-fingered robotic hand to attain a soft contact and high stability under disturbances while holding an object. Each finger is constructed using a tendon-driven skeleton, granular materials corresponding to finger pulp, and a deformable rubber skin. This structure provides soft contact with an object, as well as high adaptation to its shape. Even if the object is deformable and fragile, a grasping posture can be formed without deforming the object. If the air around the granular materials in the rubber skin and jamming transition is vacuumed, the grasping posture can be fixed and the object can be grasped firmly and stably. A high grasping stability under disturbances can be attained. Additionally, the fingertips can work as a small jamming gripper to grasp an object smaller than a fingertip. An experimental investigation indicated that the proposed structure provides a high grasping force with a jamming transition with high adaptability to the object's shape.**

I. Introduction

Robots have recently been required to work in human environments. Such robots should provide a sense of security. When focusing on the capability of handling objects, the robots should have softness to prevent injury to human users and periphery objects, as well as rigidity to firmly and stably grasp an object. Moreover, the robots should have a variety of grasping styles for adoption to a wide variety of shapes and properties (e.g., stiffness and fragility) of the objects. This study presents a robotic hand satisfying different and conflicting demands (see Fig. 1). The key solution is a hybrid mechanism of a tendon-driven and jamming transition. The hybrid structure enables forming a grasping posture when in contact with an object through small forces and impacts, and to fix the grasping posture using a jamming transition to firmly and stably grasp the object. The main contributions of this mechanism are as follows.

High adaptability: Each finger link is constructed using a rubber bag filled with granular materials. Therefore, the surface is soft during a grasping motion, and the contact surfaces of the fingers deform according to the shape of the object. Compared to conventional tendon-driven robotic hands with relatively hard surfaces [1]–[10], a larger contact area can be attained, which enhances a stable grasp.

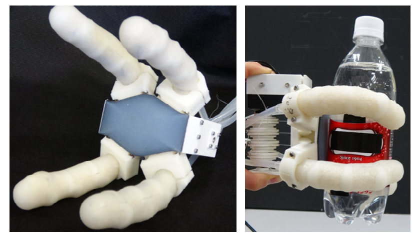

Figure 1. Multi-fingered robotic hand based on hybrid jamming transition and tendon-driven mechanism.

Conventional jamming grippers [11][12][13]–[19] have to strongly press the rubber bag against the object in one direction for grasping. The presented robotic hand has joints and can envelope an object through a closing motion. Owing to this enveloping motion, the object can be pressed from different directions, and the object can be grasped using small forces adapting to the shape of the object. Deformable and fragile objects can then be grasped without changing the shapes of the objects.

High stability under disturbances: If the jamming transition is conducted after the grasping motion, the grasping posture is fixed. The rigidity of both the surfaces and joints is increased. Additionally, in the grasping posture, the surfaces of the fingers are deformed according to the shape of the object. Thus, even if a disturbance force is applied to the object, the object can be grasped stably without increasing the grasping forces.

Segmented chamber mechanism: The jamming transition of the elongated rubber bag does not work if the bending or tensile force is applied to the bag. Such forces extend in space, and the density of the granular materials cannot decrease, and the jamming therefore fails. This paper presents a novel structure to resolve this issue. The chambers of the granular materials are separated for each finger link, and the chambers move with the rotation of the finger link, allowing the volumes of the chambers to remain constant.

Small jamming gripper style utilizing fingertip: If the target object is smaller than the diameter of the fingertip, the fingertip can be utilized as a small jamming gripper, which is an additional grasping style of the presented robotic hand.

II. Related Works

A. Multi-fingered hand with tendon-driven mechanism

The human hand has a very high DOF, which facilitates the grasping of various objects within a living space. In this context, a number of multi-fingered robotic hands imitating a human hand have been developed [1]–[10]. Tendon-driven

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systems have been popularly utilized to construct such multi-fingered robotic hands. Multiple joints can be driven using a single wire, i.e., one actuator. Actuators can be embedded in the palm or wrist. The fingers can then be slim. Thus, a small sized, lightweight, and low-cost robotic hand with a high DOF can be constructed. Examples of robotic hands based on a tendon-driven system including the i-HY hand by Odhner et al. [2], Pisa/IIT SoftHand by Catalano et al. [3], SDM Hand by Dollar et al. [4], a three-fingered gripper with passive rotational joints by Backus et al. [5], and a three-fingered robotic hand with active and passive tendons [6]. A popular structure for a robotic hand utilizing a tendon-driven system is as follows. A wire is attached to a finger link. Its corresponding joint is rotated through a pulling of the wire, which leads to a closing motion of the robotic hand. If a torsion spring is embedded in each joint, the robotic hand is opened through a release of the pulling force. To achieve a lightweight, low-cost, and easily maintained system, the utilization of a small number of actuators is preferable. It is possible to pull all of the wires to rotate the joints using only one actuator. However, if the motion of a certain finger is restricted through contact with an object, the motions of all other fingers are also restricted, and the grasping could fail. This issue can be resolved by embedding an elastic component such as a spring into the wire[3], [6]. The embedded spring for a finger restricted by an object is extended, and a closing motion of all fingers that are not in contact with the object is available. The robotic hand can then grasp the object by adapting to its shape. However, there is a drawback to this particular structure. The magnitude of the generable grasping force is determined not by the power of the actuator but by the stiffness of the embedded spring. The stiffness should slight to enhance the adaptation to the object shape, but sufficient to achieve a large grasping force. The installation of a brake between the wire and spring could be a solution. However, the components used in the brake could increase the finger size, which should be avoided for use in a wide range of fields. In addition, to attain a high adaptability to the object's shape, a soft surface is more preferable.

B. Jamming transition

A jamming transition is a phenomenon in which the state of the granular materials changes from soft to rigid, or vice versa, by changing the density of the granular materials [11][12]. There have been many previous studies on robotic hands utilizing a jamming transition [13]–[19]. One representative study is a jamming gripper developed by Brown et al. [15]. The gripper consists of a rubber bag filled with coffee beans, and its stiffness was changed by controlling the pressure of the air inside the bag. The grasping process is as follows. 1) A rubber bag with granular materials is pressed against the object, and then deforms along the shape of the object. 2) The deformed gripper is changed to a solid-like state by sucking the air around the granular materials. The state is then fixed, and the object can be grasped. Some other examples include a jammable manipulator developed by Cheng et al. [16], a two-fingered hand having a jammable fingertip by Hou et al. [17], and a two-layered jamming gripper by Fujita et al. [18]. Using this structure, the rigidity can be simply controlled through an air pressure control. One drawback is that the gripper has to strongly press against the object for the purposes of grasping, and is difficult to adopt for use with fragile or deformable objects. The presented study avoids this issue by using a jamming transition not for the grasping directly but for fixing and maintaining the grasping posture.

III. DESIGN AND FUNCTION

A. Hand design

Fig. 2 shows the developed robotic hand constructed with four fingers. The actuator (ROBOTIS, DYNAMIXEL XM430-W350-R) is located at the backside of the palm for driving all four fingers. The actuator is connected to an independent-motion-driving unit (described later). The size of the palm is 90 mm × 82 mm, and the length of each finger is 100 mm. The fingers were arranged with angles of α and β (Fig. 2), allowing the enveloping, cylindrical, and precision grasps to be realized using a single actuator. An angle α of 20° provides an intermediate grasping style between the enveloping grasp and the parallel-jaw-gripper style. It should be noted that the parallel-jaw-gripper style is effective for grasping a cylindrical object. As shown in Fig. 3(a), each pair of the two antipodal fingers can be in opposition. An angle β of 30° provides a surface contact between the two antipodal fingertips, when pulling the driving wire without jamming. These settings enable a stable precision grasp. The available grasping styles are shown in Fig. 3 with the maximum and minimum sizes of graspable objects.

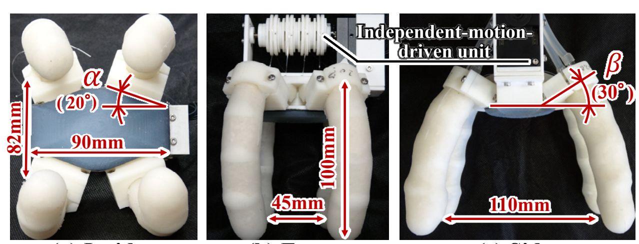

Figure 2. Outlook of the developed robotic hand

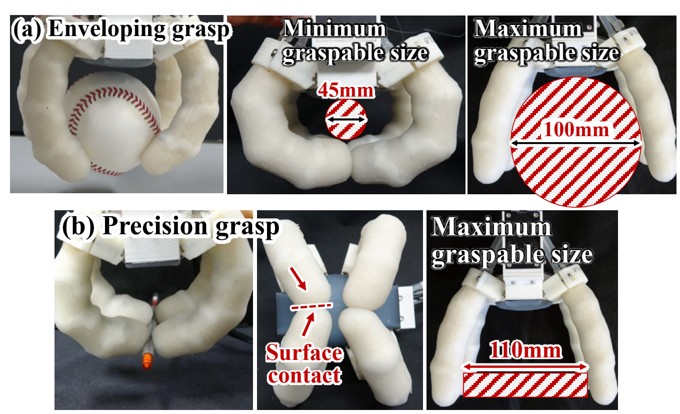

Figure 3. The available grasping styles with the maximum and minimum sizes of graspable objects; (a) enveloping grasp, (b) Precision grasp.

B. *Finger structure*

Fig. 4 shows a schematic view of the finger structure constructed using a skeleton, particles, and an outer rubber skin (Ecoflex 00-30). Fig. 5 shows the skeleton of a finger made using a 3D printer (Stratasys uPrintSE). The skeleton is composed of four links and three rotational joints. The protruded part at each joint is called the "joint block," and is connected with the distal-side link. The role of the joint block is to provide separated spaces inside the outer portion of the rubber. Air flows through the clearance between the links and joint blocks, whereas the particles do not. Thus, all segmented chambers can be jammed by sucking the air around the particles through a suction tube embedded at the root of the finger. One wire is attached to the distal joint block, and goes through the holes in the other joint blocks and finger base. All joints of the finger are driven through a pulling of the wire. To prevent air from leaking from the holes, the wire is covered with a vinyl tube, which is tightly sealed at the finger base.

The joint bock has a role in separating the chamber into three chambers for the four links, and to enhance the increase in rigidity owing to the jamming transition. The increase in rigidity is caused by an increase in the particle density. There is one weakness, however. The rigidity decreases when applying a load, which contributes to an increase in the chamber volume, blocking the operation of a jamming transition. A typical example is a case in which an external force is exerted on the flexed finger, as shown in Fig. 6. In Fig. 6(b), it can be seen that the lower part of the proximal joint is infracted. To resolve this issue, the joint block has a shape in which the inside part is a flat plate and the outside part is quarter-spherical. This prevents an undesirable movement of the particles, which increases the volume of the chamber, as shown in Fig. 7. It should be noted that a finger stiffened by a jamming transition can return to its original soft state through an unjamming process, as shown in the attached video clip.

To verify the proposed structure of the skeleton, we experimentally investigated how much force can be applied to the finger, which is closely related with the magnitude of rigidity (Fig. 8). The experimental method applied is as follows. The finger base was fixed such that the finger was horizontally arranged with its inside facing downward. After the finger was expanded straightly, a jamming transition was applied. A vertical load was then applied to the fingertip. Four kinds of fingers were prepared: (a) no skeleton, (b) a skeleton without joint blocks, and (c) a skeleton with the joint blocks. We compared the reactive force when the fingers were pushed with the same displacement (7 mm). A jamming transition was applied using a vacuum pump (G-10DA, UKVAC KIKO, Inc., with an ultimate pressure of 1.3 Pa). Five trials were applied. Fig. 8 shows the results. It can be seen that the proposed structure, namely, (c) provides an outstanding performance, which validates the structure. It should be remarked that a low applicable force occurs when there is no skeleton, which indicates the importance of a skeleton for enhancing the rigidity.

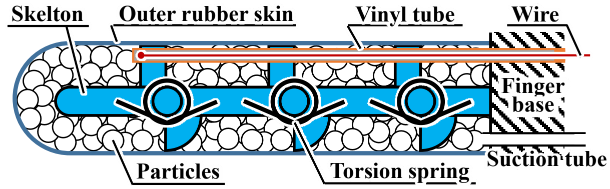

Figure 4. Schematic view of the finger structure.

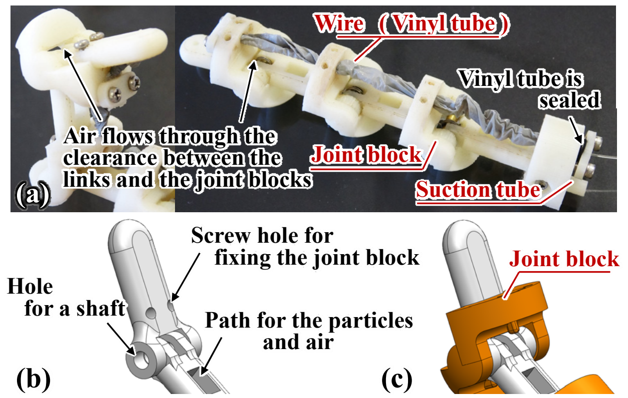

Figure 5. Skeleton of the finger: (a) photograph, (b) CAD model without a joint bock, and (c) CAD model with a joint block.

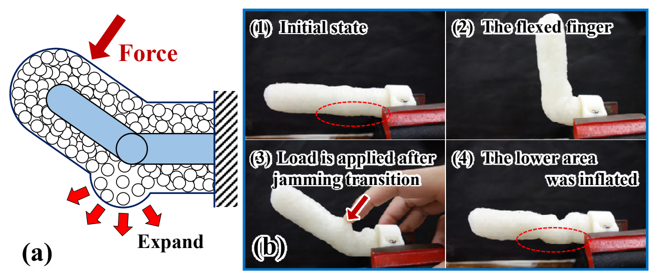

Figure 6. (a) Schematic view and (b) photograph of a case in which an external force is exerted on the flexed finger without a joint block.

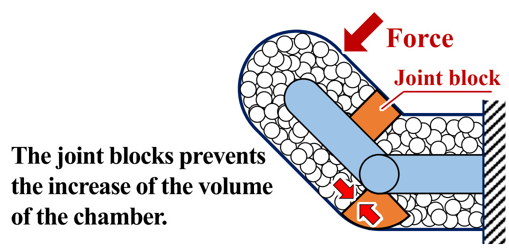

Figure 7. Schematic view of a case in which an external force is exerted on the flexed finger with a joint block.

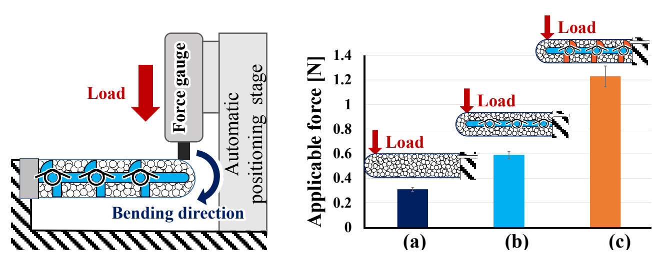

Figure 8. Applicable forces for different skeleton structures. The left figure illustrates the experimental set up while the right figure displays the results; (a) no skeleton, (b) three joints and links, and (c) three joints and links with joint blocks.

C. Particle selection

It is preferable for the particles to not disturb the rotation of the finger joints before a jamming transition, whereas the joints can be strongly fixed after a jamming transition. From this viewpoint, we experimentally investigated which type of granular material is preferable. The target materials are shown in Fig. 9. Coffee powder, which has a small particle size, is a popular material used for jamming grippers. A bead is an industrial product, and the variances in its size and shape are small. Rice is long and thin, and its variances in size and shape are large. Gravel has larger variances in size and shape than rice. The average size of a particle is largest for gravel, followed in order by rice, beads, and coffee powder.

Fig. 10 shows the experimental setup applied. The procedure is as follows. 1) The base of the expanded finger was fixed such that the inside of the finger faced upward. 2) The wire for closing the finger was attached to a force gauge (DS2-50N, IMADA) mounted on an automatic poisoning stage (MX2-500N, IMADA) through a pulley. 3) We pulled the wire using the automatic poisoning stage, and the pulling force was measured with and without a jamming transition. A jamming transition was conducted using a vacuum pump (G-10DA, UKVAC KIKO, Inc., with an ultimate pressure of 1.3 Pa). To evaluate the stiffness of the structures, we compared the increased pulling forces when pulling the same distance (7 mm) starting from the same initial pulling force (0.5 N). We repeated the same experiment five times.

Fig. 11 shows the results; the left bar indicates a case in which a jamming transition was not applied, whereas the right bar shows a case in which a jamming transition was applied. Without a jamming transition, coffee powder provided the least stiffness, and the smoothest joint motion was therefore expected. The second best was obtained using rice. With a jamming transition, rice provided the largest amount of stiffness. Because a soft surface constructed using granular materials normally provides a soft contact, a high stiffness owing to a jamming transition is more important for firm and stable grasping. Therefore, we selected rice as the granular material for the developed robotic hand.

D. Independent-motion-driven unit

To utilize the high adaptability of the proposed finger mechanism, the wires of the four fingers need to be pulled individually. As mentioned in section I, if simply pulling the four wires of the four fingers using a single actuator, a problem will occur (see the left side of Fig. 12), namely, the motions of all fingers will be restricted by the restriction caused by contact between one finger and the object. Herein, we applied a method in which we embedded a spring in the wire, similar to a series of elastic actuators (see the right side of Fig. 12). The independent-motion-driving unit provides a compact structure, allowing a solution to be realized. Fig. 13 shows a schematic structure of the unit. The unit was constructed using four smaller units for the four fingers. Each small unit was constructed using an inner ring, a torsion spring, and an outer ring. The four inner rings are serially

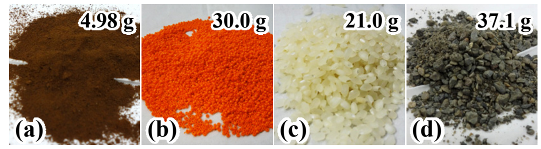

Figure 9. Examined granular materials: (a) coffee powder, (b) beads, (c) rice, and (d) gravel.

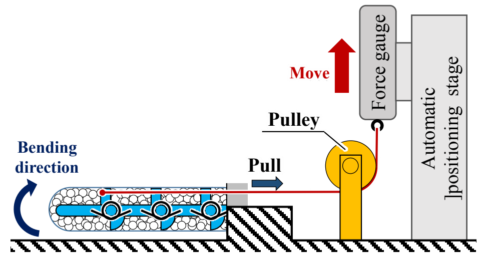

Figure 10. Schematic view of the experimental setup for selecting granular materials.

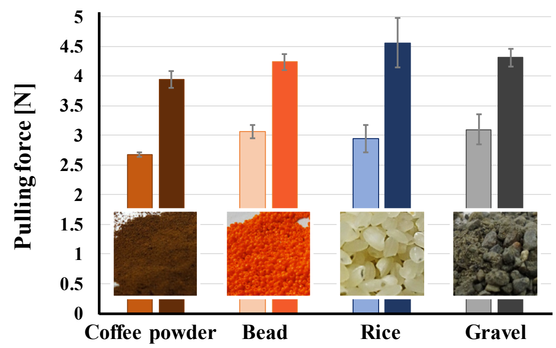

Figure 11. Pulling force when utilizing different granular materials: without (left bar) or with (right bar) a jamming transition.

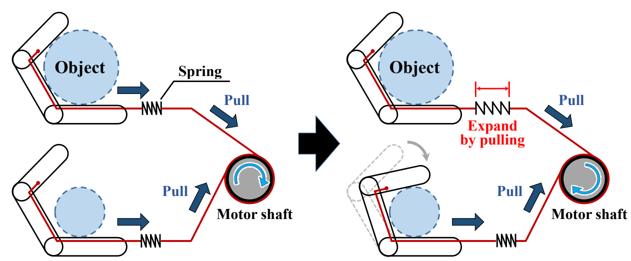

Figure 12. Role of independent-motion-driving unit.

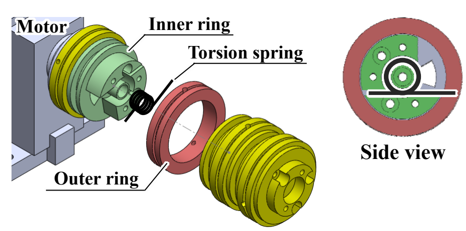

Figure 13. Schematic view of independent-motion-driving unit.

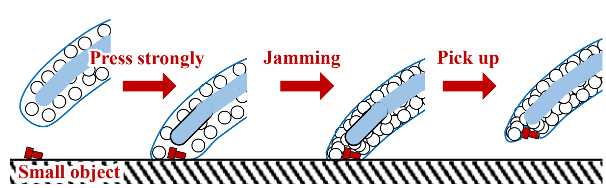

Figure 14. Function of jamming gripper. This is useful to grasp a small or thin object that is difficult to grasp with another grasping style.

connected and driven by a motor. The outer ring is attached to a wire to pull each finger. The driven torque is transmitted to the outer rings through the torsion springs connected to the inner rings individually. When the motor is driven, the four smaller units are rotated and the four wires are initially pulled. If the motion of one finger is restricted through contact with an object, the torsion spring is extended instead of pulling the wire in the corresponding unit. Thus, the motions of the other fingers are not hindered.

E. Small jamming gripper utilizing fingertip

The fingertip of the developed robotic hand can be utilized as a jamming gripper, as shown in Fig. 14. The size of a graspable object is smaller than the fingertip. This function is useful when grasping an object that is too small or thin, and is difficult to grasp using other grasping styles.

IV. EXPERIMENTAL EVALUATION

To evaluate the functions of the developed robotic hand, several experiments were conducted, the results of which are shown herein.

A. Grasping test

Figs. 3 and 15 shows the results of the grasping tests. A baseball, mug, and cord were grasped using an enveloping grasping style. A plastic bottle (500 ml) and a tomato can were grasped using a cylindrical grasping style. A black ball, a box, a small ornament, and a bunch of keys were grasped using a precision grasping style. The results indicate that the developed robotic hand can grasp a wide variety of objects by adapting to the shapes of the objects and utilizing different grasping styles. Off course, there are the limitations. The hand failed to grasp a card, large box and bottle because of too thin, too large, and too heavy for precision grasp, respectively. Focusing on the grasping of a small mug, one finger was extended owing to a contact made with the handle, whereas the other fingers were flexed. This validates the efficacy of the independent-motion-driving unit. We tried to grasp a large mug using a style in which one finger was inserted into the handle, and another finger supported the weight of the mug while making contact with the lower part of the handle. A load was exerted on the lower finger such that a flection occurred and the wire was relaxed; however, the finger posture was maintained as a constant, thereby validating the efficacy of the jamming transition.

B. Grasping stability and disturbance

Herein, we investigated the grasping stability under a disturbance through two types of operations (see the video clip). Fig. 16 shows an operation in which a deformable plastic tube including two tennis balls was grasped and shaken. It can be seen that the tube was not deformed, and the grasping posture was maintained. For the operation shown in Fig. 17, we grasped a deformable paper box including water, poured the water into a deformable plastic cup, grasped the cup, and poured the water into a vase. A deformation of the grasped objects, which are fragile and deformable, was not observed. The grasping posture was maintained even when pouring the water while tilting the objects. From the two operations, the high grasping stability under a disturbance was observed.

C. Functionality as a small jamming gripper

Herein, we investigated the functionality of the fingertip as a small jamming gripper. The target objects were M2 to M8 sized bolts, as shown in Fig. 18. Each bolt was placed on a flat surface, and pressed by the fingertip. Subsequently, a jamming transition was applied, and the fingertip was picked up. We considered the operation to be successful if the bolt was also picked up or absorbed. The operation for each bolt was applied four times. Table I shows the success rate. A low success rate was obtained when grasping the M2 and M8 bolts. An M2 bolt was too small compared to the thickness of the rubber skin, and an M8 bolt was too big compared to the sizes of the fingertips and the granular materials. The available range within which fingertip can work as a jamming gripper was close to the size of the M3 to M6 bolts.

Figure 15. Results of grapsing test

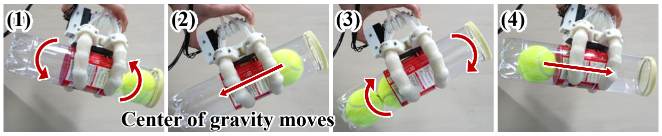

Figure 16. Operation in which a deformable plastic tube including two tennis balls was grasped and shaken.

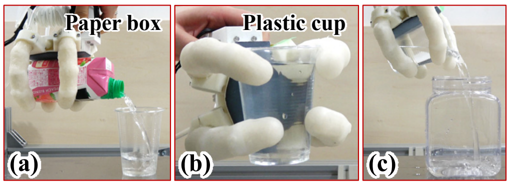

Figure 17. Operation in which a deformable paper box including water was grasped, (a) the water was poured into a deformable plastic cup, (b) the cup was grasped, and (c) the water was poured into a vase.

Figure 18. Target objects and overview of the grasping test utilizing the fingertip as a jamming gripper.

TABLE I. SUCCESS RATE OF GRAPSING TEST UTILIZING THE FINGERTIP AS A JAMMING GRIPPER

Type and length	M2×4	M3×4	M4×5	M5×5	M6×10	M8×15
Success rate	1/4	4/4	4/4	4/4	2/4	0/4

V. CONCLUSION

This study presented a novel multi-fingered hand based on the hybrid mechanism of a tendon-driven and jamming transition. Each finger was constructed using a tendon-driven rigid skeleton, granular materials (rice) corresponding to finger pulp, and deformable rubber skin. With this structure, the robotic hand can make a grasping posture while adapting to the shape of the object and without its deformation, and hold the object by fixing the grasping posture using a jamming transition. The experimental results indicate that the hand can grasp a wide variety of objects with different grasping styles according to the object shape or operation. A fixed grasping posture using a jamming transition was maintained even when several external disturbances were exerted. This indicates that a high grasping stability under disturbances can be achieved. Additionally, the fingertips can work as small jamming grippers, and the experimental results show that this function is available for objects whose size is close to that of M3 to M6 sized bolts. Future work will involve a realization of autonomous operations utilizing the developed robotic hand.

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