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A Stiffness-Changeable Soft Finger Based on Chain Mail Jamming

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***Abstract*—This paper presents a stiffness-changeable soft finger using chain mail jamming. This finger can achieve adaptive grasping and in-hand manipulation by reshaping and exerting changeable gripping force. The jamming phenomenon happens when particles in a chamber get interlocked where confining pressure is exerted at their boundaries, which is widely used to construct mechanisms with changeable stiffness. Compared with the traditional granular media, chain mail has a lower packing fraction and provides a stronger tensile force. In this paper, we proposed to apply chain mail jamming to the field of robotic finger design. Especially, we propose the design of the finger, the fabrication process, the method of predicting gripping force, and the grasping strategies. The experiments quantitatively verify the model of gripping force prediction. The demonstrations validate the advantages of adaptive grasp by picking a variety of items including foods, goods, and industrial components, and show the application of in-hand manipulation.**

***Index Terms*—Soft finger, Chain mail jamming, Stiffness-changeable mechanism, Grasp, Manipulation**

I. INTRODUCTION

SOFT grippers exhibit effective adaptation and safety in manipulating objects with various properties, stiffness, shapes, and consistencies. The functions of soft grippers mainly consist of three categories [1]: changeable stiffness [2] [3], changeable adhesion [4] [5], actuation [6] [7]. They show their advantages on different fields. One may choose and combine the preferred technologies to construct a soft gripper according to task constraints.

In this paper, we focus on stiffness-changeable soft fingers. Soft fingers can be viewed as elastomers, their gripping force relates to their stiffness under the assumption of consistent deformation. A gentle gripping force does less harm to fragile objects but may be hard to balance the gravity and tolerate disturbance. Contrarily, strongly squeezing may cause damage by inducing large deformation of objects, however, provide a stable and robust grasp. Thus, the graspability can be optimized by enabling the changeable stiffness of soft fingers.

We propose to utilize the jamming phenomenon to construct a stiffness changeable mechanism. The jamming phenomenon has been widely used in robotics [8], such as robot bodies [9], grippers [10], and fingers [11]. Conventionally, granular particles are mainly used as jamming media. However, granular jamming has disadvantages in shape recovery, lightweight design, and holding tangential load. Wang et al [12] proposed to use chain mail as jamming media to design structured fabrics, which are low packing fractions and achieve tunable stiffness in a large range. Inspired by this, we propose to use chain mail jamming in the field of soft fingers. In this paper, we design the stiffness changeable finger using chain mail jamming. The structure and prototype are shown in Fig.1. We design the finger body as a silicone chamber, which is also a container of chain mail. The root of chain mail is embedded into the root of the finger chamber, making them an integral finger. The finger base cages the finger chamber and connects the flange and pneumatic tube.

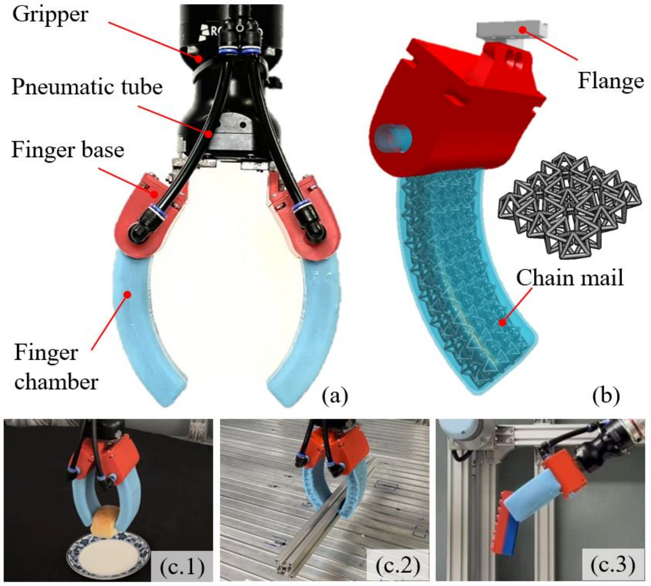

Fig. 1: (a) A pair of the proposed fingers mounted on a gripper. (b) The CAD of the finger. Chain mails are wrapped inside the finger chamber. (c) Demonstrations of adaptive grasping and manipulation: (c.1) Grasping a bread; (c.2) Grasping an aluminum bar; (c.3) Reorienting a building block with gravity.

The proposed finger can equip on an off-the-shelf gripper platform. The compliance of fingers allows the gripper to squeeze to the extreme without stalling and getting stuck. We can change the gripping force by changing stiffness, namely, adjusting confining pressure. We propose two grasping strategies. One can preset the appropriate stiffness and conduct grasping. The other way is two-step. The soft gripper can first grip an object using low stiffness, leading to reshaping

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the finger for better contact. Then, it changes the pressure to increase the grasping force to firmly grip the object. This finger enables a simplified grasp action. Grippers can always play a full-stroke grasp to realize adaptive grasp without positional control.

The contributions of this paper are three-fold:

1) Extended the concept of chain mail jamming in the field of soft gripper.
2) Designed and fabricated the silicone finger chamber with embedded chain mail.
3) Proposed the strategies for adaptive grasping and showed potential on in-hand manipulation.

The paper is organized as follows. Section II presents the related work. Section III introduces the designing and fabrication of the proposed finger. The model of gripping force and grasp strategies are presented in Section V-VI. Experiments and demonstrations are shown in Section VII. Conclusions, discussion, and future work are presented in Section VIII.

II. RELATED WORK

The proposed work relates to the stiffness changeable mechanisms and is used in the field of adaptive grasping and manipulation. Thus, the literature review concentrates on these two parts.

A. Stiffness changeable mechanisms

Robots are expected to complaintly interact with environment and humans, which extends the robots to work beyond the easy and repetitive industrial manufacture. Compared with the control-based active compliance [13], the stiffness changeable mechanisms are safe, quick-response, and low cost. Some researchers proposed to add elastic joint modules on the rigid gripper [14]. The stiffness changes with the rotation of a flexure hinge. It is compliant on a single direction, making it hard to work against large uncertainty. Soft mechanism using jamming phenomenon provides omnidirectional and continuous changeable stiffness. Granular particles are popular media to realized the pressure-controlled jamming. Mizushima et al. [2] used rice particles as the media to construct a multi-finger hands. liu et al. [15] developed to use positive pressure to control the jamming-based stiffness. Fujita et al. [16] used power particles to design a jamming layer to stiffen the gripper. In addition, researchers explored other jamming media to develop robot systems, such as, layer media [17], fiber Jamming [18], and chain-like granular jamming [3].

Unlike the traditional jamming methods, we take advantages of chain mail jamming [12] to design the finger. This method helps to keep the finger body consistent, provide larger tangential load, and design lightweight fingers.

B. Adaptive grasping and manipulation using soft grippers

Objects vary in shape, hardness, fragility, surfaceness, etc. Adaptive grasping and manipulation various objects is a challenging task in robotics. Soft grippers shows the advantages on this task without complex sensory operation. Brown et al. [10] proposed to replace individual fingers with a stiffness changeable pad, which passively adapts to various object and reshapes to complete gripping. Hao et al. [19] proposed to use inflation finger to grasp soft objects. A multi-layer soft robot gripper was proposed in [16], it can both adaptively grasp objects and reshape to complete manipulation tasks. Abondance et al. [20] developed a gripper with a set of multi-chamber inflation fingers to achieve in-hand manipulation.

In our proposed method, we avoid the difficulty on using soft unit to construct an actuator. We use motor to drive the soft fingers. Thus, we can benefit from both the stable control of gripping action and the adaptation. The stiffness changeable mechanism enable the gripper exerting adaptive force for grasping and manipulation.

III. FINGER DESIGN AND FABRICATION

A. Chain mail

Chain mails are constructed by an array of adjacent interlocked elements. The properties of chain mails relate to the shape of elements. We chose to use 3D structured chain mail elements, octahedral, and hollow octahedrons. Fig.2(a) shows two interlocked hollow octahedrons. Using this shape in CMJ proves to be effective in providing a large varying range of stiffness [12]. Compared with traditional chain mails with interlocking ring-shape and square-shape elements, the chain mail with hollow octahedrons has lower volumetric density, showing advantages in lightweight design.

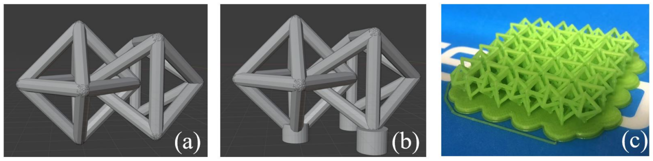

Fig. 2: (a) Two interlocked hollow octahedrons. (b) The supporting pillars on the bottom of octahedrons (c) A printed chain mail prototype.

The interlocked hollow octahedrons have plenty of suspension beams, leading to difficulty in fabrication. 3D printing is a feasible technology. Especially, 3D printers using the Selective Laser Sintering (SLS) [21] [22] are applicable to make such a model without complex support material. However, SLS is a relatively high-cost method. We propose to use the simple and cheap Fused Filament Fabrication (FFF) 3d printer to complete the fabrication. By using the feature that the fused filament can bridge the printed pillars, we ignore the support materials inside the hollow octahedrons and generate the supporting pillars on the bottom (Fig.2(b)). The pillars avoid floating elements, on the other hand, increase printing stability by creating larger contact regions with the printer bed. Fig.2(c) shows the printed chain mail. The diameter of the element edge is 1.2 mm and the edge length of this regular octahedron is 7 mm. In this prototype, we used the 3D pringer, Flashforge Creator 3, and the PLA filament. Note that we should cut the support pillars as they may affect the mobility of chain mail.

B. Finger chamber

The finger has a soft chamber containing the two-layer stacking chain mails. The finger chamber should fully wrap the chain mails, and the clearance between the chain mails and the chamber should be minimized. To increase the gripping force, we design the finger as curved shape, which provides higher inward force components under the deformation after squeezing. The shape and dimensions are shown in Fig.3(a). Fig.3(b) illustrates the finger chamber with the inserted two-layer chain mails. The chain mails overflow the chamber. We cast another silicone filler to embedded the root of chain mails into the finger chamber. This fixation makes the chamber and chain mails a integral finger. The root part of the finger chamber gets strengthened by the internal support from chain mails. And the chain mails can be well aligned, instead of changing to unpredictable configurations after being compressed to a corner. We design the molds to cast the finger chamber, as shown in Fig.4(a). The molds consist of a inner core, two side molds. There are vents on the side molds for exhausting bubbles. The hole for molding the tube is also used as pouring hole. The two pins on the inner core can be disassembled to facilitate the demoulding. Fig.4(b) illustrates the casted finger chamber. Then, we use another mold to cast the silicone filler as shown in Fig.4(c).

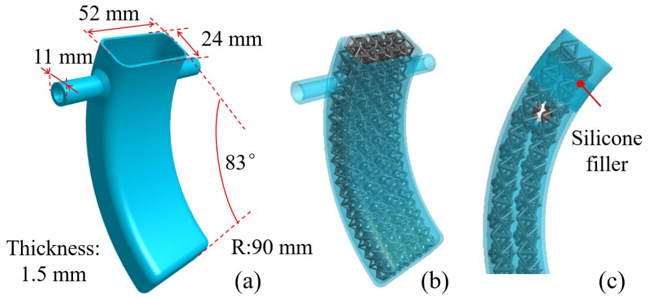

Fig. 3: (a) Dimensions of the finger chamber. (b) Finger chamber with inserted two-layer chain mails. (c) The silicon filler embedded the root of chain mail into the finger chamber.

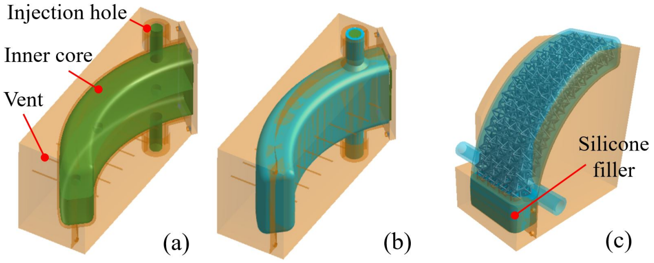

Fig. 4: (a) The molds for casting the finger chamber. (b) Casted finger chamber. (c) Casting the silicone filler to embed the chain mails.

C. Finger base

The finger base connects the flange and also cages the finger chamber. The finger base also support the tubes for connecting the pneumatic tubes. Between the shell of finger base and the finger chamber that we finished in the last subsection, we cast the silicon layer for fixation. Here the shell of finger base also works as a mold (Fig.5(a)). After curing (Fig.5(b)), we can assembly the flange on the finger base, and complete the prototype. Fig.5(c) Shows the prototype connecting with pneumatic tubes and gripper. In this prototype, we used the silicon gel, HTV-4000 (Hardness: 35A).

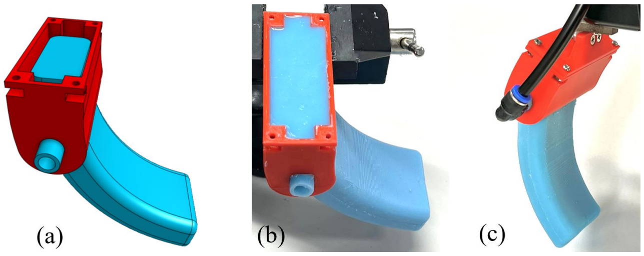

Fig. 5: (a) Pouring silicone to fix the finger chamber with the shell of finger base. (b) The Finger base after curing. (c) A complete prototype.

IV. GRIPPING FORCE AND GRASP STRATEGIES

The proposed finger with chain mails is discrete and anisotropic. However, within a certain deformation range, we can consider it as an elastomer and use an apparent elastic bending modulus E [12] to model the gripping force. We can use three-point bending test to obtain the stiffness, and further calculate E using Equation.1.

$$E = \frac{KL^3}{4bh^3}, \tag{1}$$

where K the stiffness obtained from the three-point bending test, L is the distance between support pins, b and h are the width and height of the test specimen. To be Noted that we ignored the compressed deformation after vacuum, and use the consistent b and h to compute under different pressure.

The stiffness relates to the confining pressure. We can obtain the bending moduli under different conditions by presetting the confining pressure. Then, we reshape the finger chamber as solid, and use the tested bending modulus to model it. We can use Finite Element Analysis (FEA) to compute the relation between the gripping force and deformation under given confining pressures. We show the experimental results and the predicted value using FEA in Section.V.A.

With the feature of changing stiffness, we propose two grasp strategies. The first one is the direct-grasp mode. By controlling the confining pressure, the finger stiffness can be adjusted to exert suitable gripping force. We can preset the confining pressure and directly grasp an object with feasible stiffness. The second one is the contact-grasp mode. The gripper has high compliance when lowing its stiffness. We can first use the lowest stiffness mode to make the gripper contact the object, which reshapes the fingers to adapt to the object. Then we increase the confining pressure to strengthen the gripping force. To be noted, as the finger is reshaped before vacuum, after changing to the confining pressure condition, the gripper force will not as large as the one exerted by directly using the same pressure.

V. EXPERIMENTS AND DEMONSTRATIONS

In the section of experiments and demonstrations, we show the advantages and validate the performance and practicability of the proposed finger. First, we test the mechanical property, and compare with the finger using traditional granular jamming. Second, we demonstrate the adaptive grasping for diverse objects. Especially, we select the objects including foods, goods, and industrial components. Third, we carried out demonstrations to show the potential on in-hand manipulation by a reorientation task.

A. Mechanical property

In this experiment, we first carried out the three-point bending test to obtain the stiffness, calculated the bending modulus E of the proposed stiffness changeable unit. By varying confining pressure, we can obtain the corresponding E. Then, we computed a regression equation to express the relation between E and confining pressure. Using this equation, we can predict E under different pressure, and leverage FEA to compute the displacemental deformation under varying gripping force. Fig.6 shows our experiment setting. The wrist force sensor performs a force gauge. Especially, in three point bending test, we used the flat units for accurate efficiency of experiment instead of the curved fingers.

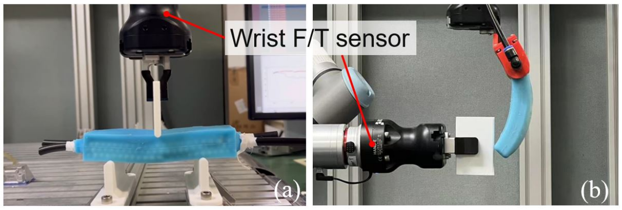

Fig. 6: (a) Three-point bending test. (b) Measuring gripping force.

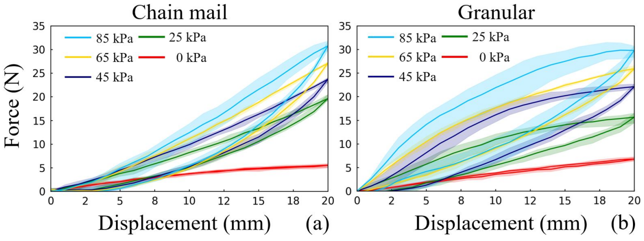

Fig. 7: The results of three-point bending test. The curves show the relation between force and displacement.

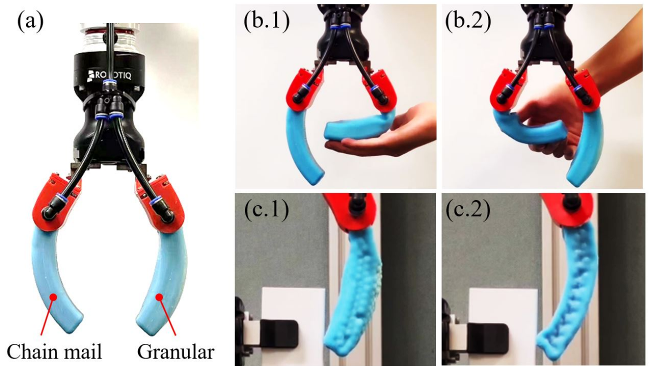

Fig. 8: Illustration of the comparison. (a) Left: chain mail jamming finger; Right: granular jamming finger. (b) Bending the fingers under normal pressure. (c) The finger shape under confining pressure. (b.1)(c.1) The granular jamming finger. (b.2)(c.2) The chain mail jamming finger.

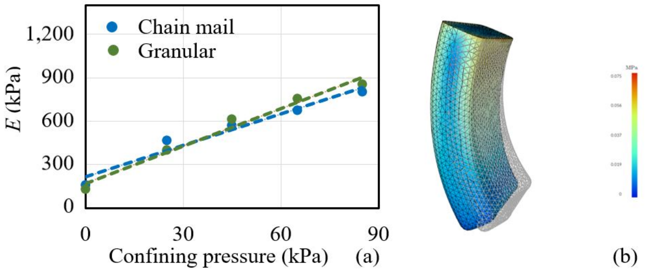

Fig. 9: (a) Bending moduli. (b) FEA simulation using the modeled bending modulus. The gripping force is 3 N and the displacement of fingertip is 22.9 mm.

Fig.7 shows the measured dependence of force on displacement. For comparison, we measured both the chain mail jamming unit (Fig.7(a)) and the granular jamming unit (Fig.7(b)). We used the plastic balls as the granular media, their diameter is 5.5 mm. Note that we recorded the data of both forward motion and backward motion, so we can find and compare the hysteresis. We can find that the linearity of the curves of the chain mail jamming is better, and the curves of the granular jamming reveals a decrease trend of stiffness. Even the stiffness of granular jamming in this configuration is larger than the one of chain mail jamming, the non-linear stiffness trend have a negative impact on predicting gripping force. We can use a linear regression to compute the stiffness from the data in Fig.7. And we can obtain the corresponding E. The results are shown in Fig.9(a). The E of the chain mail jamming unit can be expressed by $E_{cmj} = 7.2p + 215kPa$ and the one of the granular jamming unit can be expressed by $E_{gj} = 8.6p + 170kPa$, where p in the confining pressure. In general, they have the similar range of changeable stiffness. Although the linearity is poor, the granular jamming even has a larger E. However, the weights of the chain mail jamming unit and the granular jamming unit are 89.4 g and 163.5

g. Considering the volume fraction, the chain mail jamming shows the advantage.

Before the analysis of gripping force, we have an intuitive comparison between the two fingers infilled with chain mails and granular particles. We assemble the proposed chain mail jamming finger and the granular jamming finger on one gripper, as shown in Fig.8(a). It can be seen that the chamber of chain mail jamming finger keeps the initial shape but the granular jamming one has an inflated and uneven chamber. It is because the chain mails are light and their roots were fixed by the silicon filler. However, the finger chamber cannot fix the fully separated balls, and they sink to the fingertip to inflate the chamber by gravity. And the downward gathered particles make the finger root hollow. Thus, the finger's stiffness is not consistent along the profile. The root part may be suddenly folded (Fig.8(b.1)) under normal pressure. But since the chain mail evenly supports the finger chamber, the thickness of the root has no large change (Fig.8(b.2)). Fig.8(c) shows the finger shapes after vacuum. We can see the uneven shape of the granular jamming finger and the even shape of the chain mail jamming finger. The consistency of shape help to model the predictable gripping force.

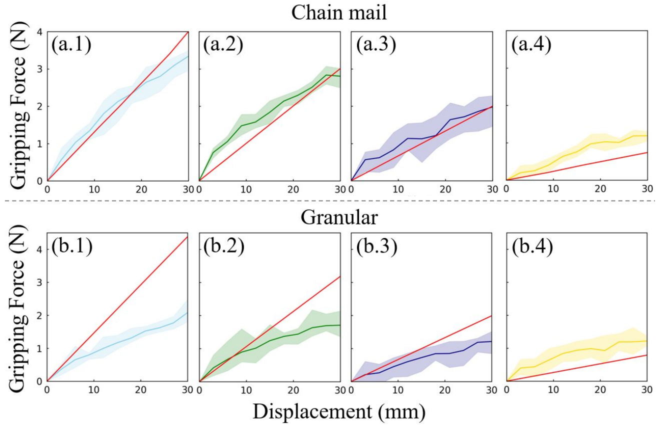

Fig. 10: Experimental results of gripping force versus displacemental deformation. Top half: chain mail. Bottom half: granular. Red lines are the simulated results from FEA. Blue curves: 90 kPa. Green curves: 60 kPa. Navy curves: 30 kPa. Yellow: normal pressure.

Then we measured the gripping force and compared with the values computed by FEA (CAEplex). Fig.9(b) shows an example where the gripping force is 3 N and the displacement of fingertip is 22.9 mm. The color map indicates the stress distribution and the displacement can be illustrated by comparing with the initial mesh (grey). The results and comparsion are shown in Fig.10. As seen from Fig.10(a), the simulated results match the experimental results, especially in the condition of 30, 60, and 90 kPa. It's worth noting that instead of showing the almost linear increase, the real data reveal a gradually lowed increasing trend. It's because there is slight relative slide among the chain mail elements, leading to unpredictable force components. The results under normal pressure are not fitted. The finger chamber has large space without confining pressure, which cannot be model as a solid body. And the gripper forces of the granular one have bad fitness with the simulation as the finger chamber is uneven and has the unpredictable deformation. Importantly, the granular jamming finger has a smaller range of gripping force compared with the chain mail jamming finger. This comparison validates the advantages of the proposed finger in providing larger range of changeable stiffness.

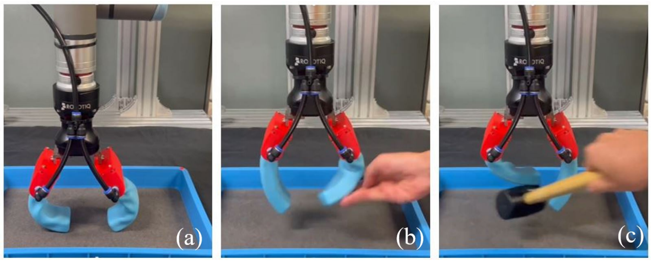

Fig. 11: Demonstrations of safe interactions.

Fig. 12: Objects used for demonstrating adaptive grasping. ① Snacks: 242 g. ② Bread: 24 g. ③ Spinach: 169 g. ④ Grape: 20 g. ⑤ Omelet: 112 g. ⑥ Paprika: 156 g. ⑦ Soda: 539 g. ⑧ Toothpaste: 129 g. ⑨ Plastic cup: 14 g. ⑩ Motor bracket: 70 g. ⑪ Valve: 26 g. ⑫ Electronic components: 36 g. ⑬ Aluminum bar: 326 g.

In the low stiffness mode, the finger is soft, making it's safe for the gripper, the environment setting, and humans. Fig.11 shows three examples: the finger is intact after poking to a tray (Fig.11(a)) or after flapping (Fig.11(b)); hammering also cannot break the finger (Fig.11(c)).

B. Adaptive grasping

In this subsection, we program the robot to grasp a variety of objects to show the adaptation. We prepared a set of objects, as shown in Fig.12. There are 13 objects: ① A pack of crispy snacks; ② A piece of bread; ③ A pack of spinach; ④ A piece of grape; ⑤ An omelet; ⑥ A piece of paprika; ⑦ A bottle of soda; ⑧ A tube of toothpaste; ⑨ A plastic cup; ⑩ A motor bracket; ⑪ A valve; ⑫ A pack of electronic components; ⑬ An aluminum bar. Their weights range from

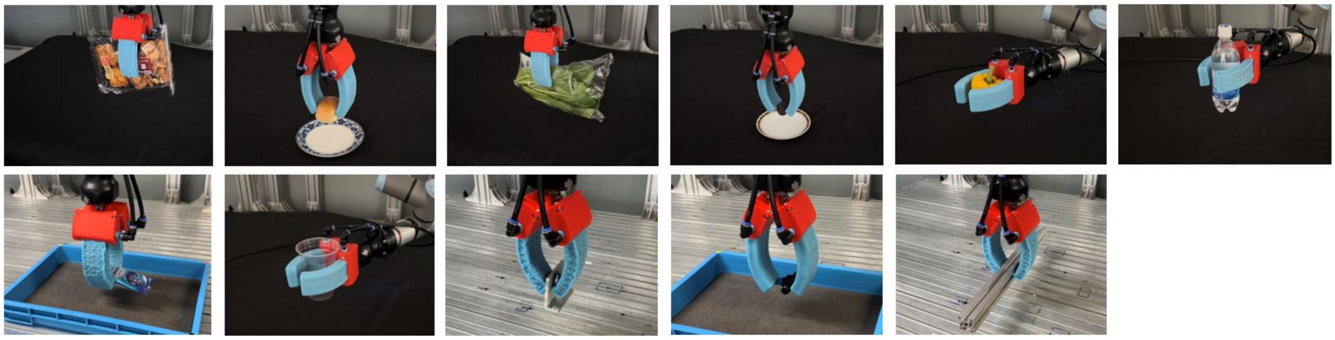

Fig. 13: Demonstrations of adaptive grasping by using direct-grasp mode with preset stiffness.

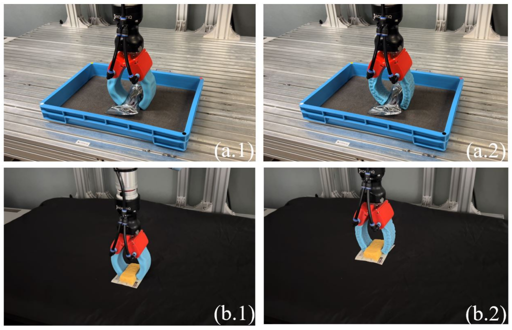

Fig. 14: Demonstrations of adaptive grasping by using contact-grasp mode. The fingers passively reshape to contact and increase stiffness to stabilize the objects

14 g to 539 g. The categories cover foods (①-⑦), goods (⑧,⑨), and industrial components (⑩-⑬). And the properties include soft/deformable objects (①-⑨,⑫), fragile objects (①-⑤,⑫), hard objects(⑩,⑪,⑬). Fig.13 and Fig.14 shows the results. In Fig.13, to grasp these objects, we chose to the direct-grasp mode with preset stiffness. In Fig.14, we apply the contact-grasp mode, the fingers first contact the objects in a low stiffness and increase the stiffness to provide enough gripping force. The attached video shows the detailed process. In the video, we also demonstrated some failure cases for comparison. These results illustrated that the proposed finger helps to grasp various object and adapts to different work fields.

C. In-hand manipulation

Besides adaptive grasping, the stiffness-changeable fingers can also contribute to in-hand manipulation. By using gravity, this finger helps to reorient objects by changing gripping force. We demonstrated an in-hand object orientation task in Fig.15. The robot first grasped a building block, held it with low stiffness, and rotated the arm. Along with the rotation, the low gripping force cannot balance the torque exerted by gravity, therefore, the relative angle between the gripper and the block was changing. When the angle reached 90°, the robot increased the confining pressure to firmly hold the object, then, returned to the initial pose to place the oriented building block. To be noticed, in this demonstration, the robot's motions and actions are manually set and taught. Here, we ignored the motion planning and control parts, and concentrate on demonstrating the potential of in-hand manipulation using the proposed finger.

VI. CONCLUSIONS AND FUTURE WORK

This paper proposed to use chain mail as jamming media to construct a stiffness changeable robotic finger. This soft finger takes the advantages of chain mail jamming to achieve a more lightweight design and exert stronger gripping force than conventional granular jamming. We developed the design and fabrication of the finger, modeled the gripping force, and proposed grasp strategies for adaptive grasping. The experiments validate the advantages of the proposed finger. And the real-world demonstrations show the prominent adaptation in grasping various objects and show the potential of in-hand manipulation. In future, we will concentrate on the shape optimization of chain mail elements and the simulation of the behavior of chain mail to contribute to the society of soft robotics and the field of grasp and manipulation:

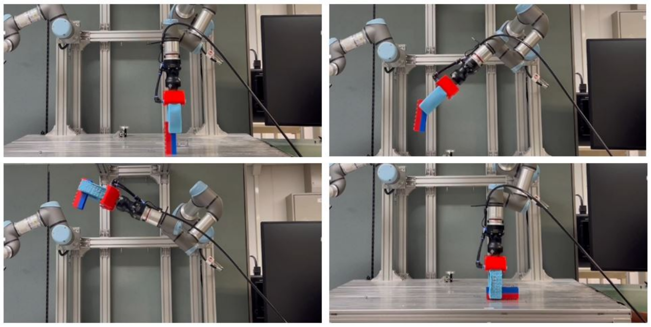

Fig. 15: In-hand orientation with gravity.

VII. ACKNOWLEDGEMENT

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