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A Non-Energized Robotic Hand Using Locking Mechanism and Silicone Belts for Grasping Heavy Agricultural Products

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Abstract— **This paper presents a robotic hand that utilizes both a locking mechanism and the elasticity of silicone belts to handle heavy agricultural products, such as radishes, addressing the labor shortage in fruit selection facilities caused by the declining birthrate and aging population. When grasping heavy agricultural products, significant force and stability are required to securely lift and transport the product. The proposed robotic hand combines a locking mechanism with the inherent elastic force of silicone belts, eliminating the need for active actuators such as motors or air compressors. The locking mechanism is embedded within the joints of the hand, allowing it to open and close through the combined effect of the silicone belts' elasticity and interaction with the environment. First, the effectiveness of this combined approach was validated through experiments involving the handling of heavy vegetables, including radishes and other similarly weighted objects. Next, the characteristics of the selected silicone material were measured, analyzed, and incorporated into the design. Finally, grasping experiments were conducted using the proposed hand, which leverages both the locking mechanism and the elasticity of silicone belts. The results indicate that the proposed robotic hand, which integrates both a locking mechanism and silicone belts, can reliably and stably grasp heavy agricultural products.**

I. INTRODUCTION

The ongoing decline in birthrate and the aging population have exacerbated labor shortages across many industries. This issue is particularly severe in the food industry, a sector known for its labor-intensive processes and low-profit margins. Consequently, there is an increasing demand for automation in the food industry, especially in the aftermath of the COVID-19 pandemic [1], [2]. Recent advancements in collaborative robotics, soft robotic end-effectors, and artificial intelligence (AI)-based recognition systems have contributed to the growing popularity of robotic systems for food handling. However, there remain several challenges that need to be addressed before robotic systems can be widely adopted in the food industry. One such challenge is the development of effective robotic end-effectors capable of handling a diverse range of food products [3]. Unlike mechanical parts, food products present unique handling difficulties due to their complex physical properties, such as softness, low friction, stickiness, and fragility. To address these challenges, various robotic end-effectors have been developed and studied[4], including shell grippers for grasping circular and elongated objects [5],[6], needle grippers for handling chopped food [7], [8], scooping-binding grippers for grasping slippery food [9], and non-contact end-effectors based on the Bernoulli principle [10], [11]. However, these end-effectors are not specifically designed for agricultural products like radishes, which require handling of significant weight. When grasping heavy agricultural products, it is essential to account for their weight in addition to other typical food characteristics such as fragility, low friction, and stickiness. Existing robotic hands for handling heavy-weight products include systems like the heavy material handling robot for agriculture, which can transport watermelons [12], and robots designed for harvesting pumpkins [13]. However, most of these systems are hydraulically driven, posing challenges in terms of cost and feasibility for implementation in fruit-sorting facilities. This study proposes a locking mechanism as a potential solution to these challenges. This mechanism mechanically transfers torque from the input side to the output side in a single direction through a wedge effect. It is compact, lightweight, and capable of generating high output power without the need for electrical or pneumatic inputs. Examples of robotic hands that operate without electricity include those that combine artificial muscles with locking mechanisms [14] and those utilizing push-latch mechanisms [15]. However, these designs are not tailored for agricultural products and do not exert sufficient force to grasp heavy agricultural products. There are limited examples of robotic hands that can generate large forces without relying on electricity.

In this paper, we propose a non-energized robotic hand featuring a locking mechanism and utilizing the elasticity of silicone to handle heavy agricultural products. The incorporation of the locking mechanism within the hand eliminates the need for electrical power during operation. Additionally, the hand is equipped with silicone belts for protective purposes, as the objects being handled are food products. The elastic force of the silicone is also utilized to open and close the hand, enhancing efficiency. Section II details the structure of the developed locking mechanism. Section III describes the hand incorporating this mechanism and presents experimental results that demonstrate the utility of the locking mechanism in the hand. Section IV discusses the use of silicone for securing the hand, and Section V concludes the paper with suggestions for future research.

II. THE LOCKING MECHANISM

A. Mechanism Overview

The mechanism of the locking system is described here. The locking mechanism transfers torque mechanically in one direction from the input side to the output side by

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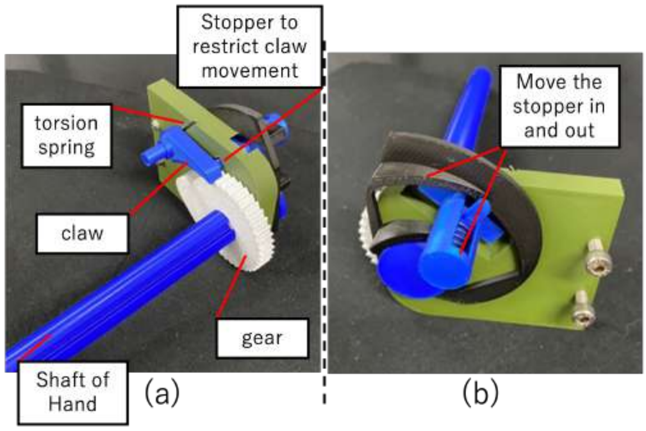

Fig. 1. Locking mechanism: (a) front side and (b) back side.

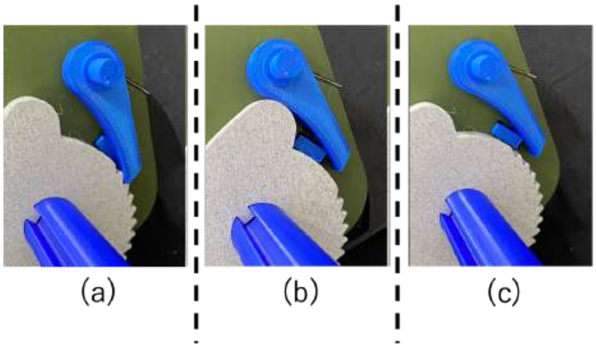

Fig. 2. Mechanism operation, (a) is locked, (b) the stopper has been actuated, (c) the stopper is about to lower in the original position

utilizing the wedge effect. It is compact, lightweight, and capable of generating high output without the need for an electric current. Typically, the mechanism involves the engagement of grooved components, such as gears, with claw-like elements to generate torque, and it has been widely applied in various fields. The locking mechanism developed in this study has been specifically modified for use in a robotic hand. In a robotic hand, the mechanism must be capable of switching between a locked state for gripping and an unlocked state for releasing. The developed mechanism incorporates a structure that limits the movement of the claw, allowing the locking state to be toggled in coordination with the overall system.

B. Mechanism Details, Design, and Fabrication

The mechanism shown in Fig.1 has distinct roles for the front and back components, which work in tandem to switch states. The front side houses the primary elements of the mechanism, including the gear and claw. The gear is directly linked to the axis of the hand and engages with the claw in a stepwise manner, as shown in Fig. 2. The claw is actuated by a torsion spring. As the gear rotates to a certain degree, it pushes the claw aside, at which point a protrusion from the back of the mechanism limits the claw's movement. The back side of the mechanism features a system that controls this protrusion, allowing it to move in and out. This system is also linked to the hand's axis, enabling coordinated operation and control of the claw's movement. The overall dimensions of the mechanism are 65mm × 80mm × 10mm, with a weight of approximately 100g. The claw's axis and torsion spring are made of metal, while the other components are fabricated using a 3D printer. The use of 3D printing offers the advantage of easy prototyping. The material used for the printed components is PLA.

III. SCOOPING HAND WITH A LOCKING MECHANISM

In this chapter, we examine whether a locking mechanism can be effectively integrated into a robotic hand for object gripping. To this end, we developed a scooping hand incorporating the mechanism, as shown in Fig.3. The hand operates through contact with the environment, scooping up objects, gripping them, and subsequently releasing them. This section presents the design of the hand's base and fingers, followed by the results and discussion of the gripping experiments conducted.

A. Base Design

In this section, we describe the overview of the base, which integrates the mechanism and fingers. The base is equipped with screw holes to attach it to the UR robot used in the experiments. Additionally, screw holes for embedding the locking mechanism and protrusions for attaching springs to open the fingers are placed on both sides. The overall size of the base is designed to accommodate the large size of radishes, which are the target objects. Furthermore, efforts were made to miniaturize the base and reduce its weight as much as possible. As a result, the dimensions are 180mm × 185mm × 125mm, and the weight is approximately 350g.

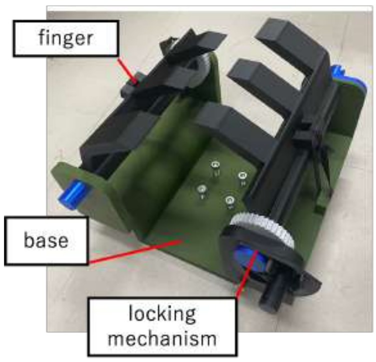

Fig. 3. Overall view of hand

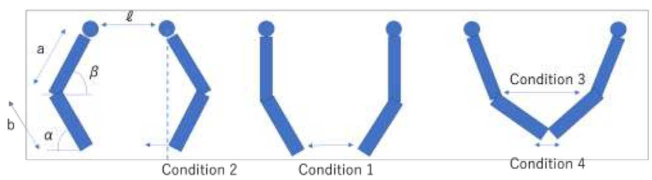

Fig. 4. Illustration of different hand conditions

B. Finger Design

This section provides an overview of the fingers designed for scooping the target objects in the experiments. The locking mechanism proposed in this paper is integrated with the fingers, enabling locking and unlocking in conjunction with finger movement. To unlock, the fingers must be pressed deeply against the environment, which results in an intersecting finger design. Additionally, because the hand operates through contact with the environment, the angle of the fingers is crucial. Therefore, the design was carried out based on the following conditions and as shown in Fig.4.

- Condition 1: At minimum locking, the distance between fingers of both sides must be less than or equal to the minimum radish size.
- Condition 2: The tip of the finger must come inside its axis to ensure smooth closing upon contact with environment..
- Condition 3: At the maximum lock, the distance between the tops of the fingers of both sides is greater than or equal to the maximum radish size.
- Condition 4: At maximum locking, the distance between the bottom of the fingers of both sides is less than or equal to the minimum radish size.

As a result, the hand was designed to be as compact as possible while meeting these conditions, with α = β = 45°, a = 20mm, and b = 60mm. The weight of each finger is approximately 150g.

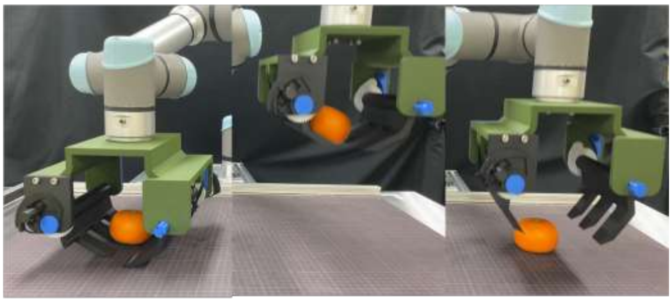

Fig. 5. Grasping experiment

TABLE I
OBJECTS USED IN GRASPING TESTS AND THEIR SUCCESS RATES.

Objects	Weight	Success rate
radish	1300 g	10/10
turnip 1	247 g	10/10
turnip 2	253 g	9/10
turnip 3	211 g	9/10
Sample oranges	50 g	10/10
Water in an angular container	519 g	10/10
Oil in round container	214 g	10/10
Sample persimmon	63 g	10/10

C. Grasping Tests on the Robotic Hand with Locking Mechanism

Gripping experiments were conducted using the developed hand. The purpose of these experiments was to verify whether the developed locking mechanism could generate sufficient force to lift the target objects. A UR5e robot from Universal Robots was used in the experiments. The procedure involved placing the target object on a metal platform, programming the robot using the direct teaching function to perform gripping, transport, and release, as shown in Fig .5. This process was repeated 10 times, and the number of successful attempts was counted. The target objects and the results of the experiments are shown in table I. These results demonstrate that the hand, equipped with the locking mechanism, can effectively grip and reliably release objects.

IV. Scooping Hand with Locking Mechanism and Silicone Belts

A. Overview

To specifically handle heavy agricultural products, the hand is equipped with silicone to protect the target object. Additionally, to improve operational efficiency, the hand's design utilizes the elastic force of the silicone for opening and closing. The hand proposed in this paper is designed with radishes in mind. This chapter describes the selection of the silicone material, the design of the molds, and the tensile testing, followed by a discussion of the gripping experiments conducted using the hand.

B. About the Silicone Used

The hand proposed in this paper is equipped with five rectangular silicone belts attached to the fingers. Although the detailed design of the hand is described later, in summary, the silicone is used to wrap around the target object, and the elastic force of the silicone belt partially closes the arm. The conditions for this are as follows:

- 1.The elastic force of the two springs used to fully open the fingers must exceed the elastic force of the five silicone belts at that point.

Fig. 6. Molds for fabricating the silicone belts

- 2.The length of each silicone belt must be shorter than the circumference of the radish and the maximum opening width of the fingers.

The spring constant of the springs used to open the finger is 0.155 N/mm, with an initial tension of 1.17 N. Calculating from this, the elastic force of the two springs when the hand is fully open is approximately 14.8 N. When five silicone belts, each 5 mm thick and 20 mm wide, are stretched by these springs, the tensile strength of the silicone is $0.0296\,\mathrm{N/mm^2}$. Assuming the silicone is stretched by approximately 1.5 times, the most suitable product is Smooth-On's Ecoflex 00-20, which has a 50% modulus of $0.028\,\mathrm{N/mm^2}$. Considering that the tensile strength of the two springs is $0.0296\,\mathrm{N/mm^2}$, the silicone can be stretched up to 53%. The minimum circumference of the intended radish is approximately 250 mm, and the maximum opening width of the fingers is approximately 210 mm. Therefore, if the silicone length is between approximately 130 mm and 210 mm, the conditions are satisfied. Thus, molds of 150 mm and 180 mm were created as shown in Fig.6. The molds were made using a 3D printer. The procedure for fabricating the silicone belts involves first pouring equal amounts of Part A and Part B of the liquid silicone into a plastic cup and mixing thoroughly. After vacuum degassing for about 10 minutes, a release agent is applied to the mold, and the silicone is poured in. Vacuum degassing is then performed for another 10 minutes before leaving the mold to sit. The silicone will cure in about half a day. Next, to obtain data on the produced silicone, a tensile test was conducted. A digital force gauge from IMADA was used for the test. The silicone was fixed to a base created with a 3D printer, as shown in Fig.7, and measured. The results are shown in table II. Although both conditions were met, the 150 mm silicone was chosen due to its stronger elastic force, as weaker elasticity could lead to instability in gripping the target object.

TABLE II
RESULTS OF TENSILE TESTS ON THE SILICONE BELTS

length	150mm silicone	180mm silicone
Force at 210mm extension	1.53 N	2.62 N
Force at 280mm extension	0.7 N	1.71 N

Fig. 7. Tensile tests on the silicone belts

C. Hand Assembly

The hand used in this chapter is based on the design of the hand from the previous Section, with modifications made to the finger shape to accommodate the attachment of silicone belt. As shown in Fig.8, five silicone belts were attached to the fingers in an intersecting pattern to ensure that force is applied evenly to the target object. The silicone was fitted by creating a space on the fingers specifically designed to hold the silicone belts, which were then securely placed into position. To prevent the attached silicone belts from making contact with the ground, the area around the silicone belts attachment points on the fingers was reinforced with additional thickness. In terms of overall operation, the silicone belts comes into contact with the target object, initiating the closure of the hand while the locking mechanism engages. Once the silicone belts has made sufficient contact, the fingers touch the ground, and the target object is held in place by both the silicone belts and the tips of the fingers as it is scooped up. Finally, the hand is pressed against the ground once more, releasing the lock and freeing the target object. By utilizing the elastic force of the silicone belts, the hand's ability to open wide has been significantly enhanced.

Fig. 8. Silicon mounting pattern

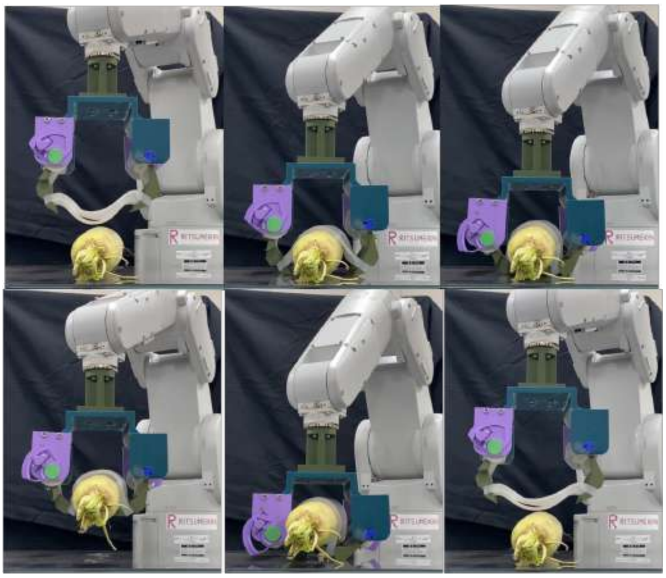

Fig. 9. Flow of grasping in the experiment

D. Grasping Experiments

To validate the performance of the hand, a gripping experiment was conducted using a radish with a diameter of approximately 100 mm and a weight of around 1.7 kg. The robot arm used for this experiment was the MELFA RV-4FRL-D, manufactured by Mitsubishi Electric. A simple pick-and-lift motion was programmed to grip the radish. The hand, in its open state, was pressed against the radish to grip it, lifted, and then pressed against the ground again to release it. As shown in Fig.9, the hand was able to grip the radish stably, demonstrating that the proposed robotic hand can effectively grip a heavy radish.

V. CONCLUSIONS

Grasping heavy agricultural products with a robotic hand requires significant force, and handling such products, especially since they are food items, presents additional challenges. While using actuators like motors or pneumatic actuators is an effective means to grasp heavy agricultural products, it also involves high costs. As a potential solution, mechanisms that do not rely on electricity, such as locking mechanisms, could be employed; however, to the best of the author's knowledge, there are no examples of robotic hands using such mechanisms specifically designed for heavy food items. In this paper, a robotic hand capable of grasping heavy agricultural products like radishes was realized by utilizing a locking mechanism and the elastic force of silicone belts. The robotic hand incorporates two custom-built locking mechanisms and is equipped with silicone belts that possesses optimal elasticity. Gripping experiments using radishes demonstrated that the hand can stably handle heavy agricultural products.. As future work, durability tests are planned to assess the hand's longevity. This robotic hand was developed with the expectation that it would repeatedly grasp heavy agricultural products, making durability a crucial factor. The results of the durability tests will inform necessary updates to the design.

REFERENCES

[1] P.Y. Chua, T. Ilschner, and D.G. Caldwell, "Robotic manipulation of food products – a review", Industrial Robot, Vol. 30, No. 4, pp. 345-354, 2003.

[2] R. Henry, "Innovations in Agriculture and Food Supply in Response to the COVID-19 Pandemic", Molecular Plant, Vol. 13, No. 8, pp. 1095-1097, 2020.

[3] Z. Wang, S. Hirai, S. Kawamura, "Challenges and opportunities in robotic food handling: a review", Frontiers in Robotics and AI: Soft Robotics, 8:789107, Jan., 2022.

[4] G. Fantoni, M. Santochi, G. Dini, K. Tracht, B. Scholz-Reiter, F. Fleischer, T.K. Lien, G. Seliger, G. Reinhart, J. Franke, et al. "Grasping devices and methods in automated production processes", CIRP Annals, Vol. 63, No. 2, pp. 679–701, 2014.

[5] Z. Wang, R. Kanegae, S. Hirai, "Circular Shell Gripper for Handling Food Products", Soft Robotics, Vol. 8, No. 5, pp.542-554, 2021.

[6] R. Kanegae, Z. Wang, S. Hirai, "Easily Fabricatable Shell Gripper for Packaging Multiple Cucumbers Simultaneously", The 2020 IEEE International Conference on Real-time Computing and Robotics, Online, Sept. 28th-29th, 2020.

[7] Z. Wang, Y. Makiyama, S. Hirai, "A Soft Needle Gripper Capable of Grasping and Piercing for Handling Food Materials", Journal of Robotics and Mechatronics, Vol. 33, No. 4, pp.935-943, Aug., 2021.

[8] Y. Makiyama, Z. Wang, S. Hirai, "A Pneumatic Needle Gripper for Handling Shredded Food Products", The 2020 IEEE International Conference on Real-time Computing and Robotics, pp. 183-187, Online, Sept. 28th-29th, 2020.

[9] Z. Wang, H. Furuta, S. Hirai, S. Kawamura, "A scooping-binding robotic gripper for handling various food products", Frontiers in Robotics and AI: Soft Robotics, 8:640805, 2021.

[10] S. Davis, J.O. Gray, D.G. Caldwell, "An end effector based on the Bernoulli principle for handling sliced fruit and vegetables", Robotics and Computer-Integrated Manufacturing, Vol. 24, pp.249-257, 2008.

[11] A. Petterson, T. Ohlsson, D.G. Caldwell, S. Davis, J.O. Gray, T.J. Dodd, "A Bernoulli principle gripper for handling of planar and 3D (food) products", Industrial Robot, Vol. 37, No. 6, pp.518-526, 2010.

[12] S. Sakai, M. Iida and M. Umeda, "Heavy Material Handling Robot for Agriculture", Proc. of IEEE International Conferance on Robotics and Automation, pp. 1062-1068, 2002.

[13] Ali Roshanianfard, Tatsuki Kamata, Noboru Noguchi, Performance evaluation of harvesting robot for heavy-weight crops, IFAC-PapersOnLine, Volume 51, Issue 17, Pages 332-338, 2018.

[14] Lokesh Saharan and Yonas Tadesse "Robotic hand with locking mechanism using TCP muscles for applications in prosthetic hand and humanoids", Proc. SPIE 9797, Bioinspiration, Biomimetics, and Bioreplication 2016.

[15] E. Ottonello, M. Baggetta, G. Berselli and A. Parmiggiani, "Design and Validation of a Push-Latch Gripper Made in Additive Manufacturing," in IEEE/ASME Transactions on Mechatronics, vol. 28, no. 4, pp. 2083-2091, Aug. 2023,