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Development of a Modular Robotic Finger for Gripping Various Shaped Objects

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Abstract— **With the introduction of the Fourth Industrial Revolution and the spread of smart factories, the demand for small-quantity batch production systems is rapidly increasing. As a result, the implementation of robotic gripper systems that can handle various objects is required. Until now, grippers have to be replaced or newly developed each time depending on the object to be gripped. In addition, conventional gripper systems require a picking system based on a sophisticated gripping plan to handle products with complex shapes. This requires the integration of vision and various sensor systems, which in turn increases the cost of the system and makes it challenging to apply it to real industrial sites. To solve this problem, we developed a robotic finger by applying the paired crossed flexure hinge (p-CFH) developed in our previous research. The p-CFH-based robotic finger is driven by an underactuated wire-driven method that can be controlled by a single motor and has compliance and shape adaptive features. It also has the advantage of being modularized, easy to install and replace, and easy to maintain. The proposed finger module has a tip force of about 0.58 kg and its impact absorption capacity has been experimentally verified. In addition, gripping experiments were conducted on a total of four objects with different characteristics, and successful gripping was confirmed.**

I. Introduction

Production methods in the industrial field have recently been undergoing various changes, and in particular, the small-quantity batch production method of many products is attracting attention as an example of these changes. Changes in production methods lead to increased product diversity and customer demands, which are difficult to respond to with existing mass production methods. Accordingly, various types of robots and automation systems are being introduced in industrial sites, and the role of grippers in these systems is becoming more important. Small-quantity batch production requires a flexible production system that can quickly respond to product changes. It must be able to respond to various shapes and sizes of products, and in particular, the performance and diversity of grippers directly affect productivity and efficiency. Recently, many studies have been conducted on soft grippers [1]–[4]. Soft grippers have the advantage of being able to handle a variety of objects and minimize damage to objects because they use flexible materials. P. Glick *et al*. developed a soft gripper incorporating biomimetic technology [5], and B. S. Homberg *et al*. developed a soft gripper that can identify objects based on information about the gripped object by inserting a pressure sensor and bending sensor at the end of the gripper [6]. S. F. Liu *et al*. developed a gripper that can change the grasping mode depending on the shape of the gripped object [7]. In addition to this, grippers using granular jamming have also been developed [8]–[10]. However, in the case of the previously developed soft gripper, it does not have the function of firmly gripping the object, so when an external force is applied after gripping the object, the position of the gripped object changes, making it difficult to implement various tasks. Therefore, it is currently only applied to simple position movement of light objects. As a result, it is impossible to respond to a large variety of products with the existing gripper system alone, and a picking system based on a sophisticated gripping plan to handle products of complex shapes is additionally required. The picking system requires an algorithm for gripping plan processing, integration with a vision-based object recognition system, and a learning process for the target object. This significantly increases the price of the system, making it difficult to apply in actual industrial sites. Therefore, a gripper system that can firmly grip objects of various shapes, weights, and strengths with a single robot and at the same time requires little gripping strategy is needed. The development of such a practical gripper system for multi-product processes is an important task that must be accomplished in the intelligentization of robots. For this purpose, grippers that combine the characteristics of rigid grippers and soft grippers are also being studied. A representative example is a gripper using a Fin Ray structure [11]–[13]. Another interesting gripper is one that modifies the material or shape of the joint. By using flexible materials as joints instead of conventional pin joints, gripping stability and strength can be improved. L. Gerez *et al*. manufactured a flexure joint using a laminar jamming structure and incorporated it into a gripper [14], and M. Dragusanu *et al*. developed a gripper by incorporating a zigzag flat spring shape into a joint [15]. However, in the aforementioned studies, the hinges are usually made of polymer materials such as polyurethane or silicone in order to have shape-adaptive properties. This limits their use in extreme working environments and shortens the lifetime of the gripper. In contrast, the hinge of the gripper we proposed used a flexure hinge made of metal, which can be used in harsh environments with a long gripper lifespan, overcoming the limitations of previous studies. The advantage of using a flexure joint as a robot joint is that there is no noise or friction, and it can be manufactured in various shapes. In addition, in our previous research, we developed a gripper with a higher stiffness than the existing CFH by using the paired crossed flexure hinge (p-CFH) on the finger joints and overcame the limitations of the conventional CFH [16]. Therefore, in this paper, we propose a modular robotic finger using p-CFH as a finger joint to develop a gripper suitable for small-quantity batch production. The proposed robotic finger is driven in an

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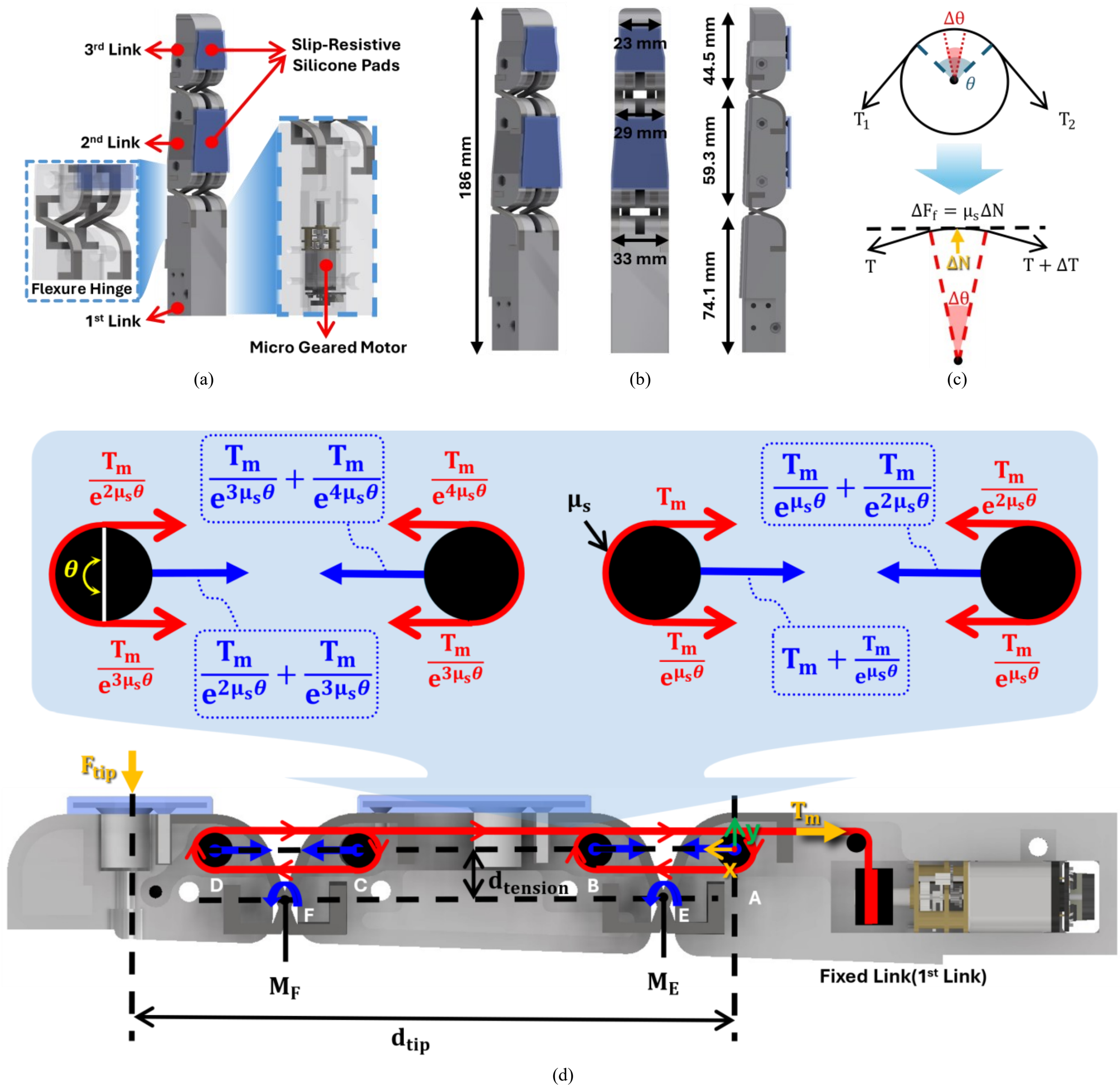

Figure 1. Design of robotic finger module. (a) Components of robotic finger module. (b) Robotic finger module with dimensions. (c) Schematic diagram: Static equilibrium pulley analysis(T: tension, T_1 & T_2: tensions corresponding to directions, ΔT: difference of tension due to friction on the pulley, θ: arc angle of encompassed contact area by wire, Δθ: arc angle of micro contact area, ΔN: normal force corresponding to contact area, ΔF_f: friction force corresponding to contact area, μ_s: static friction coefficient on the pulley). (d) Wire path of robotic finger module based on static equilibrium pulley analysis, enhancing tip force(T_m: tension by motor, M_E: moment by flexure hinge at point E, M_F: moment by flexure hinge at point F, $d_{tention}$: distance between the center of pulleys and the crossed point of flexure hinges, d_{tip}: distance between the center of pulley at point A and the point where F_{tip} is applied, F_{tip}: tip force, μ_s: static friction coefficient on the pulley)

underactuated wire-driven manner. This method allows the robotic finger to be driven with a single motor, and the shape of the finger is driven adaptively according to the shape of the grip. This does not require complex control and does not require a separate gripping strategy. The proposed gripper consists of a total of four finger modules, and when gripping large and heavy objects, all four fingers can be used to generate a strong gripping force. Only two finger modules can be used for the pinching motion when grasping small and light objects. Additionally, modular finger modules have advantages in terms of maintenance. We measured the tip force to verify the performance of the proposed robotic finger module and conducted an impactabsorption capability experiment to confirm its adaptability to external shocks. Finally, a gripper was implemented by combining four finger modules, and gripping experiments on various shaped objects were conducted through this. The structure of this paper is as follows. In section II, the design of the robotic finger module is described, and in section III, techniques for controlling the finger module are described. section IV describes experiments and results for verifying the performance of the proposed finger module, and section V concludes the paper and discusses future research.

II. Design of Robotic Finger Module

The flexure hinge-based finger module presented in this paper was designed to overcome the difficulties of handling various shaped objects in small-quantity batch production using existing commercial grippers. The purpose of this is to perform efficient gripping work in the multi-species and mixed production process by arranging the fingers according to the purpose of each finger module.

As can be seen in Fig. 1(a), it consists of three finger joints and a flexible hinge. The joint of the modular finger is a flexible hinge, and the p-CFH developed in the previous study was applied. The p-CFH applied as a flexible hinge of the finger has its own high compliance. Through this, the compliance of the finger module was improved, and it was designed to adapt the surface shape of the gripping object. In addition, a DC motor (Micro Metal Gearmotor HPCB 6V, Pololu, Nevada, USA) with a gear ratio of 298:1 was inserted into the first finger link, and a silicone slip-restive pad was applied to the surfaces of the second and third finger links to design a modular robot finger to enable robust gripping. As can be seen in the dimensions of the modular robot finger designed in Fig. 1(b), the overall length of the finger is 186 mm, and the length of each joint has a ratio of about 4:3:2,

$$\frac{T_2}{T_1} = e^{\mu_s \theta} \tag{1}$$

imitating the ratio of the human finger.

The modular finger presented in this study is designed to be driven based on an underactuated wire-driven. In Fig. 1(c), the mathematical diagram of the static equilibrium pulley analysis can be confirmed. Through this, the force acting on each pulley can be derived. In addition, as shown in Fig. 1(d), the wire path of the modular finger can be confirmed, and the wire path of the designed modular finger is designed to

$$\sum M_A = -F_{tip} d_{tip} - M_E - M_F + T_m d_{tension} \left(\frac{e^{4\mu_s \theta} - 1}{e^{4\mu_s \theta}} \right) \tag{2}$$

$$F_{tip} = \frac{T_m d_{tension} \left(\frac{e^{4\mu_s \theta} - 1}{e^{4\mu_s \theta}} \right) - M_E - M_F}{d_{tip}} \tag{3}$$

enhance the tip force by using the principle of the moving pulley. The applied wire path was designed based on the static equilibrium pulley analysis, and the analysis of the force acting in the x-axis direction in each pulley is based on Capstan equation, as detailed in (1).

As can be seen from Fig. 1(d), θ is 180 degrees, and the force acting on each pulley can be derived using (1) derived from static equilibrium pulley analysis. The derived force acting on each pulley is applied to the wire path of the finger module, and moment M_A can be expressed as follows through static analysis. From (2) derived based on the static analysis, the tip force F_{tip} of the modular finger can be finally derived as shown in (3). Based on (3), the motor and the wire path of the modular finger were designed.

The parameters utilized in (3) are defined as follows: The tension generated by the motor, denoted as T_m, is 83.4 N, derived from a motor torque of 3.4 kg·cm and the pulley diameter of 8 mm. The distance between the center of the pulleys and the crossed point of flexure hinges, $d_{tension}$, is 7.920 mm. The static friction coefficient on the pulley, μ_s, is determined to be 0.7, based on the Shore hardness of the fabricated material. Additionally, the distance between the center of the pulley at point A and the point where the tip force is applied, d_{tip}, is 102.015 mm. It is also noted that the moments generated by the flexure hinges at points E and F, M_E and M_F, are negligible in comparison to other terms in the static analysis. Based on these parameters, the generated tip force, F_{tip}, is calculated to be 6.47 N, which satisfies the desired tip force of 5 N for the proposed modular finger, enabling it to grasp objects weighing over 2 kg.

III. Controller Design

This session designs the DC motor's Proportional-Integral-Differential (PID) controller for the operation of the finger module and describes the communication protocol for interworking with the PC. ATmega2560 (Microchip Technology Inc., Arizona, USA) was used as the micro-controller for the implementation of the PID-based position

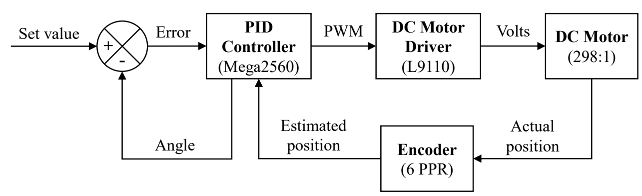

Figure 2. Block diagram for position control of the robotic finger module.

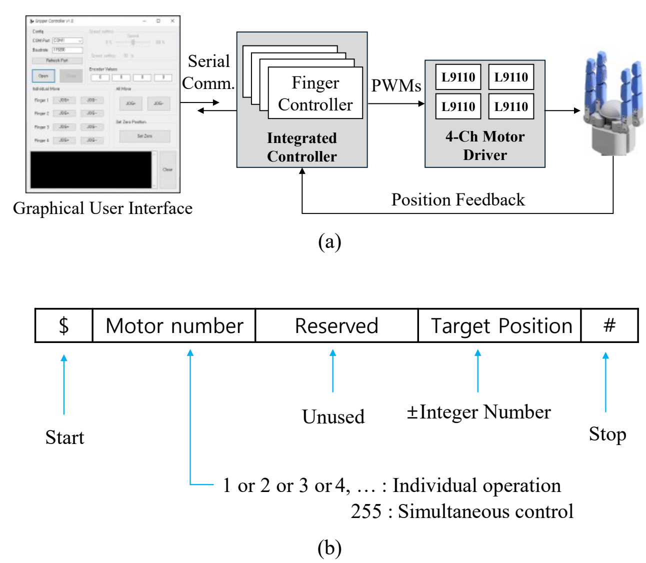

Figure 3. Block diagram of the overall system. (a) Integrated control structure for multi-finger gripper system. (b) Communication protocol for motor control.

controller, and L9110S (UMW®, Shenzen, China) was used for the motor driver. The DC motor is equipped with an incremental encoder with a resolution of 6 pulses per revolution. Since the gear ratio is 298:1, a total of 1788 pulses can be received when the pulley for wire-driving rotates once. That is, it has a resolution of about 0.2 degrees. The block diagram for position control of the DC motor is shown in Fig. 2. The controller gain selected the optimal value through the experiment, and each value is $K_P = 0.6$, $K_I = 0.05$, and $K_D = 4.15$. In addition, a graphical user interface was implemented for interworking with a PC. The microcontroller and the PC exchange data through serial communication, and the configuration of the entire system is as shown in Fig. 3(a). To control multiple finger modules, we defined a communication protocol. The data frame consists of a total of 5 segments and is shown in Fig. 3(b). To distinguish between the beginning and the end of the data frame, the first segment is set to the symbol '$' and the last segment to the symbol '#'. The second segment was set to the motor number, and the third segment was reserved for further functional additions. The fourth segment is the target position value of each motor. Each segment is separated using the symbol ','. According to the value of the segment in charge of the motor number, the finger module assigned to each number is driven, and if it has a value of 255, the entire finger module is implemented to be simultaneously controlled.

IV. Experimental Results

A. Tip Force Measurement

In order to evaluate the gripping performance of the integrated gripper system presented in this study, it was constructed as shown in Fig. 4, and a tip force measurement experiment was conducted on four-finger modules. In the experimental method, one finger module was fixed to the linear stage and the push-pull gauge was fixed to the floor. After that, while the initial finger module and the push-pull gauge were in contact, the tip force of the finger module was measured through the value measured by the push-pull gauge by the DC motor in the y-axis direction by applying a force to the push-pull gauge by the wire actuating method. Ten repetitive experiments were conducted on a total of 4 fingers in the same experimental environment, and the tip force of each finger module was derived by calculating the average of 10 data for each finger. Table I shows the experimental results. The average tip force for each finger module was found to be a minimum of 0.43 kg and a maximum of 0.69 kg, and the average tip force for four finger modules was found to be 0.58 kg. In conclusion, it was derived that each finger had an average gripping power of 0.5 kg or more, and it was verified that gripping for objects of 2 kg or more was possible when extended to the integrated gripper system.

TABLE I. Results of Tip Force Measurement

Finger Module	Average of Each Experiment	Average of Total Tip Force
Module 1	0.64 ± 0.026 kg	0.58 ± 0.024 kg
Module 2	0.69 ± 0.017 kg	
Module 3	0.43 ± 0.022 kg	
Module 4	0.55 ± 0.031 kg	

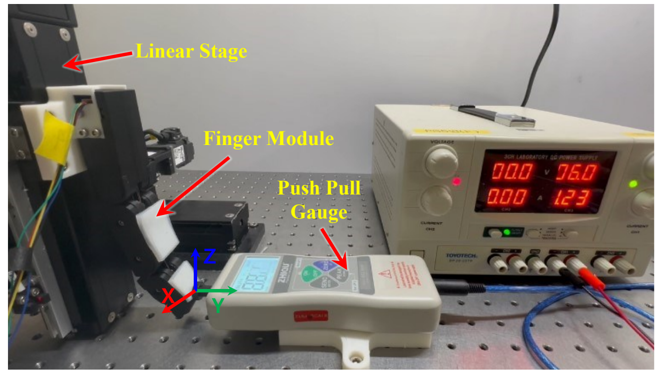

Figure 4. Experimental setting of tip force measurement.

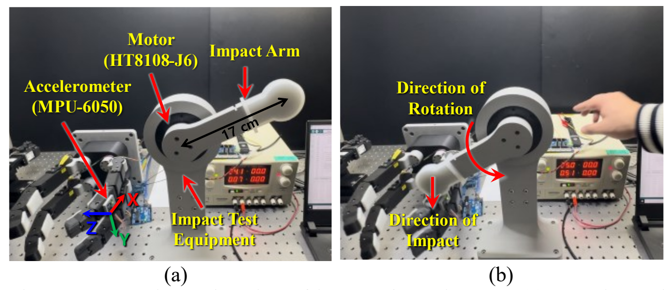

Figure 5. Experimental setting of impact absorption test. (a) Experimental environment and impact test equipment. (b) Impact direction and motor rotation direction.

B. Impact Absorption Experiment

In order to verify the impact absorption capacity of p-CFH embedded in the finger module proposed in this study, an impact absorption experiment was conducted. The experimental environment setting for the impact absorption experiment is shown in Fig. 5(a). Acceleration sensor (MPU-6050, TDK InvenSense, Tokyo, Japan) was attached to measure the impact amount at the point where the impact was applied to the finger module. The experimental method was carried out by applying the same method conducted in previous studies [16]. The Head Injury Criterion (HIC) used to measure the impact amount is generally used as a criterion to determine the degree of head damage to a person when an impact occurs in a car. However, even in robot systems, there are cases where HIC is used for impact tests [17], [18]. Therefore, we also adopt HIC as the criterion for measuring the impact amount transmitted to the finger module, and

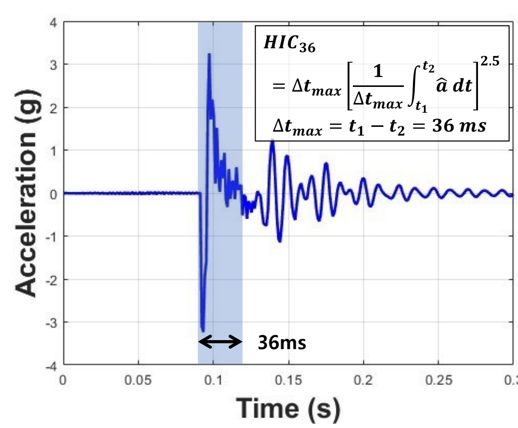

Figure 6. Acceleration graph through impact test.

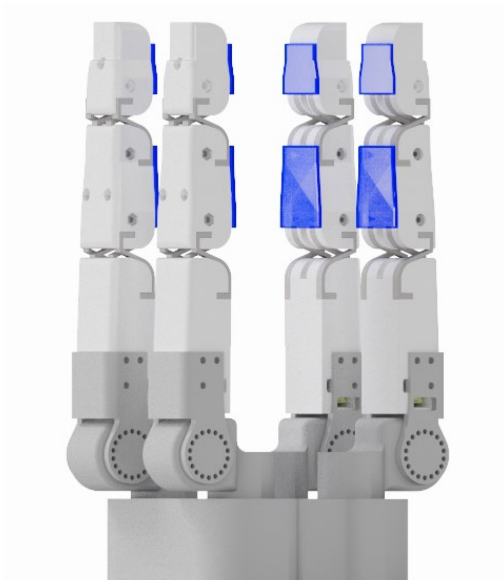

Figure 7. Modeling of four-finger gripper for gripping experiments.

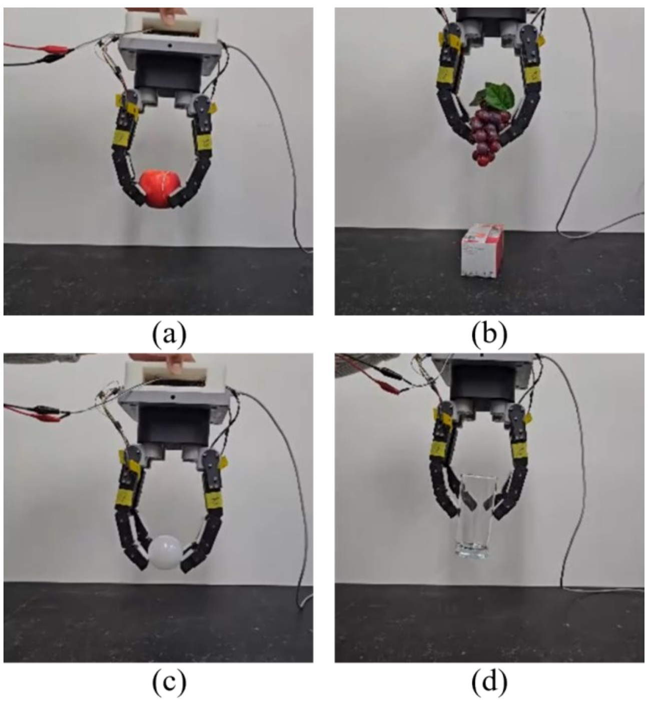

Figure 8. Modular robotic finger-based grasping experiment results for various shaped objects. (a) Apple. (b) Grape. (c) Light bulb. (d) Glass cup.

specifically, HIC_{36}, which calculated the impact amount measured for 36 ms after the impact, was used.

First, rotate the impact arm of the impact test equipment in the direction shown in Fig. 5(b) to apply the impact. When the impact arm contacts the side of the middle link of the finger, the linear velocity of the impact arm is set to 2.78 m/s, and the acceleration in the y-axis direction is measured using an acceleration sensor. The measured y-axis acceleration data is shown in Fig. 6 and based on the data corresponding to the 36 ms section based on the time the impact was applied, it was confirmed that HIC_{36} was 0.3341 $m^{5/2}\,s^{-4}$. This shows that the impact amount is reduced by about 30% compared to 0.4774 $m^{5/2}\,s^{-4}$ measured by the pin jointed gripper in [16], and the impact absorption capacity of the flexible hinge gripper was verified.

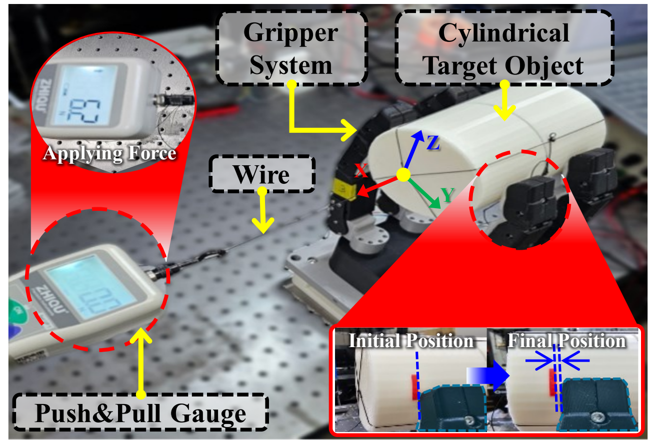

Figure 9. Experimental setting for grip robustness test of the gripper, equipped with 4 modular fingers.

C. *Gripping Performance*

To evaluate the gripping performance of the modular robotic finger for gripping various shaped objects proposed in this paper, gripping experiments were conducted on various atypical objects. For the test, a 4-finger gripper using four modular fingers was fabricated as shown in Fig. 7. A total of two pairs were placed on the rectangular mount with the modular robotic fingers facing each other. Apple, grape, light bulb, and glass cup were selected as various shaped objects for the gripping experiment, and if the object placed on the floor was lifted and gripped for 10 seconds without dropping it using only a modular robotic finger, it was judged as a success of gripping. As a result of the experiment, a gripping success rate of 100% was achieved for 4 objects, and it was proved that various shaped objects can be stably gripped. Fig. 8(a) is the result of gripping experiments on apple, (b) grape, (c) is a bulb, and (d) is a glass cup. The gripper's response time should be 0.66 s from the unfolded state to the fully folded state based on the no-load rpm of the DC motor, but the actual experimental results measured 3.08 s due to tension from the p-CFH joint structure, pulley friction, and other factors.

D. *Grip Robustness Performance*

As shown in Fig. 9, the setting for the grip robustness test involved securing the four-fingered gripper system to the test bed and connecting the push & pull gauge DS2-500N (Zhiqu Precision Instrument, Guangzhou, China) and a cylindrical object with a wire. The cylindrical object was grasped by the fixed gripper system, and its initial grip position was marked to allow for observation of any positional changes under applied force. A force of 6.2 N was then applied in the x-axis direction, and the initial grip position was compared with the position after applying the force.

This grip robustness test was designed to verify the grip robustness of the gripper, equipped with 4 modular fingers, by measuring the change in the object's position in response to the applied force. The experimental results confirmed that the gripper system demonstrated a performance of 6.2 N/mm.

V. Conclusion

In this paper, we proposed a modular robotic finger that can be used when gripping various atypical objects. The p-CFH structure was applied to the robotic finger joint and modularized to facilitate attachment and detachment. In addition, a controller for driving an underactuated wire-driven robotic finger module was designed. Based on the above design, four modular robotic fingers were manufactured, and various performance measurement experiments were conducted. First, as a result of a tip force measurement experiment, it was confirmed that an average tip force of 0.58 kg can be produced. Next, the shock absorption experiment was conducted to confirm that the impact amount was reduced by about 30% compared to the pin jointed gripper. Finally, a 4-finger gripper was fabricated using our proposed modular robotic finger. In order to confirm the gripping performance of the fabricated 4-finger gripper, a gripping experiment was conducted on four atypical objects, including apples, grapes, light bulbs, and glass cups, and it was proved that it can stably grip atypical objects with a 100% gripping success rate. Moreover, the gripper's demonstrated grip robustness of 6.2 N/mm confirms its high grip stability in the four fingers configuration.

The modular robotic finger proposed in this study can grasp various atypical objects, using two fingers for small and thin objects, and three or four fingers for larger objects. However, there is a limitation in that it is difficult to fully grasp a fragile object because there is no sensor that can receive feedback. One possible approach could be to mount a pressure sensor inside the robotic finger. Further research is planned to conduct studies that can grasp atypical objects of various strengths without damaging them.

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