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REGULAR PAPER

A Universal Soft Gripper with the Optimized Fin Ray Finger

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Abstract

This paper presents a soft gripper that improves on the Fin Ray finger for enhanced gripping capability; it can be used to transfer workpieces in manufacturing processes. A system that can switch between parallel and centric grips was designed and fabricated to extend the working geometry. The structure of the finger was investigated through simulation, and friction pads were designed to improve the gripping force. In the simulation, the effect of each individual structural parameter was analyzed, to optimize the geometry to provide the largest gripping force without losing the advantage of flexible deformation. To verify the enhanced gripping capabilities of three gripping methods, the maximum mass of workpieces that could be gripped was measured. The geometry of the objects that could be gripped was also investigated. The modified gripper significantly improved the gripping weight by a factor of approximately 4–5 compared to the original finger structure, and was able to grip various workpieces, including one with an aspect ratio exceeding 10. The advantages and disadvantages of the friction pad for the different gripping methods were discussed for further improvements.

Keywords Fin Ray effect · Fin Ray structure · Soft gripper · Grip switching system

1 Introduction

With the development of robotics, certain behaviors are no longer exclusive to humans. For example, objects can be picked up by grippers; these are robots that have fingers that act like those of a human hand, gripping objects by narrowing the gap between the fingers, and sometimes bending them. Previously, grippers typically used a jaw made of a rigid material to grip an object, and targets were limited to objects that were not easily deformed by an external force. In addition, due to its rigidity, there is a disadvantage in that safety is not guaranteed by causing a great blow when colliding with an operator [1]. Recently, however, there have been interests in soft grippers that use two or more flexible fingers that change shape according to the object. Compared to traditional grippers, soft grippers cause less damage to the surface, and less deformation of the shape, of the object [2, 3]. Moreover, they can cope with objects of softness [4].

Because of these characteristics, soft grippers are being used in various manufacturing processes. Contemporary manufacturing requires collaboration between humans and manufacturing machines, as well as different processes with many steps, and products with various masses and geometries; hence, the transfer system must be able to handle a wide range of gripping weight and show great versatility [5, 6]. The soft gripper can play a key role in transferring workpieces between different machines, owing to its extensive working geometry. Its application to human-assisted robots has also been widely investigated, because its softness significantly reduces the damage caused by gripping or impact.

In light of this, performances of 113 commercially available adaptive soft grippers were investigated [7–11]. Figure 1 shows the gripping weight according to finger length of centric grip mechanisms that use three fingers. The grippers were classified into two groups according to the width of the fingers (Fig. 1, right): < 30 mm (range 15–30 mm) and > 30 mm (maximum, ~ 50 mm). There were slight differences in the actuator, finger material, and finger shape between the groups. Nevertheless, in the width < 30 mm group, gripping weight tended to increase with finger length,

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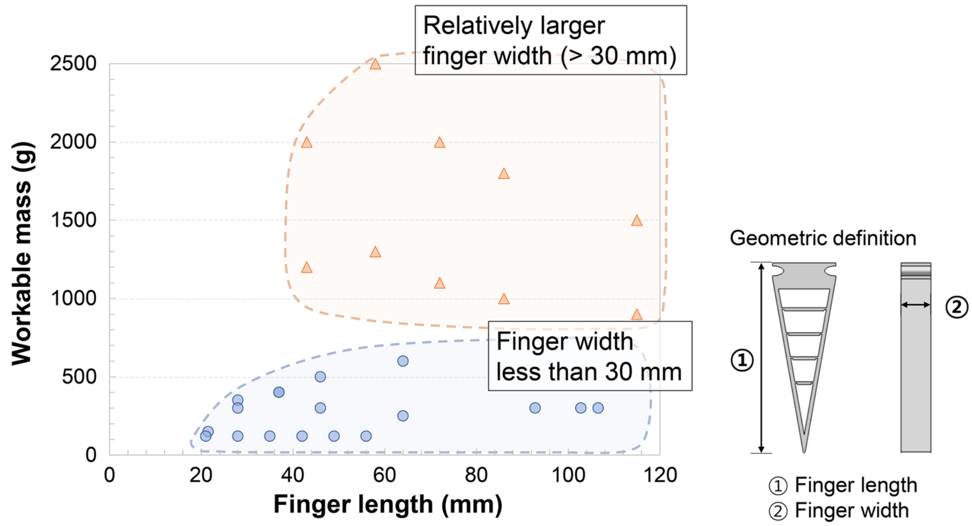


Fig. 1 Performance of existing commercial grippers in terms of gripping weight according to finger length (left) and schematic of the finger length and width measurements (right)

but mostly remained < 500 g. In the width > 30 mm group, there was a wider range of gripping weights (900–2500 g).

One of the grippers, namely the Fin Ray® finger (Festo AG & Co. KG, Germany), had an unusual structure inspired by the fin of a fish, and consisted of two parallel rays connected by elastic tissue [12]. It utilizes the effect of the structure's shape being flexibly modified by external forces [13]. However, because basic finger structure is not optimal for soft grippers, studies are underway to improve it by increasing the gripping force [14–18]. Crooks et al. [15] proposed the Tele-operable In-Home Robotic Assistant gripper, which showed a 15% greater deformation and gripped 40% more weight. Their finger is a multi-material structure that combines hard and soft materials, and was three-dimensionally (3D) printed with acrylonitrile butadiene styrene and silicone, respectively. However, this multi-material structure has a disadvantage because the 3D printing of more than two materials complicates the manufacturing process. Basson et al. [16] varied the slopes and curves of the ribs in a Fin Ray® finger and analyzed the stresses acting on, and displacement of, the modified fingers by simulation. However, the effects of rib angles, curves, and other variables were not fully examined. Elgeneidy et al. [17] developed a soft gripper finger that can handle delicate objects, such as agricultural produce in fields, by changing the angle and number of ribs of the structure and printing it from the polymer NinjaFlex. However, which structure is most effective, in terms of gripping force (regardless of object shape) and not causing damage to the object, has not yet been fully established; there is a lack of research on the effect of varying the structural parameters of each finger on the gripping force.

As can be seen from Fig. 1, a gripper having a finger width < 30 mm is not suitable for transfer systems in manufacturing because its gripping weight is generally less than 500 g. Several studies have proposed grippers with gripping weights more than approximately 500 g, but these had only a parallel or centric grip structure, and thus poor versatility [15, 16]. Therefore, in this paper, it is aimed to improve the gripping capability of a soft gripper. The goal gripping weight was at least 1 kg in a system that could switch between gripping methods.

In this study, a system capable of switching between gripping methods was designed. All 113 grippers surveyed mostly adopted one of only two gripping methods: parallel or centric. The parallel grip has the advantage of a higher gripping weight, but it also has difficulty with gripping objects such as spheres and stars due to the arrangement of the fingers. Thus, one manufacturer introduced a gripper that allows switching between two gripping methods using a pneumatically operated mechanical locking system (MultiChoiceGripper; Festo; Germany). In addition, Odhner et al. [18] proposed a gripper that can change the grip method by rotating the position of the finger using a total of five actuators with motors and tendons. Here, for a simpler independent system, a novel switching system using two electric motors was proposed. Particularly, compared to other commercial grippers, the size of the driving and auxiliary parts is small because it does not require a central driving system such as a pneumatic operator.

In addition, inspired by Emerson et al. [19] the gripping weight and deformation of the finger were investigated while varying the parameters of the Fin Ray structure. Through simulations performed using CATIA V5 software (Dassault Systèmes, Vélizy-Villacoublay, France), the effects of each parameter on gripping weight and deformation were studied, and a finger with an improved design was fabricated and tested, with the results compared against those of the simulation.

Finally, attachment pads were designed to increase the friction on the surface where the finger contacts the object.

Commercial soft fingers usually adopt polyamide, silicone, and silicone rubber. Some of the fingers described earlier were fabricated with multiple materials using 3D printing, but the fabrication process is more complicated than single-material printing. Therefore, it is aimed to improve the effectiveness of the fingers by simply attaching pads made of polydimethylsiloxane (PDMS) to their surfaces; PDMS is relatively inexpensive and easy to process [20]. By combining all these efforts in a switching system, finger design, and attachment pads, an improved soft gripper system was suggested, and the gripping capabilities were discussed per different gripping method.

2 Design and Analysis

2.1 Modeling

A novel design was investigated to switch the gripping method with an electric motor. The suggested gripper can be divided into three parts: a driving part responsible for gripping and changing the method thereof, a working part for gripping an object, and a coupling part for fixing the gripper to the support and store the motor connected to the fully threaded bolt. The design is shown in Fig. 2.

The driving part is located above the servomotor (SG90; Tower Pro, Hong Kong, China), fully threaded bolt, and a stepper motor (SM-42BYG011-25; Sparkfun, Boulder, CO, USA). The fully threaded bolt connected to the stepper motor drives a moving plate up or down according to the rotation of the motor (ball-screw mechanism). Since the fingers are connected to the moving plate through the support, the fingers also move as the moving plate moves up and down (Fig. 2b). In addition, two connected gears connected to the servomotor are also connected to two of the three fingers through a fixture. When the servomotor rotates, the gears rotate to change the relative angles of the two fingers (Fig. 3). Thus, the posture of one finger remains the same, but the gripping method can be switched by changing the posture of the other two fingers.

The working part grips the object according to the movement and deformation of the fingers. The object

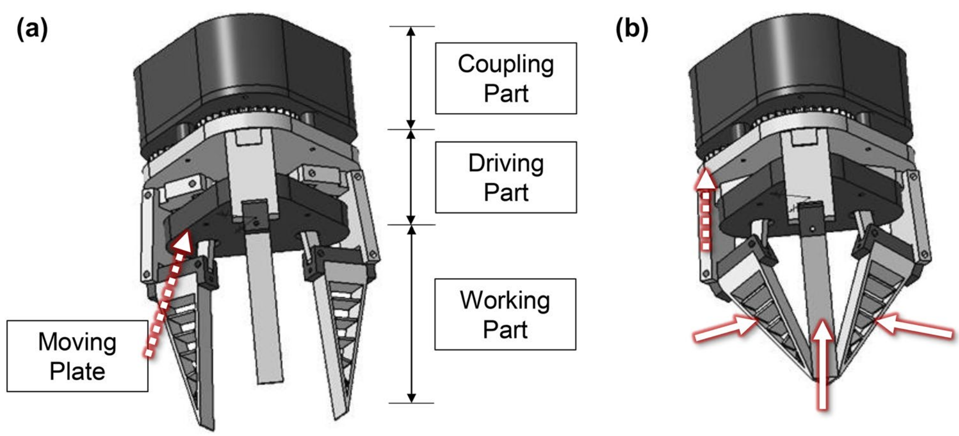


Fig. 2 **a** Modeling of gripper and **b** the designed gripping mechanism

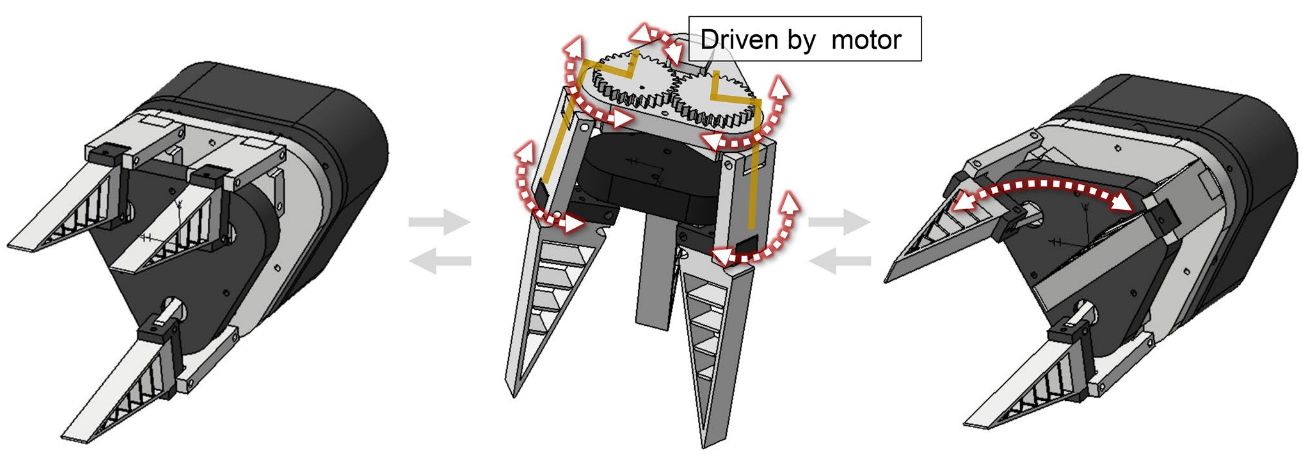


Fig. 3 Parallel (left) and switching mechanism (center) and centric (right) gripping methods

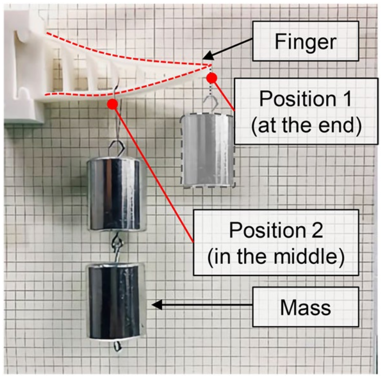


Fig. 4 Displacement experiment configuration. Position 1 is at the end of the finger and position 2 is 35.5 mm from the end of the finger

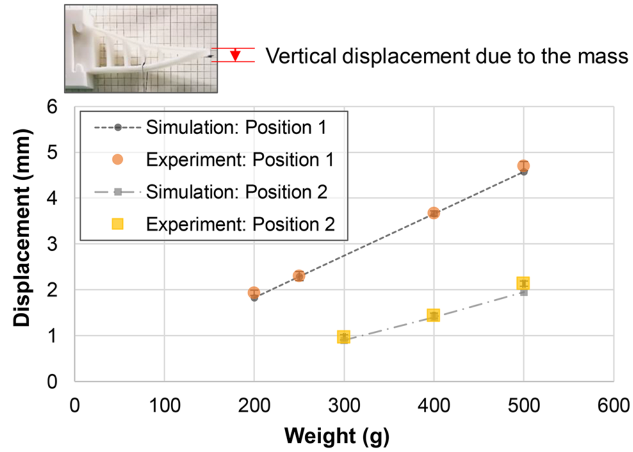


Fig. 5 Results of vertical displacement experiments and simulations for positions 1 and 2

used to test the centric gripping method is assumed to be spherical, with a diameter of 1–8 cm. The coupling part has a bolt to fix the gripper to the support, and there is space to store the stepper motor and electric wires.

2.2 Design of the Finger Structure

2.2.1 Preliminary Experiments to Prepare for the Simulation

The physical properties of a 3D printed object, such as its elastic modulus, differ significantly from those of the bulk material. Therefore, displacement experiments were conducted first to identify the stiffness of the test object required to precisely model the actual behavior, and thus ensure the reliability of the simulation. The finger structure was made of thermoplastic polyurethane (TPU)—detailed geometry is explained in Sect. 2.2.3. After fixing a finger to a wall, the vertical displacement generated by applying a load at a specified position was measured with three times of repetition per each condition, in the weight range of 200–500 g, and compared to our simulation. The experimental setup is shown in Fig. 4.

Through the experiments, the mechanical properties of 3D printed TPU was confirmed. Displacements showed a linear trend in terms of weight within the given range. For ease of analysis, it is assumed that the finger just has isotropic material properties from a combination of multiple 3D printed layers in different directions. As shown in Fig. 5, the experiments and simulations exhibited similar displacements, with an error range of 0.04–0.2 mm. Therefore, the reliability of determined mechanical properties was sufficient. The values are listed in Table 1.

Table 1 Properties of thermoplastic polyurethane

Property	Reference (bulk) [21]	Printed filament
Young's modulus (MPa)	2410	39
Poisson's ratio (−)	0.39	0.39
Yield stress (MPa)	37	37
Printing temperature (°C)	–	250

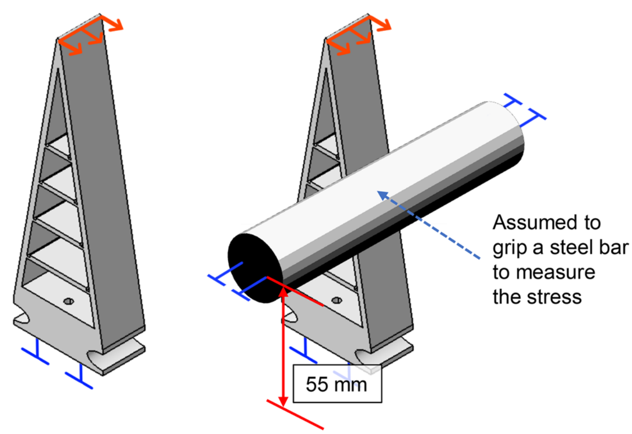


Fig. 6 Conditions of the simulations for assessing (left) displacement and (right) stress

2.2.2 Analysis Conditions

Modeling and simulation were executed with CATIA V5 software. In the simulations, the displacement of each finger and the stress on the object were measured. To simulate displacement, the bottom of the finger was fixed, as shown in the left part of Fig. 6, and a uniformly distributed load with a total magnitude of 10 N was imposed on the surface contacting the object. A distributed, rather than concentrated, load was applied to assess the overall deformation of the finger. In the stress simulation, the maximum stress that a finger would exert on a steel bar while gripping was obtained by applying a uniformly distributed load of 10 N to the fingertip. As shown in the right part of Fig. 6, the bottom of the finger was clamped, and a steel bar was fixed in position. The bar was 55 mm from the base of the finger, as is typical when gripping an object. After the finger deformed, the maximum displacement does not always occur at the fingertip with respect to the structure geometry. Nevertheless, as the gripping of the object was strongly influenced by the displacement of the fingertip, the displacement of the fingertip was considered as the main result, as well as the stress exerted on a steel bar. The aim was to obtain a finger design in which the displacement at the end of the finger was similar to or larger than that of the original Fin Ray structure, with the highest stress being exerted on the surface of the steel bar.

2.2.3 Effects of Geometric Parameters on Displacement and Stress

Here, in order to analyze the effect of structural parameter, a reference structure, herein referred as the original Fin Ray structure, was set based on the original Fin Ray® structure [8]. Most of geometric factors were the same, but the size was scaled up from the finger length of 60 mm to that of 65 mm, to fit with the designed switching system. It has a symmetric design with 80° outer wall slope (Fig. 7).

Three geometric finger parameters were considered: the number of ribs, slope of the outer wall, and slope of the ribs. A rib is an internal wall that, in the original Fin Ray specification, is parallel to the underside of the finger. The slope of the outer wall is the angle between the base and external wall (ray). To identify trends in stress and displacement while varying a given parameter, all other parameters were kept constant. The given single parameter was solely optimized step by step, in terms of the influences on gripping performances, following the results from some preliminary searching attempts. The number of ribs had a significant impact on the displacement, the most important value of the finger design, among three geometric parameters. The outer wall slope then influenced the stress the most, while the effects of the slope of the ribs were relatively small compared to two other variables. The effects of each structural parameter on stress and displacement are significantly different to each other. Quantitative results are more in detail in the next with the results in Fig. 4.

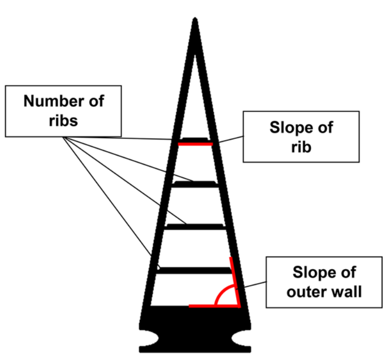


Fig. 7 Original Fin Ray finger and specification parameters

As the number of ribs increased, the stress applied to the object increased and the displacement of the fingertip decreased (Fig. 8a). Here, additional ribs were arranged with the same interval calculated from existing ribs and were placed on the top. The distribution of the rib may significantly influence the performance of the gripper, as ribs are core components influencing the stiffness of the finger. Also, there would be a wide variety of combinations in the distribution of the ribs. However, in this study, the simplest distribution was just considered for ease of analysis. Nevertheless, it is intuitive that the number of ribs still has a marked effect on the Young's modulus of the finger. Thus, it is necessary to find the optimum number of ribs for simultaneously satisfying the gripping weight, displacement, and stress requirements. From the analysis, the number of ribs was set to five to acquire the minimum displacement that is necessary for the complete grip in the centric grip method with three fingers.

Then the effect of the outer wall slope was studied. As the slope of the outer wall increased, the stress increased, peaking at 86° and decreasing again thereafter; the displacement did not show a consistent trend (Fig. 8b). An outer wall slope angle of 86° was set to be the optimum, because the plot showed that it was the inflection point in every set of simulations, even with different combinations of other values. Compared to the original Fin Ray structure, the stress increased by 132% while displacement remained almost unchanged.

At the last, the effect of making some or all of the ribs slope was considered. When the number of ribs was set to five, the slope of the outer wall was set to 86° and the inclination of all ribs was changed. Displacement and stress were greatest when the inclination of the most distal rib was 55°, so that value was used thereafter. Simulations were then kept being ran while varying the inclination of the second rib; Fig. 8c shows that results as an example. The stress did not show a consistent trend, but the displacement showed an increasing trend and reached a maximum of 18° (Fig. 8c). Displacement then tended to decrease when all ribs sloped, as opposed to only the two ribs closest to the surface in contact with the object.

The final specification for the modified finger was as follows: five ribs, and 86°, 18°, and 55° slope angles for

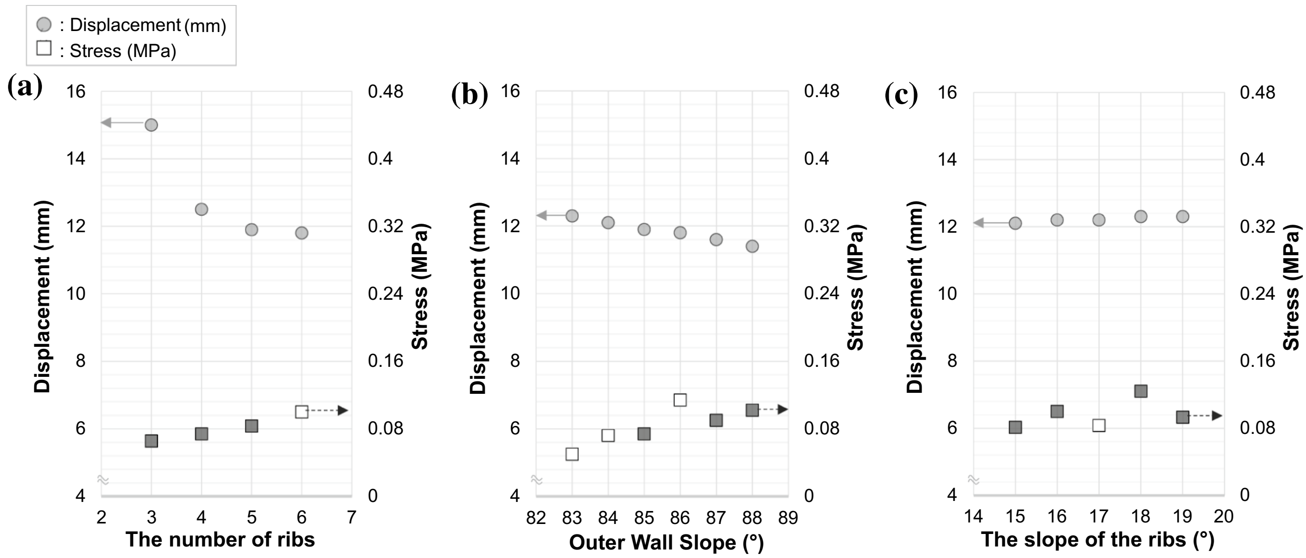


Fig. 8 Displacement and stress according to **a** the number of ribs, **b** the slope of the outer wall with five ribs, and **c** the slope of the second most distal rib (with five ribs) when the slope of the outer wall is 86° and the slope of the most distal rib is 55°

Table 2 Performance of the modified finger compared to the original Fin Ray finger

	Original Fin Ray finger	Modified design	Improvement (%)
Displacement	12.6	12.3	− 2.38
Stress (MPa)	0.0578	0.124	114.53

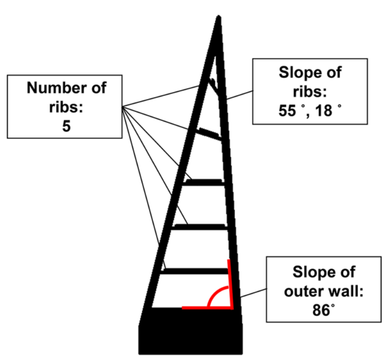


Fig. 9 Shape of the modified finger according to the final specification

the outer wall, second-most distal rib, and most distal rib, respectively. The performance under this specification is summarized in Table 2, and the finger shape is shown in Fig. 9.

2.3 Attachment Pads

TPU is a suitable material for gripper fingers because it has excellent elasticity, so its shape changes according to the shape of the object. However, it is aimed to further improve the gripping performance by increasing the frictional force on the surface. For this, PDMS pads that were attached to each finger were manufactured. PDMS, as an inert material, is highly chemically stable and exhibits few chemical reactions [22, 23]. It also adheres well to objects and has a high level of elasticity, similar to rubber, allowing it to grip objects effectively with high friction while not deforming the finger. Due to this characteristic, PDMS has been attached to the surface of the finger to improve the gripper's grip characteristics [24].

Inspired from the nature, like the tree frog and rock frog have the hexagonal pattern of their toes for high frictional force [25, 26], a hexagonal pattern was used to maximize the frictional force of the pad or to minimize the vacancy between the pattern. A mold was designed to fabricate attachment pads with various geometries, which was 3D printed with the hexagonal pattern on the surface. PDMS (Sylgard® 184 silicone elastomer; Dow Silicones Corporation, Midland, MI, USA) was poured onto the fabricated mold and left to harden. A vacuum was used to remove bubbles produced during the pouring.

Figure 10 shows two pattern parameters: lengths 1 and 2. The minimum and maximum values of length 1 were 2 mm (considering the maximum accuracy of 3D printing) and 2.5 mm (to avoid interfering with object gripping), respectively. The depth of the pattern was 1 mm. Pad patterns were produced with various specifications, as listed in Table 3,

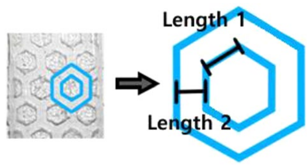


Fig. 10 Parameters of the hexagonal pattern

Table 3 Pad pattern specifications

	Level 1	Level 2	Level 3	Level 4
Length 1 (mm)	2	2.25	2.5	–
Length 2 (mm)	1.25	1.5	1.75	2

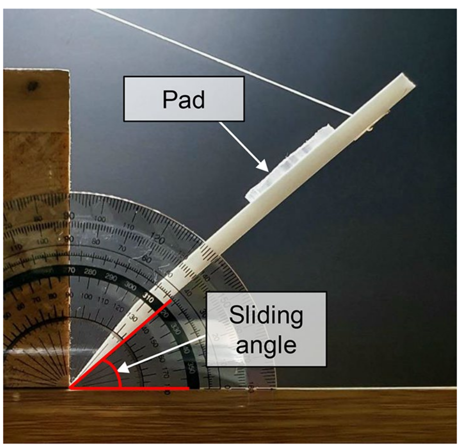


Fig. 11 Coefficient of friction experiment set up

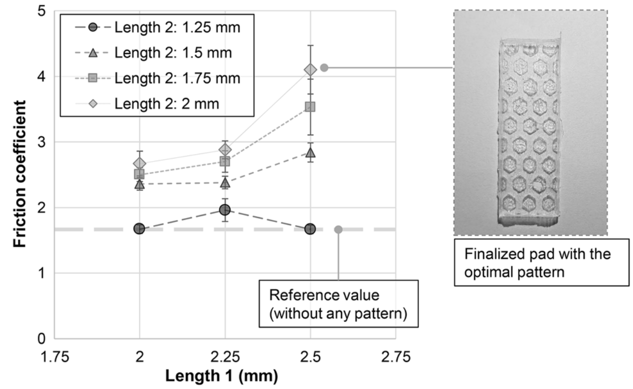


Fig. 12 Coefficient of friction according to pattern parameters and finalized polydimethylsiloxane (PDMS) pad with the optimal pattern applied

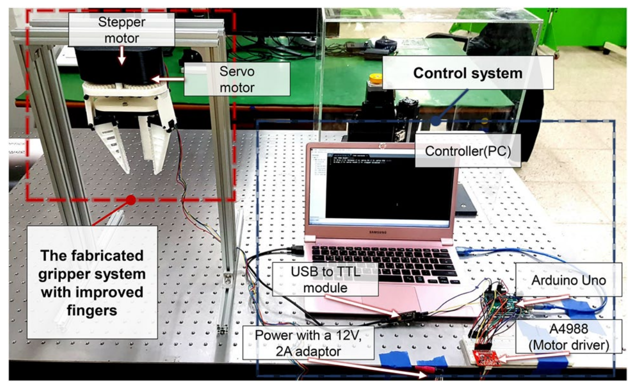


Fig. 13 Photograph of the gripper system

which were tested in a coefficient of friction experiment (Fig. 11). After placing an object on a surface, the angle of the surface was increased in increments of 1°. The coefficient of friction was calculated from the angle at which the object started to slide.

The experimental results are shown in Fig. 12. In most cases, the coefficient of friction increased with increases in length 1. It is presumed that this is because the area of contact between the pad and object is proportional to the square of length 1; the area of the single hexagonal pattern can be calculated as $3\sqrt{3}/2$ times the square of length 1. Among the tested specifications, length 1 = 2.5 mm and length 2 = 2 mm gave the highest coefficient of friction; this specification was therefore used for the final pads, as shown in Fig. 12.

3 Main Experiments and Results

3.1 Details of the Experiment

In the main experiment, to measure the gripping weight, the gripper was attached to an apparatus fixed to a surface, as shown in Fig. 13. For operation, an Arduino Uno received input from a PC keyboard via its serial port, and converted this into a command. The system consisted of an Arduino Uno, a servomotor for changing the gripping method, a stepper motor for driving the gripper, a power source, a motor driver (A4988; Pololu Robotics and Electronics, Las Vegas, NV, USA), and a USB to TTL module.

In this experiment, fingers with four designs were tested: the original Fin Ray finger (reference), the original Fin Ray finger with a 4 mm-thick attachment pad, the modified finger specification, and the modified specification with a 4 mm pad. The test method was as follows. The gripping weight was measured by placing water, weights, aluminum rods, or iron rods into a water bottle and measuring the resulting mass three times; the average value was used in the analysis. The bottle was placed on a pedestal, and the gripper then gripped it. After removing the pedestal, if the object was gripped without slipping for 3 s and does not fall out due to its own weight or external force, the trial was recorded as a success. Three attempts were made; if two of these were successful then it was recorded as "pass" and the gripping weight was recorded as the mass of the object. This experimental method followed was that of Crooks et al. [15]. The experiments were performed using the three gripping methods (vertical centric, vertical parallel, and horizontal parallel) for four gripper cases (total of 12 experiments for a single set). Also, the ability of the grippers to grip different kinds of objects was tested. The aspect ratio and mass of the gripped object were measured using the same procedure described above.

3.2 Results

3.2.1 Gripping Weight

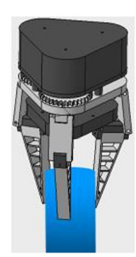
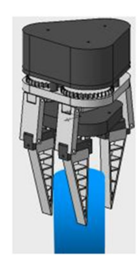
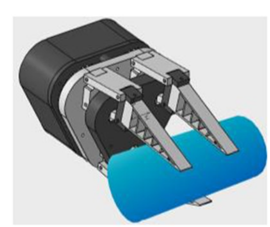
Table 4 lists the maximum gripping weights for the different finger designs and gripping methods. With a weight smaller than the maximum value in Table 4, all the grips were stable enough, and neither vibration nor sliding was not observed at all. As one exception, in the horizontal parallel gripping test, distortion of the finger was observed when a load of 1200 g or more was applied, and the experiment was stopped to preserve the fingers and gripper structure. Distortion was mainly due to the gripper body, which is made of 3D printed polylactic acid, rather than the finger properties.

The modified finger achieved 44%, 45%, and 60% increases in the gripping weight with the vertical centric, vertical parallel, and horizontal parallel grips, respectively. In the simulation, the gripping stress increased about two-fold compared to the reference, but the improvement in overall gripping performance was smaller because of differences between the simulation and main experimental conditions. The objects were gripped via their interaction with the three fingers. Although the gripping weight improvement was less marked that of gripping stress, it is clear that the modified design improved the gripping weight and Young's modulus of the finger. Among the gripping methods tested, the improvement in the horizontal parallel grip was largest, at more than 40%.

When the 4 mm pad was attached to the modified fingers, the gripping weight of the vertical centric, vertical parallel, and horizontal parallel grips improved by 458%, 341%, and 264%, respectively, over that of the original Fin Ray finger. The attachment pad contributed even more to the improved gripping capability than the modified finger design. From this, it is inferred that the surface characteristics are significantly related to the gripping capability. In particular, the improvement in the coefficient of friction appeared to directly improve the gripping weight with the horizontal gripping method. The coefficient of friction increased by 141%, compared to the 264% improvement in gripping weight.

However, compared to the changes seen with the vertical centric grip, adding 4 mm pads to the fingers when using the vertical or horizontal parallel grips did not improve the gripping weight as much. The object could not be placed in the optimal position during gripping because it would not slip naturally into the central position. In particular, when using the centric grip with the attachment pad, the object was gripped mainly by the fingertips, rather than the whole finger. This explains why the gripping weight improved less when using the pads in the parallel compared to the centric grip. It can be concluded that adjusting the friction on the surface through the appropriate use of different materials can play an important role in improving the gripping weight, and that the effect is greater than that of any structural change.

Table 4 Gripping weight (g) for each finger design according to the gripping method

Finger design	Vertical		Horizontal parallel
	Centric	Parallel	
			
Original Fin Ray fingers	340.44	385	330
Original Fin Ray fingers (with 4 mm pad)	1450	960	995
Modified finger design	490	560	530
Modified finger design (with 4 mm pad)	1900	1700	1200 (Stopped)

3.2.2 Types of Grippable Objects

For the final grip test, a total of 17 types of object used in daily life and industrial facilities were randomly selected. Table 5 lists the name, aspect ratio, and weight of each object, with photographs shown in the top part of Fig. 14. All items were successfully gripped; they had an average width and length of 78.4 and 58.68 mm, respectively, and masses of 1–443 g. The gripper even successfully gripped various foodstuffs, such as bread and an apple (Fig. 14 bottom, left and right panels, respectively), as well as miscellaneous goods, such as ballpoint pens, spray cans, and tools such as wrenches and clamps. It worked not only with rigid and heavy objects, but also with objects composed of soft materials. The PDMS attachment pad can be expected to prevent damage to the object surface because it is softer than the TPU of the finger; it also improves the gripping capability.

The gripper demonstrated versatility, gripping objects with an aspect ratio in the range 1–10, and even a long, thin object with an aspect ratio of 145. As shown in Fig. 15, objects with a mass below 500 g and an aspect ratio in the range 1–12 can be expected to be grasped without difficulty, as the gripper successfully gripped objects as heavy as 1.2 kg regardless of the gripping method.

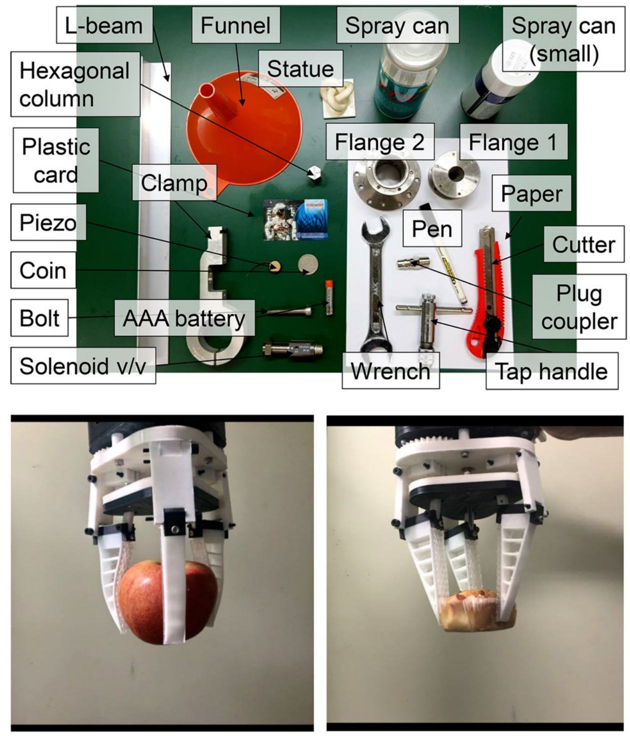


Fig. 14 Photographs of the objects used in the grip test (top) and the gripper holding two foodstuffs (bottom, left and right)

Table 5 The gripped objects

Object	Aspect ratio	Mass (g)
Bolt	1	20
Pen	1	6
Glue (5 g)	1	10
Spray can (standard)	1	217
Spray can (small)	1	143.7
Hexagonal column	1	16.2
Flange 1	1	342.2
Flange 2	1	443
Funnel	1.04	40
Statuette	1.17	18.2
Clamp	2.38	184.5
Plug coupler	3.15	23.3
Solenoid valve	3.45	79.6
Cutter	3.45	65.4
Tap handle	4.39	184.1
Wrench (labelled 1922)	11.45	138.6
L-beam	145.71	123.8

4 Conclusion

In this paper, a versatile soft gripper that has a larger gripping weight than the gripper with the original Fin Ray finger was presented; the gripping method can be changed and the gripper is applicable for smart manufacturing. Mechanical properties were analyzed using CATIA software to ensure reliability, and a finger structure was sought to improve the performance of gripper. The trend of stress applied to the

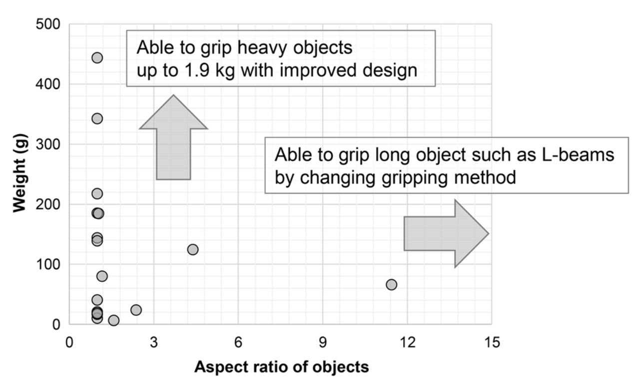


Fig. 15 Gripping weight according to the aspect ratio of the object being gripped. Note that the L-beam (aspect ratio, 145) is not shown

finger and the displacement of the fingertip were presented according to the increase or decrease of each variable. Compared to the original Fin Ray finger, we increased the number of ribs to five, and the most and second-most distal ribs with respect to the fingertip had slope angles of 55° and 18°, respectively. The outer wall of the finger had an incline of 86°. The performance (gripping weight) of the modified finger improved by 40%. To further increase the gripping weight, a PDMS pad with a hexagonal surface pattern was attached to the finger surface and increased its friction. The gripping weight increased significantly with use of the modified design with the pad, from 340, 385, and 330 g to 1900, 1700, and 1200 g for the vertical centric, vertical parallel, and horizontal parallel gripping methods, respectively.

The gripper configuration was simplified, and the weight reduced, by changing the driving method from the existing pneumatic system to an electric one. Thus, in addition to the improved gripping performances, the gripper presented in this paper has a great advantage in terms of independence and the weight of the gripper, as it does not require such a central actuation system. From this perspective, wider applicability is expected in various fields requiring independence and less weight, such as drones or unmanned aerial vehicles (UAVs) applications. With our modified design, it is possible to freely switch between centric and parallel gripping methods using a servomotor. Moreover, because this gripper can grip objects with an aspect ratio in the range 1–145, it should be suitable for smart manufacturing and compatible with workpieces of various shapes. In future work, a finger structure will be studied more in detail with more geometric parameters, i.e., the distribution of ribs. Further, the design of a lighter gripper that does not sacrifice gripping capability will be investigated.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests of personal relationships that could have appeared to influence the work reported in this paper.

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