Improvement of precision grasping performance by interaction between soft finger pulp and hard nail

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Abstract

In this study, we investigated the effect of the presence or absence of fingernails on precision grasping using artificial anthropomimetic fingers. We hypothesized that fingernails improve precision grasping performance by increasing the friction coefficient while suppressing fingertip deformation. To test our hypothesis, we developed artificial fingertips, each composed of bone, nail, skin, and soft tissue, and fabricated three types of artificial fingers with different skin softness grades and artificial fingers without nails as the control condition. Pull-out experiments of cylindrical objects and T-shaped blocks were conducted using the developed artificial fingertips with and without nails, and the magnitude of the holding force was compared. The nail contributed to object grasping stability because the magnitude of the holding force was significantly increased by the presence of the nail in the artificial fingertip with soft skin. The rate of increase in the magnitude of the holding force of the T-shaped block was more significant (3.10 times maximum) than that of the cylindrical object (1.08 times maximum) because the finger pulp deformation was suppressed by the nail, and the form closure, that is, geometric constraint, was formed for the grasping object. The results of this study show that soft fingertips and hard nails can significantly improve the grasping performance of soft robotic hands. And these results suggest that the human nail improves precision grasping performance by forming geometric constraints on the grasped object, suppressing finger pulp deformation.

Keywords: artificial finger, nail, precision grasping

Introduction

The goal of developing a robotic hand is to improve grasping performance. Specifically, grasping performance includes the ability to achieve various grasping postures and motions and perform different functions, such as sensing. The ability to stably grasp an object is required for many robotic hands. Although different definitions of stable grasping have been proposed, stability of the holding force (which indicates how well the hand can keep grasping an object against a given disturbance while holding an object) is a critical index for evaluating stable grasping with a robotic hand. The anthropomimetic approach is often used to determine the stability of the holding force of a robotic hand. The anthropomimetic approach is based on the principle that human fingers contain elements that play a significant role in grasping an object. For example, it is known that the opposing structure of the thumb and the other four fingers not only grips an object but can also grasp it with precision, and this knowledge has been applied in developing robotic hands [1]. Many robotic hands have been developed to mimic the human hand [2].

The distal phalanges (fingertips) play a crucial role in human precision grasping. The surface of the human phalanges is covered with skin and nails. The inner surface of the skin consists of several substances, including tendons, blood vessels, nerves, and distal bones. The nail is produced from the nail matrix on the periosteum of the distal phalanx and extends from the inside to the outside of the skin. The nail and distal phalanx are fixed through the surrounding tissue. The flexible fingertips soften the impact of contact with an object and generate frictional force by adhering to the object. The fingernails play a role in scratching, hooking, and concentrating forces on the fingertips.

In recent years, soft robotics has advanced, and artificial fingers and robot hands have been developed using soft materials. Shimoga et al. developed artificial fingers made of several materials, including rubber, sponge, and gel; they demonstrated that artificial fingers made of soft materials effectively soften the impact of contact with objects and adapt to the shape of objects [3]. Controzzi et al. conducted grasping experiments using a robotic hand equipped with flexible artificial fingers and found that the magnitude of the holding force significantly improved compared to the case of stiff fingertips [4]. These studies show that the flexibility of the fingertips contributes to an improvement in grasping performance.

Several robotic hands that combine nails with flexible tissues have been developed. Iwata et al. succeeded in picking up a straw by attaching nails to a soft robotic hand [5]. Matsuno et al. succeeded in lifting a thin plate [6]. In addition, the glove developed by our research group showed that the hand with nails could pick up thin objects such as coins, keys, and cards more easily than the hand without nails [7]. Murakami et al. attached a sensor to a nail and succeeded in rolling up a sheet of paper [8]. As demonstrated in these studies, a robotic hand can perform several dexterous tasks with the nail. Han et al. compared the friction coefficients of artificial fingertips with and without nails and found that the friction coefficients were higher when the nails were present [9]. Therefore, if the presence of nails increases the friction coefficient, the stability of grasping an object using the fingertips is expected to improve.

The aim of this study is to develop an artificial anthropomimetic fingertip equipped with a nail mechanism and test the hypothesis that the interaction between the nail and soft tissue improves grasping performance in precision grasping. The grasping performance in this context indicates that a large force can sustain the grasp of the object. The ability to exert greater force is thought to improve stability. In the experiments, the object precisely grasped by the artificial fingers was pulled out, and the maximum force exerted during the pull-out was measured as the magnitude of the holding force. Two types of objects, a cylinder and a T-shaped block, which have different shapes of contacting parts on the finger pulp, were grasped precisely. By comparing the magnitude of the holding force of these two methods of grasping an object with artificial fingertips with and without nails, we investigated the effect of the nails on precision grasping.

Materials and Methods

Development of artificial fingers

Human fingertips are composed of bones, nails, skin, and soft tissues that fill the space between them. Each of these four elements plays a role. The bones support the entire fingertip and prevent excessive dorsal flexion when grasping an object. The nails receive deformation from the skin and the flexible tissues. The skin changes the frictional properties of the fingertips and restricts the deformation of the tissues under the skin. Soft tissues modulate the stiffness properties of fingertips. Thus, the four elements interact with each other. To date, most studies on robotic hands and artificial fingers focused on three or fewer of these four elements [10][11][12][13]. However, in this study, we developed an artificial finger that combines all four components (bone, nail, skin, and soft tissue) to mimic the human fingertip precisely. The artificial fingers developed by Jamali et al. and Fishel et al. replicated these structures but did not focus on the shape of the human finger [14][15]. The artificial fingers developed by Controzzi et al. and Shao et al. included these four elements and mimicked the human finger shape but did not precisely replicate the structure penetrating the skin and joining the nail to the skeleton [4] [16]. In this study, we developed an anthropomimetic fingertip not only according to its components but also its structure, shape, and size based on the method described in our previous study [17].

Fig. 1 shows the artificial finger structure developed in this study. The cross-sectional images shown in Fig. 1a are colored for clarity. To perform precision grasping, we developed an artificial thumb and an index finger, as shown in Fig. 1b. An artificial distal phalanx was inserted into the skin. From the dorsal side of the bone, the nail insertion part, which held the nail in place, extended through the skin, and the nail was integrated with the bone. The space between the skin and bone was filled with a soft material.

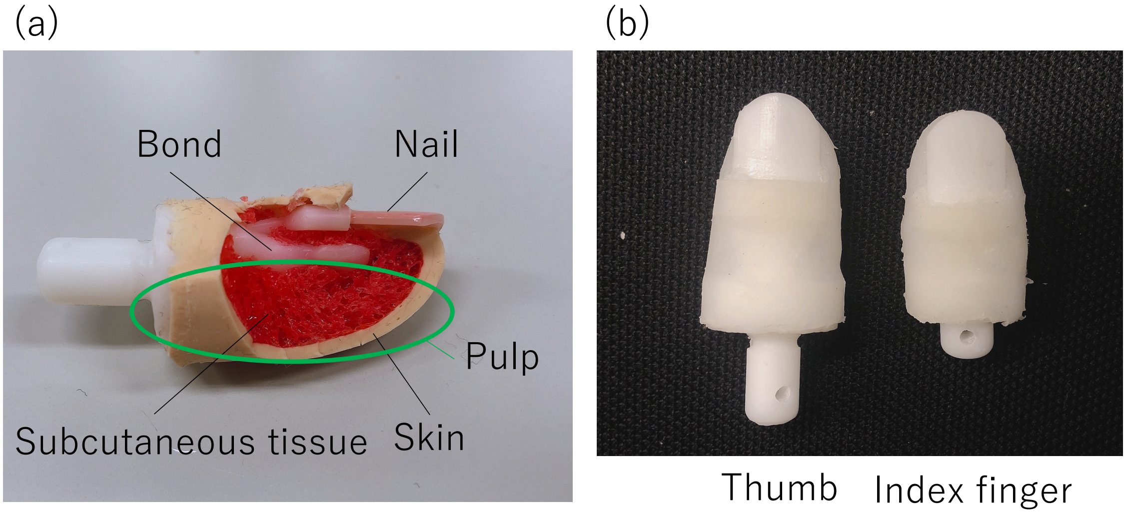

Fig. 1 Developed artificial fingertip. (a) The artificial fingertip consists of four elements. (b) The developed artificial thumb and index finger.

We believed that we could implement the effects of human nails on artificial fingers by developing material properties close to those of humans. In recent years, materials suitable for producing soft fingers for robotic hands have been investigated [18]. Contorozzi et al. constructed an artificial finger from two layers of silicone rubber with different hardness values. Because the artificial finger exhibited higher stiffness than the human finger, it was considered that the stiffness would be closer to that of humans using materials, such as foams and gels [4]. Therefore, we decided to use silicone foam as a sponge material for flexible tissue based on Controzzi et al. Three types of artificial fingers were formed by developing skin using three silicone types with different hardness values to clarify the relationship between fingertip hardness and its interaction with the nails.

The artificial bones and nails were sculpted with resin using a three-dimensional (3D) printer (Form3, Formlabs Inc., USA). Silicone foam (Soma Foama, Smooth-On Inc., USA) was used as the soft tissue. We considered that the response with and without nails depends on the softness of the fingertips. Therefore, we decided to change the softness of the skin in stages instead of using silicone foam for the subcutaneous tissue for fabrication reasons. The following three silicone rubber types were used as the skin material: silicone rubber with shore hardness grades of A60 (TSE3466, Tanac Co. Ltd., Japan), A30 (TSG-A30, Tanac Co. Ltd., Japan), and E10 (TSG-E10, Tanac Co. Ltd., Japan). The silicone rubber fingers were denoted A60, A30, and E10 artificial fingers. For comparison with artificial fingers with nails, artificial fingers without nails were fabricated for each artificial finger.

The skin of the artificial finger influences the overall shape of the artificial fingertip. The external shape of the artificial finger was designed based on the 3D scan data of a human finger. The outer mold was designed to resemble the outer shape, and the core was designed to offset the outer mold surface (Fig. 2a). The silicone was poured to fill the space between the outer mold and the core, and the solidified material was removed as the skin and nails were attached. When silicone foam resin was poured into the skin and agitated, foaming occurred along the finger shape, and the flexible tissue of the artificial finger was formed (Fig. 2b). The bone was pushed into the skin immediately before the silicone foam reaction was completed, and it was joined to the nail.

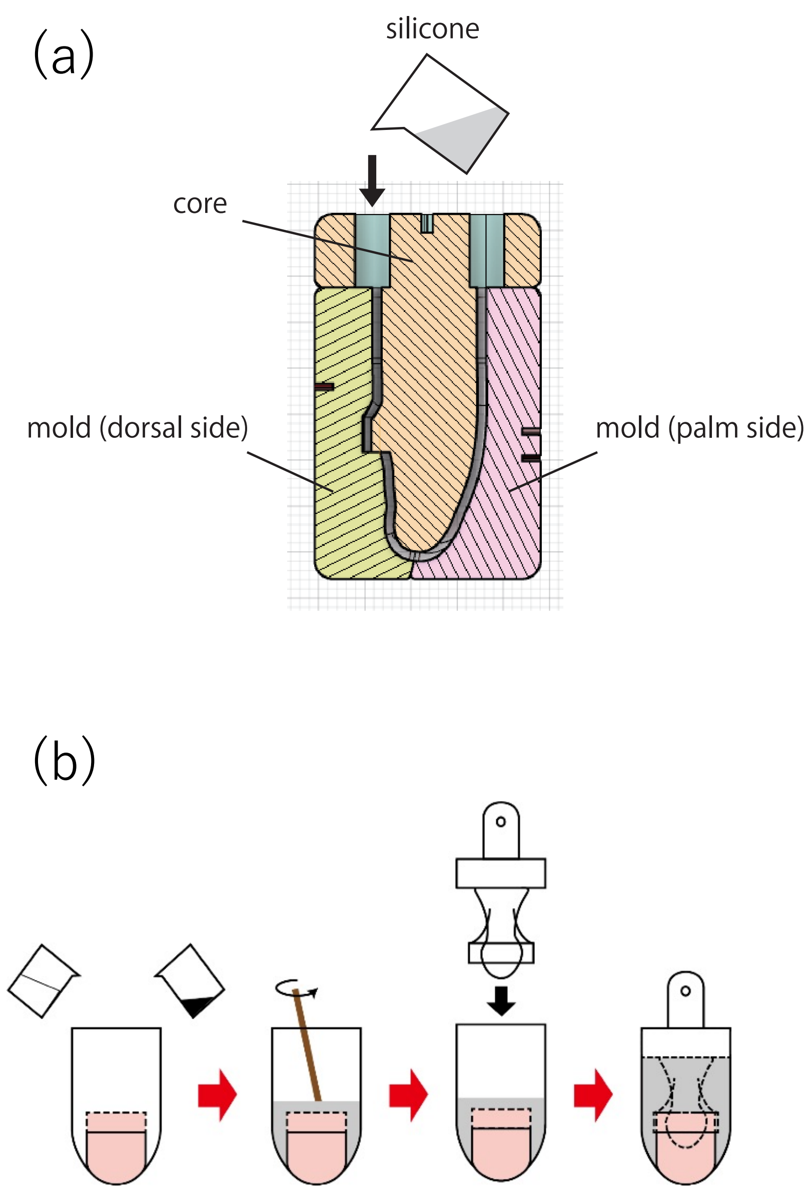

Fig. 2 Processing of artificial fingers. (a) The artificial skin is shaped by injecting the silicone between the core and the mold. (b) Silicone foam is poured into the skin, the bone is pressed in, and an artificial finger is formed.

Experimental Methods

Softness measurement

Young's modulus of the skin and pulp (combined skin and subcutaneous tissue area) of three types of artificial fingers were measured by different methods.

The Young's moduli of skin were measured using a commercially available softness measuring device (Softgram, Shinko Denshi Co., Ltd., Japan). An image of the experimental system is shown in Fig. 3. The softness measuring instrument used Hertz's elastic contact theory to measure the modulus of elasticity based on the degree of indentation of the measuring element and the reaction force. The amount of indentation was set to 0.5 mm, and it was possible to measure the surface softness of artificial fingers, i.e., skin softness (skin thickness: 1.0 mm). The softness measuring instrument was fixed to the traction part of the tabletop tensile testing machine (MCT-2150, A&D Co. Ltd., Japan) using a jig. The measurement was performed by pressing the measuring instrument against the artificial finger fixed to the table. The tensile testing machine was used to perform the pull-out experiments. The pressing speed was set to 1 mm/s. The softness of each artificial fingertip was measured 10 times.

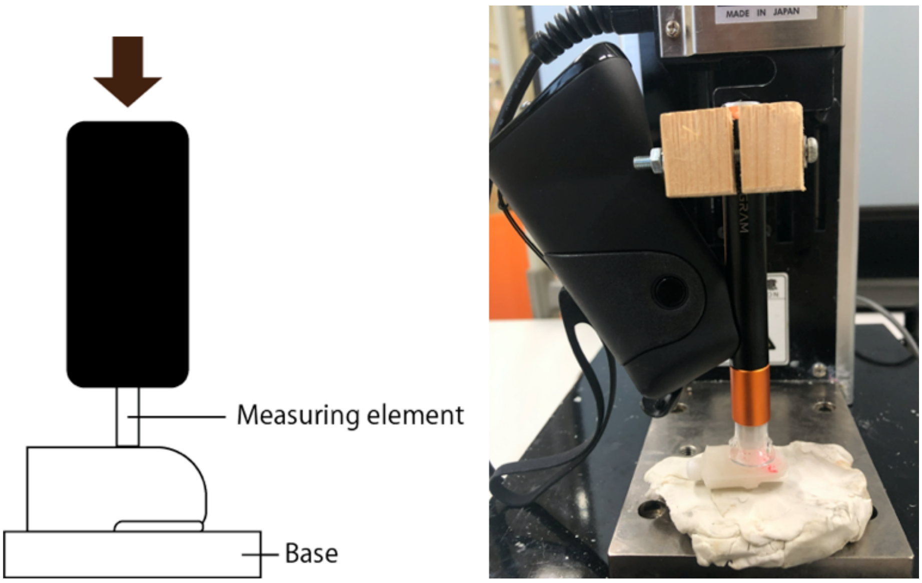

Fig. 3 Softness measurement experiments.

For the measurement of Young's modulus of pulp, we used a softness measuring device (Fig. 4) developed by our research group. In the softness measurement device, the amount of indentation of the artificial finger was adjusted manually. For each 0.1 mm push-in, the reaction force data were measured for 30 frames at 10 Hz. Measurements were terminated when the artificial finger was pushed down to 3.0 mm, which reflects the softness of both the skin and the subcutaneous tissue. Measurements were taken only once for each artificial finger.

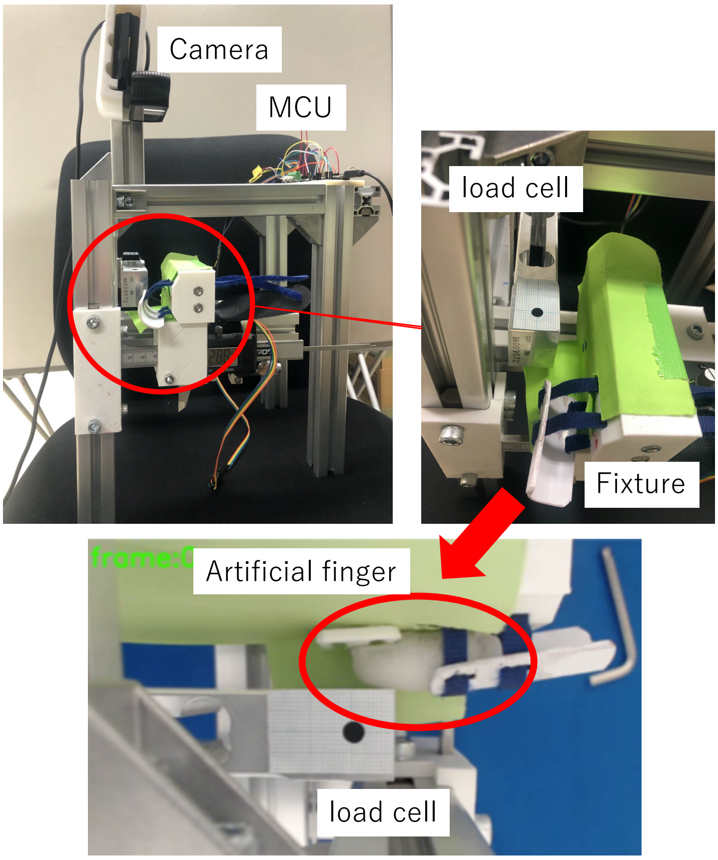

Fig. 4 Developed softness measurement device. The device measures the reaction force from the load cell and the amount of indentation of the artificial fingertip. The softness is calculated by using these measured data.

The stiffness coefficient K was obtained by dividing the obtained reaction force by the amount of displacement. Inoue *et al*. showed that the stiffness coefficient K can be derived from the Young's modulus E and the amount of displacement d by assuming a virtual spring perpendicular to the direction normal to the hemisphere fingertip [19].

$$E = K/2\pi d \tag{1}$$

Obata *et al*. used the method of Inoue *et al.* to obtain Young's modulus for artificial fingers [20]. In this study, too, Young's modulus was calculated using the method of Inoue *et al.* Calculated Young's moduli of the skin and the finger pulp were averaged for the thumb and the index finger.

Pull-out experiment

To compare the grasping performance of artificial fingertips with and without nails, we conducted pull-out experimental tests on an object with a simple shape. An image of the experimental system is shown in Fig. 5. An object grasped by the artificial thumb and artificial index finger was pulled upward using the tensile testing machine. Before pulling up the object, the artificial fingers were coated with talc powder. The frictional force and the degree of movement of the object were measured at a sampling frequency of 100 Hz until the object was pulled out of the artificial finger. Pulling was performed at a speed of 5 mm/s. The pull-out experiments were performed under the following two grasping conditions.

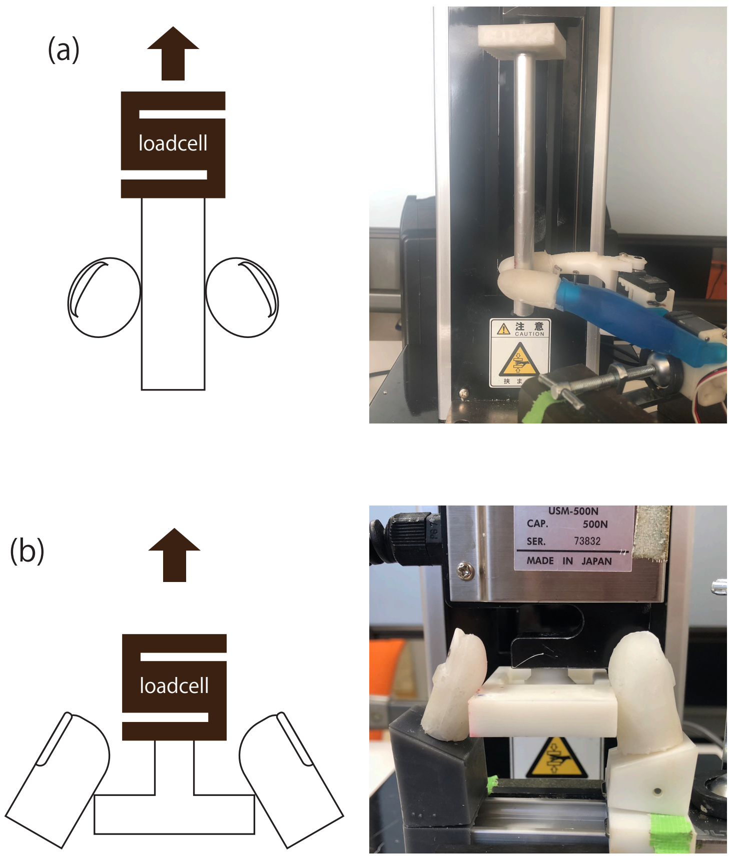

Fig. 5 Pull-out experiment. Artificial fingertip grasping the (a) cylinder and (b) T-shaped block, respectively.

(a) Cylindrical object

The robotic hand grasped a cylindrical object with a diameter of 12 mm in a posture similar to grasping a pen. An artificial fingertip was attached to the robotic hand fingertip to mimic a grasping posture. The contact angle was set based on the precise grasping posture of the human finger [17]. The hand was designed based on the two-degree-of-freedom (2-DOF) simple prosthetic hand developed by our research group, consisting of only the thumb and the index finger. Moreover, the hand exhibited a 1-DOF movement such that only the MP joint of the index finger rotated [21]. The position of the

MP joint of the index finger was controlled using a servo-motor, and the cylinder was grasped with maximum flexion using a servo-controller. After grasping the cylinder, 10 measurements were performed for each artificial finger while the power was on.

(b) T-shaped block

A T-shaped block with a width of 40 mm was grasped by hooking it onto the fingertips. For the experiments, the distance between the bases was fixed to 45 mm.

Two types of measurements were performed 10 times, each on artificial fingers with and without nails.

Data Analysis

By plotting the data measured during the pull-out experiment, we obtained the force–displacement curve shown in Fig. 6. The magnitude of the holding force was the maximum value of the graph. A comparison test for the difference in the magnitude of the holding force was conducted to compare the artificial fingertips with and without nails. In deciding whether to test for the difference using means or medians, we first performed the Shapiro–Wilk test to determine the normality of each group. If the null hypothesis was rejected, the Mann–Whitney u-test was performed. If the results were not rejected, Bartlett's test was performed to determine the equivariance between the groups. We performed Welch's t-test if the null hypothesis was rejected, and Student's t-test if it was not rejected. The significance level of each test was 0.05, and all p-values less than 0.0005 were indicated as 0.000. The data were presented as box plots for the u-test and bar graphs for the t-test.

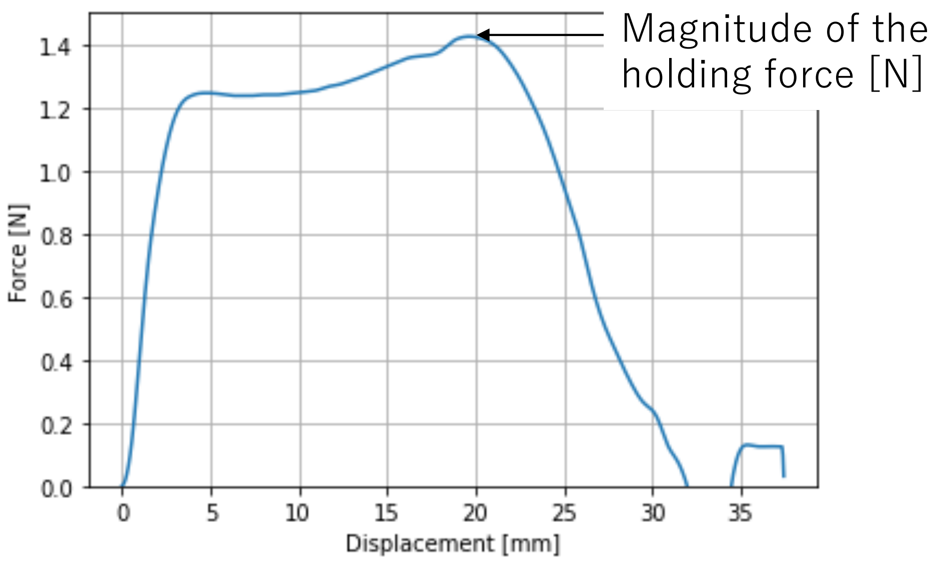

Fig. 6 Force–displacement curve obtained from pull-out experiment.

Results

Softness measurement

The means and standard deviations of Young's moduli of the measured artificial fingertips are listed in Table 1. In order of softness magnitude of the skin and pulp, the artificial fingers were made of E10, A30, and A60 silicones. These results indicated that the softness of the developed artificial fingertip was dominated by skin softness. Moreover, the softness of the finger pulp showed same tendency. Since bone and nail are sufficiently harder than skin and pulp, the specification of the material are listed as reference value of hardness.

Table 1 Young's modulus of artificial fingertips

Part	Silicone type	Young's modulus /kPa
Bone	-	4.1×10^6
Nail	-	4.1×10^6
Skin	A60	1302.6±138.1
	A30	445.6±125.7
	E10	77.9±12.0
Pulp	A60	63.1±0.4
(skin and subcutaneous tissue	A30	43.7±16.7
	E10	22.1±5.0

Pull-out experiment

The mean and median values of the magnitude of the holding force measured during the pull-out experiments for the cylindrical and T-shaped blocks are presented in Fig. 7 and Table 2, and Fig. 8 and Table 4, respectively.

Table 2 Values of magnitude of holding force in pull-out experiments with cylindrical object. The asterisks indicate significant differences.

Artificial finger	Without nail	With nail	Magnification
A60	1.712	1.769	1.033
Standard error	0.026	0.028	
A30	1.722	1.780	*1.034
Quartile range	0.017	0.064	
E10	1.385	1.495	*1.080
Standard error	0.012	0.024	

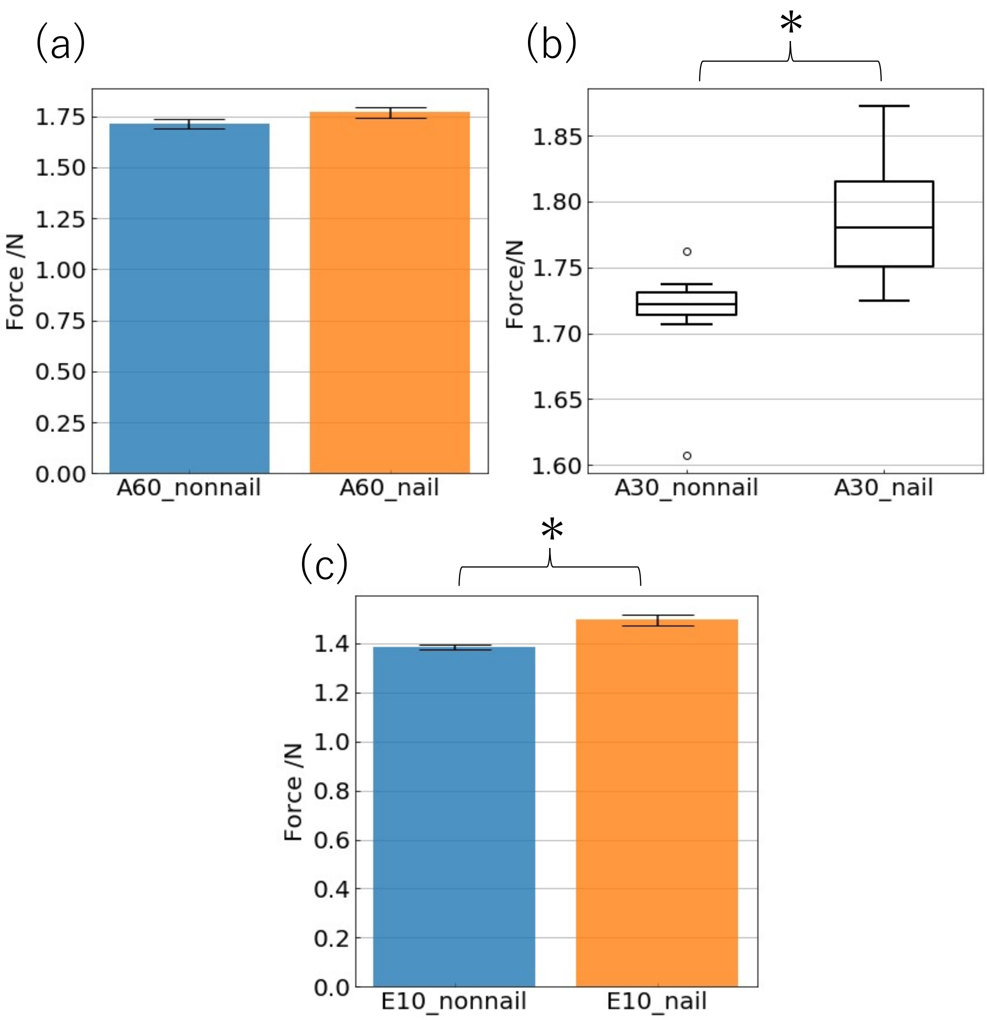

Fig. 7 Pull-out experimental results for cylindrical object. The magnitude of holding force are for artificial fingertips made of (a) A60, (b) A30, and (c) E10 silicones. The asterisks indicate significant differences.

Table 4 Values of magnitude of holding force in pull-out experiments with T-shaped block. The asterisks indicate significant differences.

Artificial finger	Without nail	With nail	Magnification
A60	2.417	3.151	*1.345
Quartile range	0.050	0.208	
A30	1.974	2.801	*1.471
Standard error	0.005	0.056	
E10	1.124	3.484	*3.101
Quartile range	0.067	0.267	

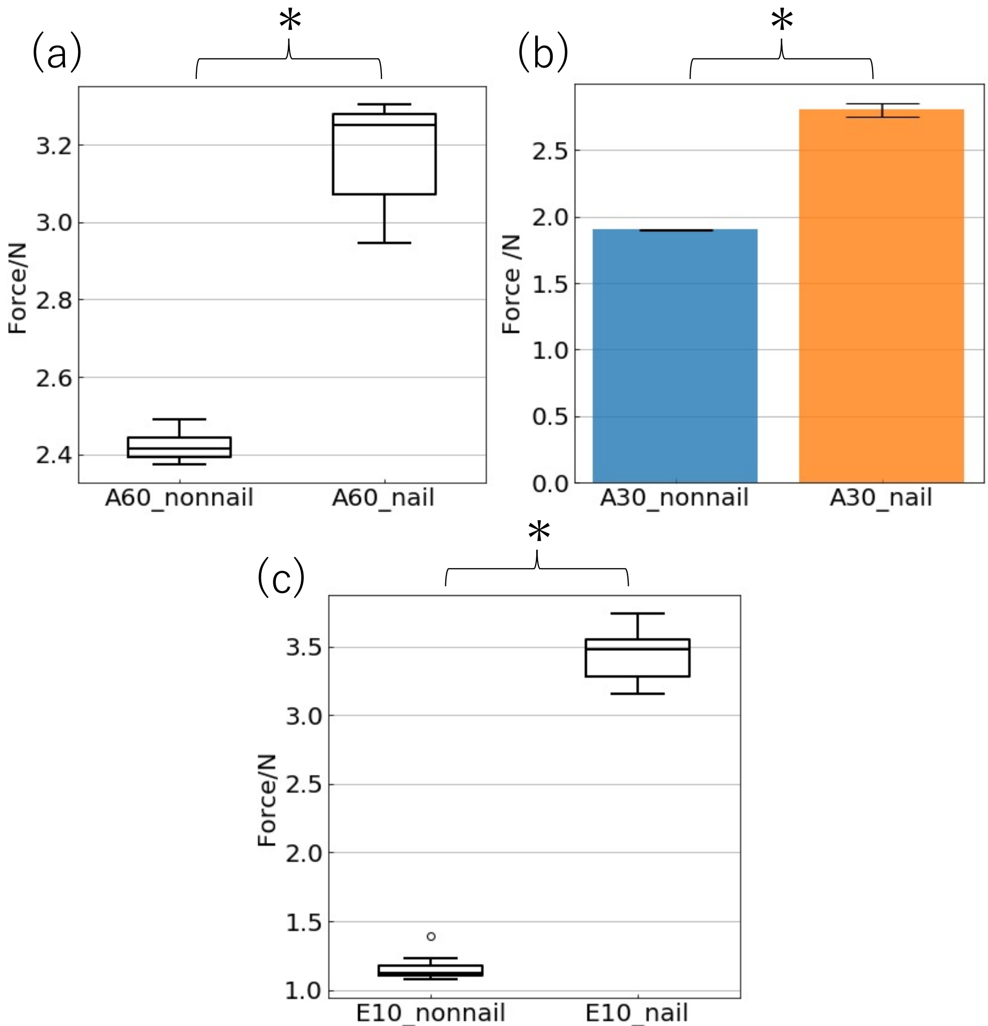

Fig. 8 Pull-out experimental results for T-shaped block. Magnitude of holding force of artificial fingertips made of (a) A60, (b) A30, and (c) E10 silicones. The asterisks indicate significant differences.

The bar graphs and box plots (Figs. 7 and 8) show comparisons of the results for each artificial finger with and without a nail. Tables 2 and 4 list the mean and median values of the magnitude of the holding force of each artificial fingertip and the magnification of the magnitude of the holding force of the artificial fingertip with the nail when that without a nail is set to 1. From the statistical analysis results, it is possible to compare the difference between the median for the A30 artificial finger and the mean for the other two artificial fingers in the case of cylinder pull-out. For the T-shaped block pulling, the A30 artificial finger was used for the mean value, and the other two artificial fingers were selected for the median values.

For the pull-out experiments with the cylinder, there was no statistically significant difference between the artificial fingertips with and without nails only for A60. For the other two artificial fingertips, the magnitude of the holding force of the artificial fingertip with the nail was significantly higher than that without the nail. The *p*-values are listed in Table 3. It should be noted that the magnifications were 1.03 and 1.08 times for the A30 and E10 artificial fingertips, respectively, indicating a slight difference. In addition, the softer the material, the more significant the effect of the nails. These results demonstrate that the nail slightly improved the grasping performance of the cylinder.

Table 3 *p*-values in statistical analyses for pull-out experiments with cylindrical object

Artificial finger	Shapiro−Wilk test Without nail	 With nail	Bartlett's test	Comparison test
A60	0.998	0.597	0.839	0.153 (Student's t-test)
A30	0.002	0.652	-	0.001 (Mann−Whitney u-test)
E10	0.527	0.569	0.046	0.001 (Welch's t-test)

For the pull-out experiments with the T-shaped block, the magnitude of the holding force of the artificial fingertip with nails significantly exceeded that without nails for all three artificial fingers, including A60. The p-values are listed in Table 5. Even for A60, which had the smallest magnification, the difference was 1.3 times. E10, which exhibited the most significant difference, had a difference of 3.1 times. Based on the pull-out experimental results obtained for the cylinder, the softer the material, the more significant the nail effect. The nail effect on the T-shaped block was more significant than that on the cylinder. These results showed that the nail significantly improved the grasping performance of the T-shaped block. Moreover, the improvement in the grasping performance of the nail was strongly influenced by the shape of the object.

Table 5 p-values in statistical analyses for pull-out experiments with T-shaped block

Artificial finger	Shapiro−Wilk test Without nail	 With nail	Bartlett's test	Comparison test
A60	0.362	0.033	-	0.000 (Mann−Whitney u-test)
A30	0.240	0.129	0.000	0.000 (Welch's t-test)
E10	0.006	0.732	-	0.000 (Mann−Whitney u-test)

Discussion

We hypothesized that adding nails to the fingertip improves the performance of grasping an object and performed two different grasping experiments to test this hypothesis. In all the experiments, except for the pull-out experiment on the cylindrical object with the hardest A60, the magnitude of the holding force of the artificial fingertips with nails significantly exceeded those without nails. As hypothesized, the nail improves the performance of grasping an object. In particular, the difference in the magnitude of the holding force between the fingertips with and without nails was more evident for the T-shaped blocks than for the cylinders. For the pull-out experiments with the T-shaped block, the softer the skin, the more the fingertips deformed along the contacted object, forming a geometric constraint (Fig. 9). This geometric constraint was also observed in the human fingertip and was believed to have significantly increased the magnitude of the holding force by forming a form closure [22] at the fingertips. These results clarify that nails improve the precision grasping performance of objects. Thus, human nails perform a functional role in improving the precision grasping performance by forming a geometric constraint on the grasped object, suppressing the finger pulp deformation.

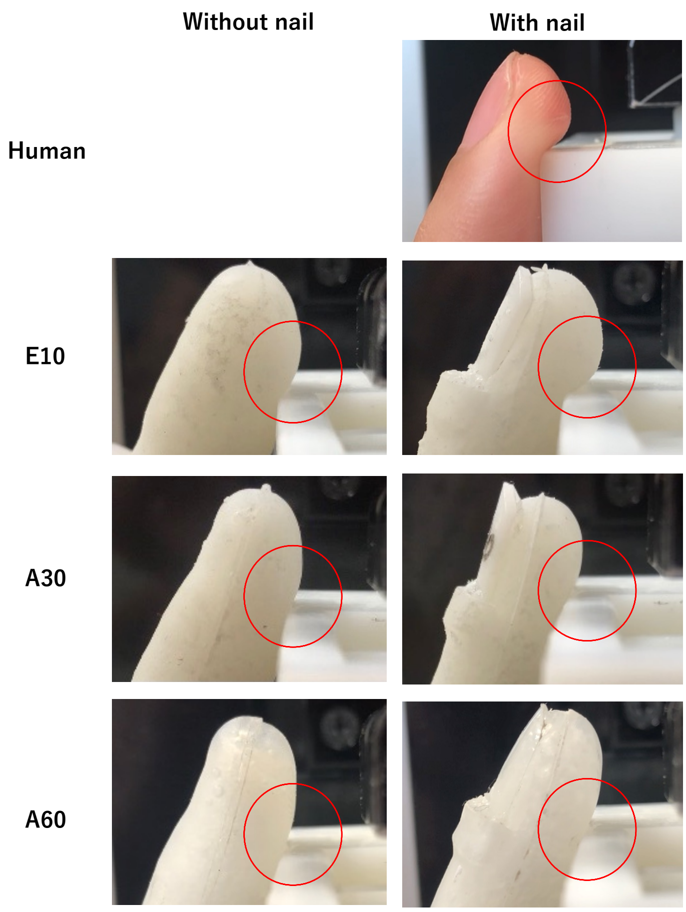

Fig. 9 Deformation of finger pulp of artificial fingertips during pull-out experiments with T-shaped block.

It is believed that nails, the skin, and flexible tissues interact to grasp an object firmly. By receiving the load applied to the finger pulp by the nail, the pulp can deform along the object. When an object slides on the fingertip surface, the soft tissue is dragged by the object and deformed in the shear direction, and the fingertip is compressed and stiffened. This experimental study demonstrated that hardened skin wraps around the sliding object and forms a form closure, that is, geometric constraint, preventing the object from moving and stabilizing the grasp. In the fingertip made of E10 silicone, the skin of the artificial finger with a nail deformed along the corner of the contacted T-shaped block to form a constraint when the T-shaped block was withdrawn. Similar deformations were also observed in human fingers. For fingers that underwent such deformation, the skin pulled upward against the corner of the block possibly returned downward, increasing the magnitude of the holding force. In the A60 and A30 silicone fingertips, smaller deformation occurred along the block corner because of the hard skin, regardless of the presence or absence of nails. Therefore, the difference in the magnitude of the holding force between the fingertips with and without nails was lower in A60 and A30 silicones than in the E10 silicone. Our results confirm that the soft finger pulp and hard nail are necessary to generate form closure in the fingertip.

The formation of form closure by the finger pulp is also frequently observed in the human grasping of everyday objects. For example, when grasping a thin object such as a pen, the finger pulp deforms to form an arch along the cylindrical shape, and the soft tissue in the center of the pulp is pushed to the edge; hence, the entire pulp rigidly wraps the object (Fig. 10). Similar deformation also occurs when grasping objects smaller than the size of the fingertip, such as marbles, pills, or thin objects. Thus, the formation of form closure in fingertips is a common phenomenon that occurs daily, and it is inferred that it significantly improves human precision grasping. The main point of this study is that by attaching the nail to the soft artificial fingertip, form closure can be applied to the fingertip of the soft robotic hand, and the precision grasping ability of the soft robotic hand can be improved significantly.

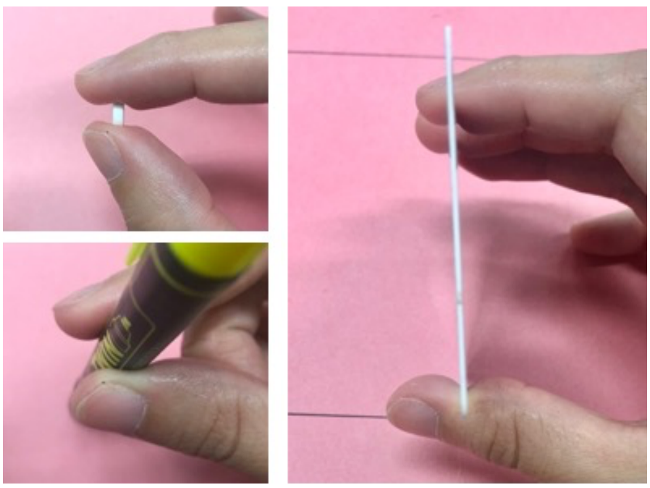

Fig. 10 Example of human grasping of everyday objects.

Conclusions

In this study, to test the hypothesis that the nail improves grasping performance, we conducted pull-out experiments with cylindrical objects and T-shaped blocks using developed artificial fingertips with and without nails and compared the magnitude of the holding force. For the pull-out experiments with cylinders, no difference in the presence or absence of nails was observed only in the fingertip made of A60 silicone. However, significant differences were observed in the A30 and E10 silicone fingertips. In the T-shaped block, significant differences were observed in all artificial fingertips. The difference was more significant for softer fingers than more rigid fingers. In the pull-out experiment with the T-shaped block by the E10 silicone fingertip, the presence of the nail caused the skin to deform along the corner of the block, forming a geometric constraint. These results suggest that the human nail has a functional role in improving precision grasping performance by forming geometric constraints on the grasped object, suppressing finger pulp deformation. In future studies, the effects of skin thickness and nail length on finger pulp deformation and the analysis for critical design parameters for stable grasping of objects should be investigated. In addition, quantitative comparisons and experimental comparisons with human fingers, including stress distributions at finger pulp, is important future work.

Author Disclosure Statement

No competing financial interests exist.

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