Experimental investigation of effect of fingertip stiffness on friction while grasping an object

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Abstract— **In this study, we experimentally investigated the effect of robot fingertip stiffness on friction during grasping of an object. To make robots more human-friendly, robotic hands with soft surfaces have been developed. A soft fingertip, i.e., one with low stiffness, is considered desirable because it produces high friction. However, in our experiments, we were able to obtain high friction from a stiff fingertip under a certain condition. We initially investigated the maximum resistible force when solid objects with different angled surfaces were grasped by spherical fingertips of different stiffness. When the contact surface was flat, a stiffer fingertip produced larger frictional force. When the contact surface was highly convex, the maximum frictional force increased with decreasing fingertip stiffness. Secondly, we examined the relationships among the contact area, the load, and the maximum frictional force. We reformulated the relationship between the load and the maximum frictional force and, together with our experimental results, used it to determine the factor that increased the maximum frictional force.**

I. Introduction

There have been recent demands for robots that are capable of working among humans. The hands of such robots play an essential role in supporting human activity and replacing humans in the performance of everyday tasks. For robotic hands to perform such tasks, planning of the grasp [1] is important and several libraries and software have been developed for this purpose. Typical examples are Graspit [2], Openrave [3], and GraspPlugin for Chorenoid [4]. The frictional conditions are important in grasp planning because they determine whether the robotic hands would be able to grasp the target object. The frictional conditions are based on the Amontons-Coulomb friction model. It is valid for contacts between solid surfaces. However, a robotic hand cannot always produce sufficiently large frictional force for the stable grasping of a solid surface. To increase the frictional force while also taking affinity for humans into consideration, robotic hands with soft fingertips were recently developed [5], [6]. In this case, the contact is referred to as soft-finger contact [7]. The Amontons-Coulomb model is also considered valid for this contact. Unfortunately, it is not true for a fingertip with low stiffness [8]. Furthermore, considering that high fingertip stiffness affords relatively high manuability and low fingertip stiffness produces large frictional forces [9], robotic hands with changeable fingertip stiffness have been developed [6], [10]. However, the determination of the low fingertip stiffness that will produce a large frictional force is intuitive, and it is uncertain whether a low fingertip stiffness can actually produce large frictional forces. For reasonable grasp planning, a more detailed analysis of a soft finger is required. In this study, we investigated the effect of the fingertip stiffness on the frictional shear/tangential force.

Analyses of soft fingers were conducted by Kao et al. [8], [11], [12] and Hirai et al. [13], [14]. Xydas and Kao [11] presented the relationship between the normal force and the radius of the contact area when a semispherical fingertip contacts a flat surface, and used it to develop a model of the frictional condition. Kao et al. [12] presented the relationship between the normal force and the deformation when a semispherical fingertip contacts a flat surface. Inoue and Hirai presented a model that considered both the normal and the tangential deformations. Tiezzi et al [8] presented a model of the frictional force and examined the effect of the fingertip compliance. Based on their theoretical and experimental results, they concluded that, if the fingertip stiffness was low, a large frictional force could be applied. However, as we will show in this paper, this is not always true. Ho and Hirai presented a cantilever model of a soft fingertip, but their interest was sliding contact.

In a study in the field of tribology, the mechanics of the contact and friction of rubber were analyzed [15]. However, the interest was kinetic friction and not static friction. Generally, kinetic friction is more important in the tribology field. There have been very few studies on static friction in the tribology field. Deladi et al. [16] analyzed the static friction between rubber and metal objects. However, the stiffness of the materials was not considered. In his dissertation [17], the similar numerical and experimental results to Tiezzi et al [8] were presented: if the fingertip stiffness was low, a large frictional force could be applied. As mentioned above, this is not always true. Stiffness was not his main interest issue and there is no theoretical analysis on the stiffness. Derler and Gerhardt [18] reviewed about friction of human skin, but any researches on the stiffness were not found.

With this in mind, we experimentally investigated the effect of fingertip stiffness on frictional force. We examined the maximum resistible force when grasping a solid object with several angled surfaces by fingertips of varying stiffness. We used the results to examine whether the ability of a low fingertip stiffness to produce a large resistible force depended on the shape of the contact surface. Specifically, under a particular condition, the frictional/resistible force increases with increasing fingertip stiffness. This phenomenon cannot be explained by conventional theories [8], [17] or a model based on the Hertz contact theory (for an example, see [19]). The resistible force consists of the frictional and (tangential) elastic forces, with the shearing frictional force constituting the major

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and fundamental part. We also examined the relationship between the apparent contact area and the load, and that between the maximum frictional/shear force and the load, for varying fingertip stiffness. We reformulate the relationship between the maximum frictional/shear force and the load and, together with our experimental results, use it to investigate which factor increased the frictional force with increasing fingertip stiffness, and which factor increased the frictional force with decreasing fingertip stiffness.

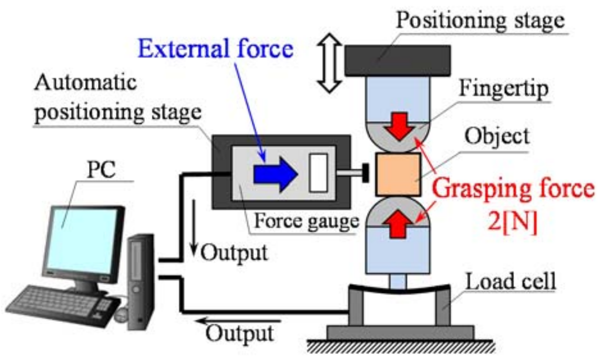

Figure 1. Schematic illustration of the experimental set up used to investigate the effect of the fingertip surface and the shape of the object surface on the maximum resistible force

TABLE I. COMPOSITION RATIO AND MATERIAL OF THE FINGERTIP

Fingertip	Silicon	Hardener	Hardener Volume [%]
S1	KE-1308	CAT1300	6
S2	KE-1308	CAT1300L-3	6
S3	KE-1316	CAT1300	10
S4	KE-1300T	CAT1300	10

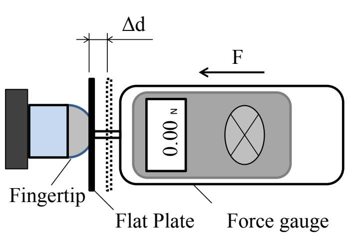

Figure 2. Compression test setup.

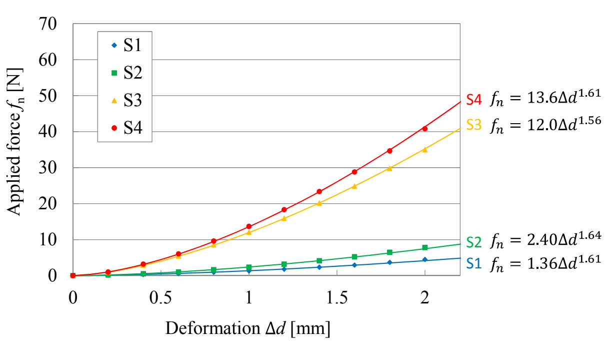

Figure 3. Force-deformation curve.

II. MAXIMUM RESISTIBLE FORCE: A SOLID OBJECT WITH SEVERAL ANGLED SURFACES IS GRASPED BY SEMISPHERICAL FINGERTIPS OF VARYING STIFFNESS

One of the most important factors of grasping stability is the magnitude of the force that the grasp can resist [1]. Regarding this factor, the magnitudes of the generable frictional and elastic forces in the tangential direction are important and are affected by the fingertip stiffness and the surface conditions. We investigated the variation of the maximum resistible force in the tangential direction with the fingertip stiffness and the shape of the object.

A. Experimental set up

Fig.1 is a schematic view of experimental set up for the investigating the effect of the fingertip stiffness and the shape of the object surface on the maximum resistible force. The object was grasped by two fingertips in antipodal postures. The magnitude of the grasping force was 2[N], which was measured by a load cell and controlled by the positioning stage. Conversely, an external force was applied to the object from the side such that the directions of the grasping force and the applied external force were perpendicular to each other. The external force was applied through a force gauge used for measuring the magnitude of an external force. The force gauge was attached to the automatic positioning stage. The speed of the automatic positioning stage was set to 5.0[mm/s] and the external force was increased. The external force was increased until the grasp failed. We measured the maximum external force at this point, which is the maximum resistible grasping force. We conducted the same experiment five times for each pair of fingertips and object.

B. Fingertips and objects

Fingertips of four different stiffness values were used. The fingertips were identified as S1, S2, S3, and S4. We made them from silicon and a harder, both of which were produced by Shin-etsu Silicone Company. The composition ratios are shown in Table I. The radius of the semi-sphere was 11[mm]. To generate the same tribological surface condition, the fingertips were covered by a thin latex rubber. We conducted a compression test and experimentally investigated their stiffness. Fig.2 shows the experimental setup. We fixed the fingertip and pushed and deformed its surface by using a flat plate attached to a force gauge (IMADA DS2-50N). Fig.3 shows the results. The markers show the experimental results, whereas the curves are the regression curves obtained using the equation presented by Kao [12]:

$$f_n = C\,\Delta d^{\zeta}. \tag{1}$$

where f_n is the applied force, Δd is the deformation, and C and ζ are parameters. The values of the parameters were obtained by the least squares method. It can be seen that the ascending order of stiffness is S1, S2, S3, and S4.

Fig.4 shows the photos of the objects being grasped by four fingertips of different stiffness values. The four objects were different: their surface angles at the contact areas were 180°, 150°, 120°, and 90°, respectively. All the objects were made from duralumin and weighed 3.0[g] each. Their shapes were the same but their contact surfaces were different. The distance between the apices of the grasping points/areas was 20[mm] and the distance between the other sides was 10[mm].

C. *Experimental results and discussion*

Fig.5 shows the results. The mean value and standard deviation for each setting are shown. When the contact surface angle of the grasped object was 180°, the maximum resistible force increased with increasing fingertip stiffness. This contradicts intuitive expectation and the findings of conventional studies [8], [17]. When the object with a contact surface angle of 150° was grasped, the maximum resistible force decreased with the fingertip stiffness in the order S2, S1, S3, and S4. Comparison of the results for a contact surface angle of 180°, reveals that the maximum resistible force decreases drastically when grasping using S3 and S4, whereas that does not when grasping using S1 and S2. It can be seen from Fig.4 that the contact area when grasping the object with a surface angle of 150° using S3 or S4 is much smaller than that when grasping the object with a contact surface angle of 180°. It is our consideration that the decrease in the contact area significantly affects the magnitude of the maximum resistible force. The difference between the contact areas for grasping using fingertip stiffness of S1 and S2 is not very large, and the difference between the magnitudes of the maximum resistible force is also small. When grasping the object with a contact surface angle of 120°, the difference between the maximum resistible forces for S1 and S2 is very small, and the descending order of the maximum resistible forces is S1/S2, S3, and S4. When grasping the object with a contact surface angle of 90°, the descending order of magnitudes of the maximum resistible force is S1, S2, S3, and S4. In this case, the magnitude of the contact area might strongly affect the magnitude of the maximum resistible force (see also Fig.4). With decreasing contact surface angle (increasing steepness of the object surface), the magnitude of the contact area might become more important to achieving a large resistible force.

Conversely, if the fingertip is fixed to investigate the effect of the contact surface angle, different results would be obtained. Considering the case of grasping with the S1 fingertip, the maximum resistible force increases with decreasing contact surface angle. This might be due to the increase in the area/volume that the fingertip envelopes with decreasing contact surface angle. When grasping with the other fingertips, the maximum resistible force decreases with decreasing contact surface angle (increasing steepness of the object surface). The rate of the decrease increases with increasing fingertip stiffness. This suggests that to ensure stable grasping, the corners of the fingertips should not be used except when they are very soft. As can be seen from Fig.4, with decreasing softness, the fingertip is more easily able to envelope the apex of the surface, and can achieve larger contact area. This might affect the results.

III. Investigation of the Contact Area and Maximum Static Frictional Force of a Flat Contact Surface

As described in the previous section, we obtained results that contradicted those of conventional studies [8], [17], especially when grasping the flat area of an object. In addition, the contact between the fingertip and a flat surface is fundamental, and the effect of the elastic force in the tangential direction can be neglected in the macroscopic range; only the frictional/shear force need be considered. We therefore conducted a more detailed investigation of this case by experimentally examining the contact area and the maximum frictional/shear force.

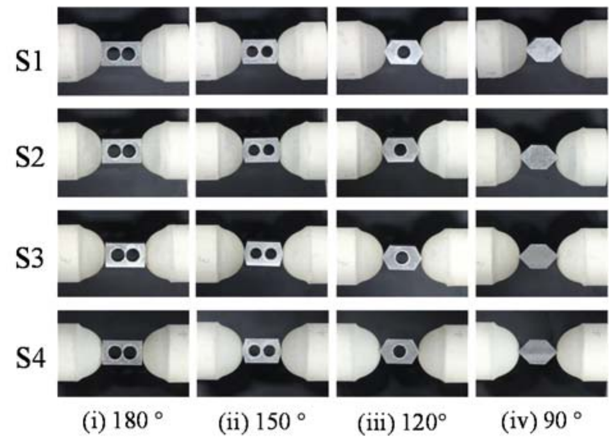

Figure 4. Photos of the grasp. The fingertips are identified as S1, S2, S3, and S4, with the respective numbers corresponding to the magnitudes of ther stiffness (S1 is the lowest and S4 the highest). The objects are of four types and their surface angles in the contact areas are respectively 180°, 150°, 120°, and 90°.

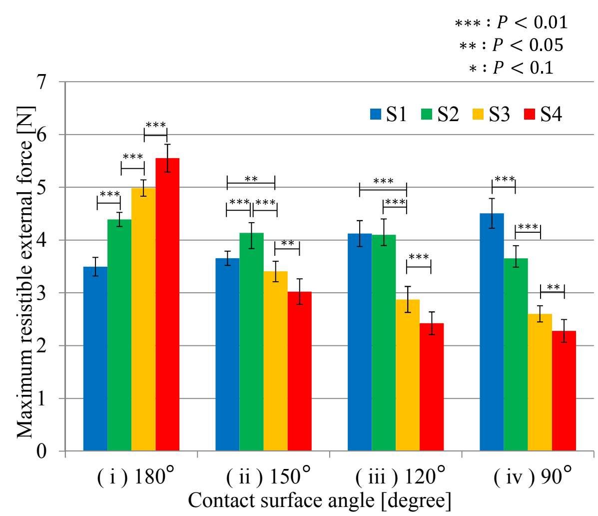

Figure 5. Maximum resistible external force for grasping an object. The ascending order of the fingertip stffness is S1, S2, S3, and S4, and the contact surface angles of the objects are respectively 180°, 150°, 120°, and 90°.

A. *Investigation of the contact area*

A schematic illustration of the experimental setup is shown in Fig.6. We daubed the fingertip with colored ink and used it to touch a sheet placed on the stage so that the area of the sheet that was colored by the ink corresponded to the contact area. The load was applied from the upper side using a weight and a linear guide as shown in Fig.6. The applied loads were 5, 10, 20, 30, and 50 [N]. The applied fingertips were the same as those in the previous section: S1, S2, S3, and S4. After loading, we measured the radius of the colored area (contact area) on the sheet. Fig.7 shows the results, where the markers are the measured values and the curves are the regression curves. The equation of the regression curves was presented by Xydas and Kao [11]:

$$r = D\, {f_n}^{\gamma}. \tag{2}$$

where r is the radius of the contact area, and D and γ are parameters. The parameter values were obtained by the least squares method. It can be seen that, if the fingertip stiffness is low, the radius would be large.

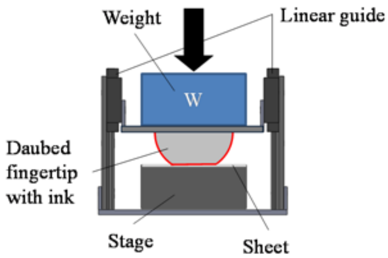

Figure 6. Shematic illustration of the experimental setup for investigating the contact area. The fingertips contact the flat surface.

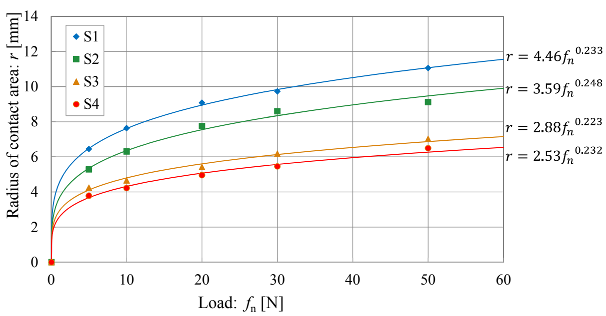

Figure 7. Load (applied force) versus radius of the contact area.

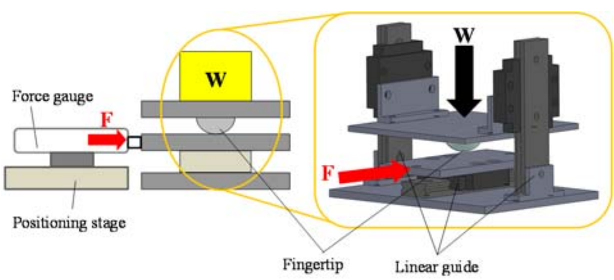

Figure 8. Shematic illustration of the experimental setup for investigating the static maximum frictional force. The fingertips contact the flat surface.

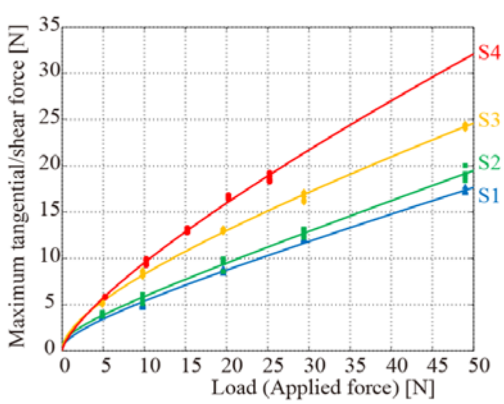

Figure 9. Load (applied force) versus maximum tangential/shear force.

B. *Investigation of maximum frictional/shear force*

The schematic view of experimental set up is shown in Fig.8. In the experimental set up shown in Fig.6, we added another linear stage such that we can measure tangential/shear force. We connect the added linear guide and force gauge. The force gauge is attached on positioning stage, and by controlling the stage, we applied tangential/shear force to the contact area between fingertip and the plate (made of duralumin) attached on the linear guide. Normal force is applied to the contact area by controlling the weight placed on the plate connected to the two other linear guides. The used fingertips are S1, S2, S3 and S4. The applied weight was 0.5, 1.0, 2.0, 3.0 and 5.0 [Kg] for S1, S2 and S3, and 5.24, 10.24, 20.24 and 30.24 [N] for S4 (note that the difference of the setting is due to the usage of different plate for attaching the fingertip). If increasing the applied tangential/shear force, the slide occurs at the contact area. At that time, we can measure maximum tangential/shear force. We examined the maximum tangential/shear force. We repeated five times for each set up. It should be noted that the investigation of the adhesion force when every fingertip contacted the plate was targeted at determining the effect of the properties of the contact surface such as the roughness. The measured values ranged between 1 and 3 [mN]. These values are very small and their effects are hereafter neglected.

Fig.9 shows the results, where the markers indicate the experimental results and the curves are the regression curves (the equation of the regression curves will be described later). It can be seen that the maximum frictional/shear force actually increases with increasing fingertip stiffness.

C. *Discussion*

According to tribology theory [19], the maximum static frictional force is given by

$$f_t = sA_r \tag{3}$$

where f_t is the maximum frictional force (shear force), s is material shear stress, and A_r is the real contact area. If the material is a polymer (for example, silicon), the shear stress can be expressed as

$$s = s_0 + ap_r \tag{4}$$

where p_r is the mean pressure on the real contact area A_r, and s_0 and a are material constants. If A represents the apparent contact area, and p the mean pressure on the apparent contact area A, then

$$f_n = A_r p_r = Ap. \tag{5}$$

The real contact area A_r increases with increasing load (normal force) f_n because the likelihood of contact increases under a high local pressure. Therefore, considering (2), we suppose that $A_r \propto {f_n}^{\alpha}$; hence

$$A_r = b{f_n}^{\alpha}. \tag{6}$$

where α and b are parameters. From (3), (4), (5), and (6), we obtain

$$f_t = \tau_0 {f_n}^{\alpha} + af_n \tag{7}$$

where $\tau_0 = s_0 b$. This is the equation of the regression curves in Fig.9. The parameter values for the regression curves are listed in Table II. They were obtained using the curve fitting toolbox in Matlab (MathWorks). If (7) is divided by f_n, we obtain

$$\mu = \frac{f_t}{f_n} = \frac{\tau_0}{{f_n}^{1-\alpha}} + a \tag{8}$$

It should be noted that, here, $0 \leq \alpha \leq 1$, and if $\alpha = 1$, (8) will be the same as the Amontons-Coulomb friction model. As can be seen from Fig.9 and Table II, the Amontons-Coulomb model cannot be used to represent the phenomenon. Most grasp planning [1-4] are based on the Amontons-Coulomb model. The presented results suggest the necessity of a careful consideration of friction in grasp planning. Table II and (8) indicate that, if the load (normal force) becomes very large, μ would converge to a, in which case the fingertips with relatively low stiffness produce larger frictional force. When fingertips with relatively small stiffness (S1 and S2) are used, the values of τ_0 and α would not be high, and it is easier for μ to converge to a. As can be seen from Fig.7, the radius of the contact area converges faster to a constant value with increasing load. This might affect the relatively fast convergence of μ to a. However, if the load (normal force) is not large, the effects of τ_0 and α would be significant. The fingertips with relatively high stiffness would therefore produce larger frictional forces.

Focusing on A_r and A, equations (2) and (7) can also be expressed as

$$f_t = s_0 \frac{A_r}{A} A + a f_n = s_0 \frac{A_r}{A} \pi D^2 {f_n}^{2\gamma} + a f_n$$

Here, A_r/A is the ratio of the real contact area to the apparent contact area. Because both A_r and A are power functions of f_n, we can define the following:

$$s_0 \frac{A_r}{A} = b_0 {f_n}^{\beta} \triangleq \tau. \tag{9}$$

We then have

$$f_t = \tau A + a f_n = b_0 {f_n}^{\beta} \cdot \pi D^2 {f_n}^{2\gamma} + a f_n \tag{10}$$

where

$$b_0 = \frac{\tau_0}{\pi D^2} = \frac{s_0 b}{\pi D^2},\ \beta = \alpha - 2\gamma.$$

The values of b_0 and β for each fingertip can be calculated from the data in Fig. 7 and Table II. Table III gives the calculated values. If $\beta = 0$, then (10) becomes the same as the model presented in [8]. It can be seen from Table III that $\beta \cong 0$ for S1 and S3, for which the model presented in [8] is valid. However, this is not the case for S2 and S4. It can be seen from the results for S1 and S2 in Fig.7 and Fig.9 that the relationship between the load and the maximum shear/frictional force is close, whereas the relationship between the load and the radius of the contact area is not. Therefore, the model presented in [8] does not represent the phenomenon in the case of S2. It is also true for S4. It can be said that the model expressed by (7) comprehensively represents the phenomenon.

From Table II, it can be seen that $\tau_0 > a$ can be seen. We therefore focus on the term $\tau_0 {f_n}^{\alpha}$ in (7). $\frac{A_r}{A}$ in (9) is relatively large when the fingertip stiffness is high because the real contact area A_r is related to the magnitude of the local pressure, whereas the apparent contact area A is relatively small when the fingertip stiffness is high. It can therefore be said that τ, defined by (9), increases with increasing fingertip stiffness. As mentioned above, and from Fig.7, the apparent contact area A increases with decreasing fingertip stiffness. Therefore, if the effect of τ in (10) is relatively strong, the maximum frictional/shear force increases with increasing fingertip stiffness. This corresponds to the case when the contact surface of the object is flat (contact surface angle of 180° in Figs. 5 and 9). If the effect of A in (10) is relatively strong, the maximum frictional/shear force increases with decreasing fingertip stiffness. This might be the case for a 90° contact surface angle in Fig.5. The intermediate case may correspond to a contact surface angle of 150° or 120° in Fig.5.

It can be seen from Table III that the sign of β is positive when the fingertip stiffness is high, whereas it is negative when the fingertip stiffness is low. Also, with increasing load, τ in (9) decreases when the fingertip stiffness is low, and increases when the fingertip stiffness is high. This suggests that, if the fingertip stiffness is low, increasing the load would increase the importance of the contact area in achieving a large maximum static frictional force.

TABLE II. PARAMETERS τ_0, α, AND a IN (7) FOR THE REGRESSION CURVES IN FIG.9. $f_t = \tau_0 {f_n}^{\alpha} + a f_n$ (R^2: COEFFICIENT OF DETERMINATION, RMSE: ROOT MEAN SQUARED ERROR)

Fingertip	τ_0	α	a	R^2	RMSE
S1	1.17	0.409	0.237	0.996	0.358
S2	1.49	0.290	0.297	0.994	0.457
S3	1.92	0.501	0.218	0.998	0.309
S4	1.61	0.683	0.175	0.994	0.397

TABLE III. PARAMETERS b_0 AND β IN (9)

Fingertip	b_0	β
S1	0.0188	-0.0564
S2	0.0367	-0.206
S3	0.0739	0.0559
S4	0.0797	0.220

TABLE IV. PARAMETERS d AND δ IN (11) (R^2: COEFFICIENT OF DETERMINATION, RMSE: ROOT MEAN SQUARED ERROR)

Fingertip	d	δ	R^2	RMSE
S1	0.973	0.738	0.994	0.384
S2	1.05	0.744	0.992	0.514
S3	1.74	0.675	0.998	0.350
S4	1.71	0.746	0.994	0.381

D. Approximate relationship between the load and the maximum static frictional force

(7) given in the previous subsection is useful for comparison and discussion, but practically not easy to cope with since there are multiple terms. Here, we consider another relationship between load and maximum static friction force. By directly considering (3) and (6), we can have

$$f_t = d {f_n}^{\delta} \tag{11}$$

where d and δ are parameters, the values of which are listed in Table IV. They were obtained using the curve fitting toolbox in Matlab (MathWorks). Comparing R^2 and RMSE in Tables II and III, (11) can be appropriately used to represent the relationship, although the fitting is poorer than or equal to that of (7).

E. *Remarks on how to deal with the friction condition in grasp planning*

To consider the friction condition in grasp planning, it may be easier to use (11) than to use (7). Our remarks here are based on (11). As can be seen from Table IV, δ in (11) is less than 1. Supposing that d is the coefficient of friction, when the normal force is increased, the assumed maximum usable frictional force is larger than what is actually available. Hence, for grasp planning, the assumed available maximum normal force should be used. If the value of the maximum normal force ($f_{n_{max}}$) is set, (11) can be approximated

$$f_t = (d(f_{n_{max}})^{\delta-1})f_n \tag{12}$$

It should be noted that $d(f_{n_{max}})^{\delta-1}$ is constant. Hence, by assuming $d(f_{n_{max}})^{\delta-1}$ the frictional coefficient, the conventional grasp planning strategy can be used.

IV. Conclusion

In this study, we experimentally investigated the effect of fingertip stiffness on the maximum static frictional force, for the purpose of developing stable object grasping using soft fingertips. We first showed the experimental results regarding how a large external force can be resisted by a grasp. We also noted that for a non-flat contact surface, the maximum resistible force consisted of the tangential elastic and static frictional forces. For the experiments, we used objects with different surfaces grasped by fingertips of different stiffness. We examined the effects of the fingertip stiffness and the shape of the contact surface of the object. We found that when the contact surface was flat, the maximum static frictional force (resistible force) increased with increasing fingertip stiffness. We found that, if the contact surface was convex and its angle steep, the maximum resistible force increased with decreasing fingertip stiffness. Conversely, we found that when the fingertip was stiff, the maximum resistible force decreased with increasing steepness of the contact surface angle. However, when the fingertip was soft, the maximum resistible force increased with increasing steepness of the object surface.

We conducted a more detailed experimental investigation of the relationship between the maximum static frictional force and the normal force using different fingertip stiffness. The experimental results revealed that the maximum frictional force depended on the contact area and shearing parameter τ defined by (9). If the effect of τ is strong, the maximum frictional force would increase with increasing fingertip stiffness. However, if the effect of the apparent contact area is strong, the maximum frictional force would increase with decreasing fingertip stiffness.

We also presented a simple relationship between the maximum static frictional force and the normal force for easy consideration of friction in grasp planning and made some remarks about dealing with friction in grasp planning.

Grasp panning also requires the condition of the frictional moment about the normal direction [1]. A detailed investigation of cases of objects with convex surfaces was not conducted in this study. We will experimentally analyze such cases in a future work.

Acknowledgment

The authors would like to thank Mr. Ryosuke Arima and Mr. Masahiro Uchida for helping this work by making experimental setup and conducting experiments.

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