

Experimental Investigation of Effect of Fingertip Stiffness on Resistible Force in Grasping

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Abstract— In this study, we experimentally investigated the effect of robot fingertip stiffness on the maximum resistible force. The maximum resistible force is defined as the maximum tangential force at which the fingertip can maintain contact when applying and increasing tangential/shearing force. We include in the definition of this term the effect of fingertip deformation. In contrast to our previous study [11], cylindrical fingertips with flat surfaces were used in this study so that the contact area would remain the same when there was no tangential/shearing force. This made it possible to see the effect of fingertip stiffness more clearly. We also investigated the effect of curvature of the contact surface, which was not investigated in depth in [11]. The main findings are as follows. 1) Harder fingertips produce larger resistible forces, irrespective of the shape of the contact surface (flat or curved). 2) For harder fingertips, the maximum resistible force depends largely on the shape of the contact surface, while for softer fingertips, the shape has little effect. 3) For softer fingertips, the magnitude of the resistible force changes little even when the normal force increases.

I. INTRODUCTION

In recent years, robots have been required to be capable of working in human society. Among the key functions of such robots are activities, including everyday tasks that humans perform with their hands. A basic hand task is grasping, and grasp planning [1, 2] is important for robotic hands. Several libraries and softwares for grasp planning have been developed. Graspit [3], Openrave [4], and GraspPlugin for Chorenoid [5] are well known. In grasp planning, friction is a key issue because friction is embedded in criterion function associated with grasp stability in grasp planning [1, 2]. The well-known Amontons–Coulomb friction model is widely used in grasp planning. Early application of this model to grasp planning pertained to contact between solid surfaces. More recently, robotic hands with soft fingertips have been developed to increase friction and affinity for humans [6], [7], [8]. Therefore, frictional conditions for soft fingertips must be developed. Frictional conditions for soft fingertips, based on the Amontons–Coulomb friction model, have been proposed

[9]. However, these conditions do not apply to fingertips with low stiffness [10]. In addition, the relation between stiffness and friction is unclear. With this in mind, we experimentally investigated this relation in a previous study [11]. We found that harder fingertips produce larger frictional (resistible) forces on flat surfaces than softer fingertips. However, the results obtained are very limited. In the experiments, semispherical fingertips were used, so the contact area depended on the fingertip stiffness. The contact area is closely related to the frictional forces achieved. Therefore, it remained unclear whether fingertip stiffness was a significant and direct factor in the results obtained. In addition, deformation in the tangential contact direction was not considered. We also did not investigate the effect of curvature of the contact surfaces in detail. We investigated cases in which contact surfaces were angled, but the normal force/load was fixed at 2 [N]. Furthermore, we did not consider cases in which the contact surfaces were curved, which the surfaces of many articles that must be manipulated by hand in everyday life are.

With this in mind, in this study, we experimentally investigated the **resistible forces** that result when cylindrical fingertips of various stiffnesses with flat contact surfaces are in contact with flat and curved surfaces. The contact area was the same irrespective of the magnitude of the normal force (load) and the stiffness when a tangential/shearing force was not applied. When the normal force was applied, the cylindrical silicone fingertips swelled to the shape of a barrel, while deformation of the contact surface was negligible due to the contact constraints.

In fingertips with low stiffness, deformation in the tangential contact direction could occur and affect the magnitude of the maximum static frictional force. Unlike in studies focused only on the contact area, in grasping or robotic hands, fingertips have volume, and thus, deformation of fingertips affects the magnitude of the maximum tangential force, which is the maximum force at which the fingertip can maintain contact while applying and increasing a tangential/shearing force. Whether the effect should be included in the frictional force is a divisive issue. In this paper, we define the **maximum resistible force as the maximum tangential force at which the fingertip can maintain contact**. The resistible force could include not only the frictional force but also the force resulting from fingertip deformation. For the purposes of grasp planning, we want to know how much the magnitude of an external force can be balanced, i.e., how heavy an object can be grasped. Thus, the force that a grasp planner needs to know is not the frictional force without the force resulting from fingertip deformation but rather the resistible force. The focus of this investigation

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was therefore the resistible force. The main findings obtained are as follows:

1. Harder fingertips produce larger resistible forces, irrespective of the shape of the contact surface (flat or curved).
2. For harder fingertips, the maximum resistible force depends largely on the shape of the contact surface, while for softer fingertips, the shape has little effect.
3. For softer fingertips, the magnitude of the resistible force changes little even when the normal force increases.

A. Related works

In the robotics, analyses of soft fingers, including modeling and experimental investigations, have been conducted by Kao et al. [9], [12], [13], Hirai et al. [14], [15], Ciocarlie et al. [16] and Watanabe et al. [8], [11], [17]. Except in [9] and in our previous study [11], the relationship between the finger stiffness and the resistible/frictional force has not been examined. In contrast to our previous study [11], Tiezzi et al. reported that a low fingertip stiffness produces a large frictional force. In the tribology field, Persson [18] has analyzed the kinetic friction between rubber and metal objects, and Deladi et al. [19] have analyzed the static friction between rubber and metal objects. In general, kinetic friction is more important in the tribology field. Hence, in the tribology field, there have been very few studies of static friction, which is more important in grasping than kinetic friction is. Deladi [20] presented numerical and experimental results similar to those obtained by Tiezzi et al. [10] that showed that low fingertip stiffnesses produce large frictional forces. As mentioned above, this is not consistent with our previous experimental results [11]. However, fingertip stiffness was not the main focus of that study, and no detailed analysis of fingertip stiffness was conducted as a part of that study. One reason for this discrepancy might be that in these studies [10], [11] the effects of deformation around/near the contact surfaces could be neglected. Derler and Gerhardt [21] reviewed of the literature on human skin friction but did not find any studies on the relationship between fingertip stiffness and frictional force.

II. MAXIMUM RESISTIBLE FORCE BETWEEN FINGERTIP AND FLAT CONTACT SURFACE

In this study, we examined the maximum resistible force produced when soft fingertips with various stiffnesses pressed on a flat surface. The maximum resistible force is defined as the maximum external force on the surface (object) under which the fingertip can maintain contact [1]. The resistible force basically corresponds to the frictional force. However, if the fingertip or object is soft, deformation of either also affects the resistible force. In this case, we should consider not the frictional force but the resistible force for real grasping problems. Therefore, we use the term “resistible force” to distinguish the resistible force from the frictional force. In our previous study [11], we investigated the maximum resistible force produced when semispherical fingertips with various stiffnesses pushed several edged surfaces. When semispherical fingertips are used, the contact area changes with the fingertip stiffness and the normal forces. A change in the contact area makes the effect of fingertip stiffness on

friction unclear. To eliminate the effect of changes in the contact area, cylindrical fingertips, which have constant contact areas irrespective of the fingertip stiffnesses and normal forces, were used in this experiment.

A. Experimental Setup

Fig. 1 is a schematic view of the experimental setup used to investigate the effect of fingertip stiffness on the maximum resistible force when a fingertip pushes on a flat surface. Fig. 2 is a photograph of the experimental setup. In a typical test, a fingertip was pressed vertically downward on an acryl plate while a tangential force was applied to the acryl plate. An automatic positioning stage was used to press the fingertip against the acryl plate. The fingertip was attached to a hand-made load cell unit (0–50 [N]) attached to the automatic positioning stage. The load cell unit was used to measure and control the magnitude of the pressing force, which is the normal force. The fingertips used were made of silicone. Another automatic positioning stage was used to apply the tangential force to the acryl plate. A force gauge (IMADA DS2-50N) was attached to the positioning stage to measure the magnitude of the tangential force on the acryl plate. As shown in Fig. 2, the acryl plate was transparent, which made it possible to observe the contact area using a camera positioned under the acryl plate.

We increased the tangential/shearing force by moving the automatic positioning stage at a speed of 1 [mm/s] until slippage occurred. We defined the measured tangential/shear force at that time as the maximum resistible force. The normal force levels applied were 1, 2, 5, 10, 15, and 20 [N].

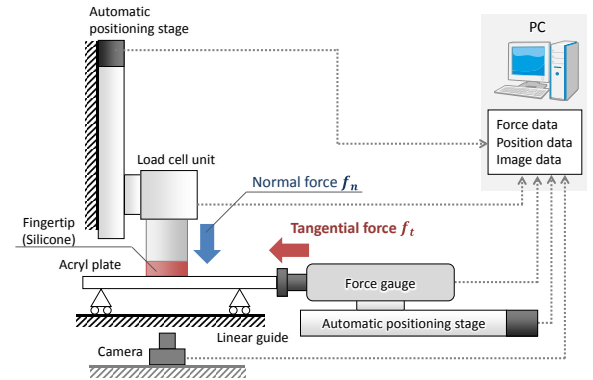


Figure 1. Schematic illustration of the experimental setup for investigating the effect of fingertip stiffness on the maximum resistible force when the fingertips push against a flat surface.

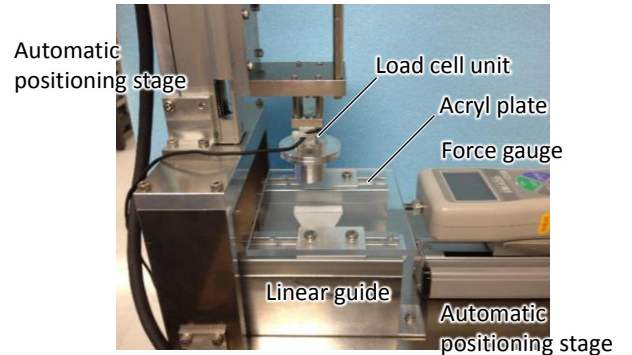


Figure 2. Photo of the actual experimental setup

We repeated each test three times. The frictional force of the linear guide attached to the acryl plate was measured beforehand to eliminate its effect.

B. Fingertip and Surface Shape

We used the silicone fingertips shown in Fig. 3 in this study. Based on the size of the semispherical finger used in the previous study [11], we chose to use fingertips with diameters and heights of 22 [mm] and 11 [mm], respectively. We made the fingertips from base materials and hardeners, both of which were produced by the Shin-etsu Silicone Company. Fingertips with different stiffnesses can be made by changing the ratios of the component materials used. To make observation of the contact area easier, the fingertips were colored red.

We conducted compression tests, as illustrated in Fig. 4, to measure the stiffnesses of the fingertips. Fig. 5 shows the results of the compression tests. The markers represent the experimental results, whereas the curves are regression curves obtained using the model form proposed by Kao [13]:

$$f_n = C \Delta x^\zeta \quad (1)$$

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

C. Experimental Results and Discussion

Fig. 6 is an example of time series data for the tangential force for S2. The arrows point to the first peak of each curve, which is the point at which the fingertip and the acryl plate started to slip. We obtained the maximum resistible force from the tangential force at this peak. After this peak, stick-slip can be seen from Fig. 6. Fig. 7 shows the normal force versus the maximum resistible force. The markers correspond to the experimental results, whereas the curves are regression curves

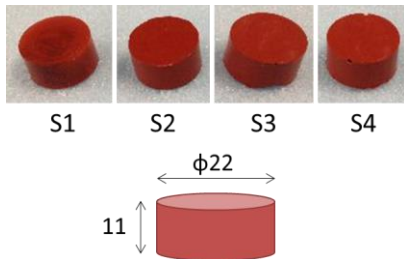


Figure 3. Silicone fingertips used in the experiments, S1, S2, S3, and S4, shown in ascending order of fingertip stiffness from left to right (see Fig. 5).

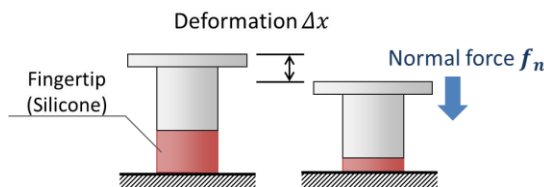


Figure 4. Compression test setup for the measurement of fingertip stiffness

obtained using the model form proposed by Watanabe [11]:

$$f_t = \tau_0 f_n^\alpha + a f_n \quad (2)$$

where f_t is the maximum resistible force, and α and a are parameters. The values of the parameters were obtained by the least squares method and are shown in Table II.

As Fig. 7 shows, higher fingertip stiffness resulted in larger resistible forces. This trend is similar to that observed for semispherical fingertips in our previous study [11]. We discussed this trend in [11] and associated differences in the contact area with differences in fingertip stiffness. In this experiment, cylindrical fingertips were used, so the contact areas were constant when there was no tangential force (in the initial state). However, when the fingertip and the acryl plate

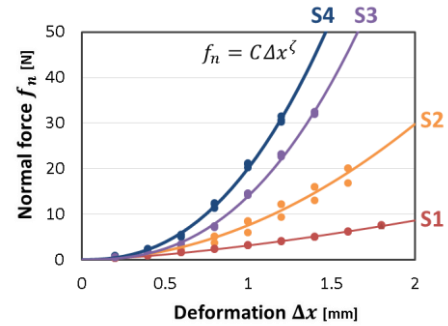


Figure 5. Force-deformation curve for the fingertip stiffness. Note that the measurement limit for the force gauge is 50 [N], and the experiments were stopped when the normal force exceeded this limit.

TABLE I. STIFFNESS PARAMETERS C AND ζ IN (1) FOR THE REGRESSION CURVES SHOWN IN FIG. 5 (R^2 : COEFFICIENT OF DETERMINATION, RMSE: ROOT MEAN SQUARED ERROR)

Fingertip type	C	ζ	R^2	RMSE
S1	3.13	1.46	0.973	1.07
S2	7.58	1.97	0.998	0.107
S3	14.0	2.52	0.997	0.600
S4	20.1	2.39	0.997	0.575

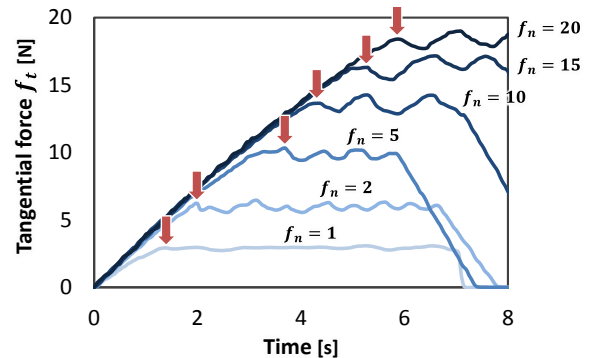


Figure 6. Time series data for the tangential force for S2. The first peak (indicated by the red arrow for each curve) is defined as the maximum resistible force..

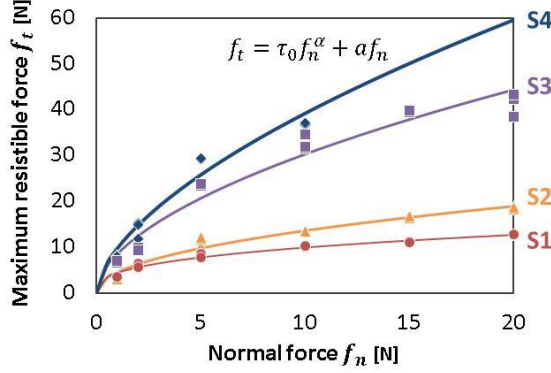


Figure 7. Normal force versus maximum resistible force. Note that when S4 was used to apply normal forces of 15 and 20 [N], the tangential force exceeded the measurement limit of the force gauge.

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

Fingertip type	τ_0	α	a	R^2	RSME
S1	4.41	0.353	1.47×10^{-10}	0.977	0.483
S2	4.54	0.477	4.48×10^{-11}	0.966	1.10
S3	8.53	0.550	6.96×10^{-9}	0.962	2.90
S4	9.76	0.604	3.08×10^{-13}	0.951	2.75

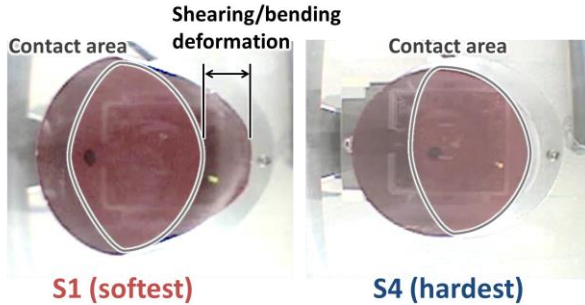


Figure 8. Photo of the contact areas (areas bordered by lines) when slip occurred between the fingertip and the acryl plate in the cases of S1 (the softest fingertip) and S4 (the hardest fingertip). For the softer fingertip, the deformation of the contact area and the shearing/bending deformation were larger.

started slipping, the shape and position of the contact area changed, as shown in Fig. 8. When a forced tangential force/displacement was applied, deformation by bending and shearing occurred in the fingertip. This deformation affected the deformation of the contact area and the stress distribution over the contact area. As Fig. 8 shows, the shearing/bending deformation and the deformation of the contact area were more evident for the softest fingertip (S1). For the hardest fingertip (S4), the change in the contact area was smaller, and shearing/bending deformation was not evident. The deformations of the softer fingertip (S1) were assumed to

reduce the magnitude of the normal stress and consequently reduce friction. On the other hand, in terms of the amount of

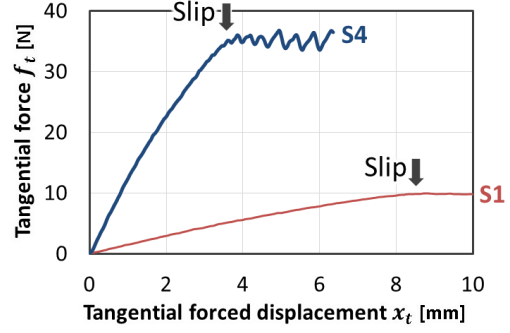


Figure 9. Tangential forced displacement versus tangential force in for cases of S1 and S4.

tangential/shearing forced displacement, the softer fingertip offers an advantage, as shown in Fig. 9. The softer finger is thus more suitable when it is necessary to resist a large forced displacement (see Fig. 9 S1), and the harder finger is suitable when it is necessary to resist a large tangential/shearing force (see Fig. 9 S4).

III. MAXIMUM RESISTIBLE FORCE WHEN FINGERTIPS PUSHED AGAINST CURVED CONTACT SURFACE

In the real world, there are objects with various shapes. Contact surfaces are not always flat. We therefore investigated the effect of fingertip stiffness on the resistible force when the fingertips were in contact with curved surfaces.

A. Experimental Setup

Fig. 10 is a schematic view of the experimental setup used to investigate the effect of fingertip stiffness on the maximum resistible force when the fingertips pushed against curved surfaces. This setup was basically the same as the setup shown in Fig. 1, except that curve surfaces were used and the camera was removed. R15 and R25 curved surface parts, shown in Fig. 11, were used. These parts were attached to the acryl plate. Because these parts' surfaces are not transparent, the contact area could not be observed, so the camera was removed. The same fingertips (S1, S2, S3 and S4) as used in the previous

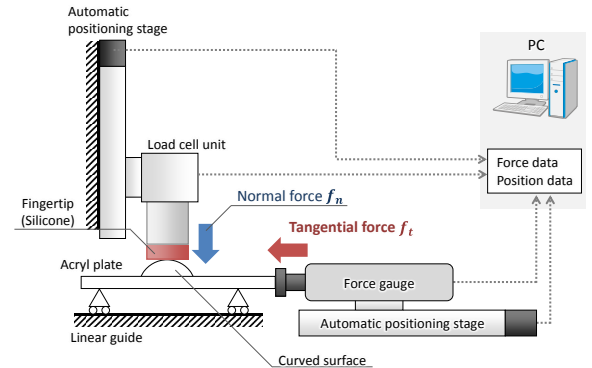


Figure 10. Schematic illustration of the experimental setup for investigating the effect of the fingertip stiffness on the maximum resistible force when the fingertips pushed against R15 and R25 curved surfaces. This setup did not

permit observation of the contact surface because the R15 and R25 curved surfaces are not transparent.

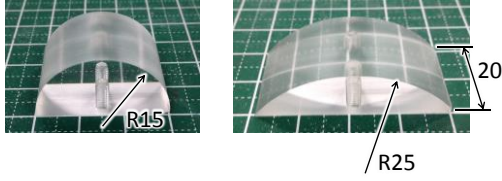


Figure 11. Photos of acrylic curved surface parts having with R15 and R25 curved surfaces. They were made of acrylic

series of tests were used in this series. The experimental procedure was also the same as that used in the previous series of tests. The speed of the positioning stage for applying the tangential force was 1 [mm/s]. We measured the maximum tangential force, which we considered the maximum resistible force, at the start of slippage. The normal force levels applied were 1, 2, 5, 10, 15, and 20 [N]. We repeated each test three times. Strictly speaking, the direction of the tangential force in this setup is only tangential at the initial state. The direction of the applied, initially tangential force could change according to the fingertip deformation and curvature of the contact surface. However, practically speaking, this alteration in direction does not occur when applying the force in the exact tangential direction, but given the impact of this direction change and its interest to many researchers, we believe a model of this system is worth exploring.

B. Experimental Results and Discussion

Fig. 12 and Fig. 13 show the normal force versus the maximum resistible force for the R15 and R25 curved surfaces, respectively. The markers correspond to the experimental results, whereas the curves are regression curves obtained using Equation (2). The values of the parameters were obtained by the least squares method and are shown in Table III and Table IV. As the values of the coefficient of determination (R^2) and the root mean squared error (RSME) show, the greater the surface curvature is, the poorer the fit of the regression equation was. The greater the curvature is, the smaller the contact area is and the easier it is for a deviation to occur. As a result, the variance of the maximum resistible force tends to be larger. This is believed to be the reason for the poorer fit of the regressions for the more curved surfaces.

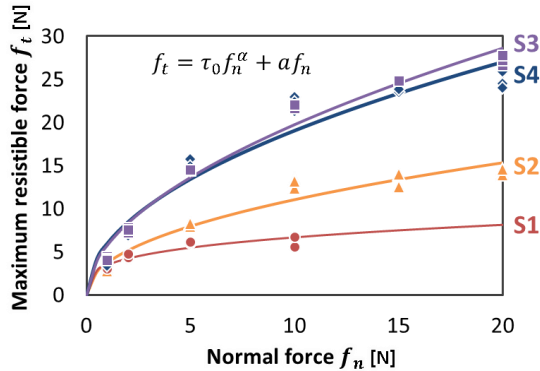


Figure 12. Normal force versus maximum resistible force for the R15 curved surface. Testing using S1 was stopped at 10 [N] because the normal deformation was excessive and breaking was observed when normal forces of 15 and 20 [N] were applied.

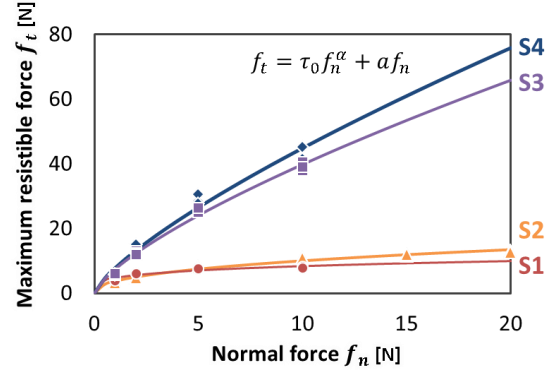


Figure 13. Normal force versus maximum resistible force for the R25 curved surface. Testing using S1 was stopped at 10 [N] because the normal deformation was excessive and breaking was observed when normal forces of 15 and 20 [N] were applied. For S3 and S4, application of normal forces of 15 and 20 [N] resulted in the tangential force exceeded the measurement limit of the force gauge.

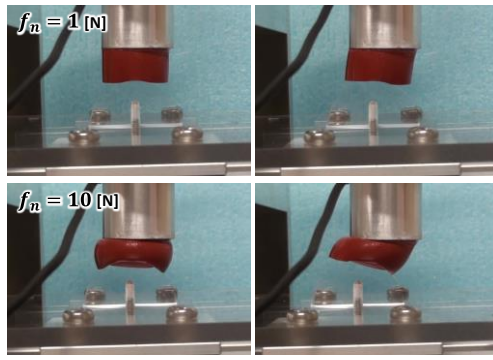
TABLE III. PARAMETERS τ_0 , α , AND a IN (2) FOR THE REGRESSION CURVES SHOWN IN FIG. 12 (R15). $f_t = \tau_0 f_n^\alpha + a f_n$ (R^2 : COEFFICIENT OF DETERMINATION, RMSE: ROOT MEAN SQUARED ERROR)

Fingertip type	τ_0	α	a	R^2	RSME
S1	3.47	0.284	1.72×10^{-12}	0.856	3.19
S2	3.72	0.472	2.03×10^{-09}	0.943	20.7
S3	5.76	0.535	9.53×10^{-09}	0.976	31.3
S4	5.97	0.504	1.31×10^{-10}	0.935	80.0

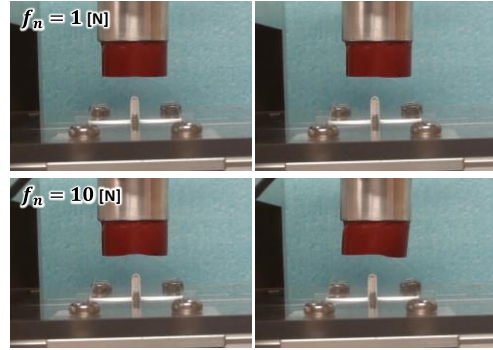
TABLE IV. PARAMETERS τ_0 , α , AND a IN (2) FOR THE REGRESSION CURVES SHOWN IN FIG. 13 (R25). $f_t = \tau_0 f_n^\alpha + a f_n$ (R^2 : COEFFICIENT OF DETERMINATION, RMSE: ROOT MEAN SQUARED ERROR)

Fingertip type	τ_0	α	a	R^2	RSME
S1	4.73	0.248	4.04×10^{-11}	0.891	2.96
S2	3.75	0.426	6.64×10^{-10}	0.970	7.37
S3	7.49	0.726	1.53×10^{-09}	0.988	22.7
S4	7.85	0.757	7.39×10^{-11}	0.980	51.6

As in the case of contact with a flat surface, the harder fingertips (S3 and S4) resisted higher tangential forces than the softer fingertips (S1 and S2) in both cases, as shown in Fig. 12 and Fig. 13. Fig. 14 and Fig. 15 are side-view photographs of the S1 (softest) and S4 (hardest) fingertips. Fig. 14 and Fig. 15 show that bending/shearing deformation (see Fig. 8 for the definition) occurred. The contact areas and bending/shearing deformation of the softer fingertips were larger than those of the harder fingertips. As shown in Fig. 16, with curved surfaces, large bending/shearing deformations can progress to slippage because of the moment produced by the deformation and the deviation of contact in the normal direction (i.e., part of the original normal force can act as a tangential force). In addition, a large contact area indicates a small normal stress/pressure on the contact area. These factors might be the reasons for harder fingertips producing larger resistible forces.

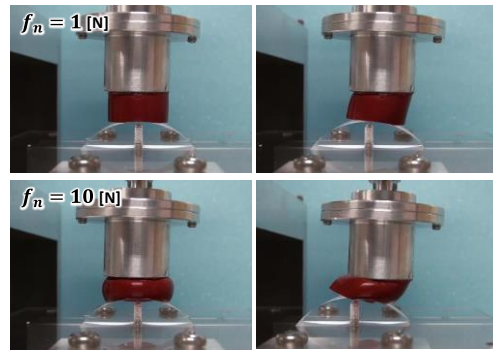


(a) S1 fingertip

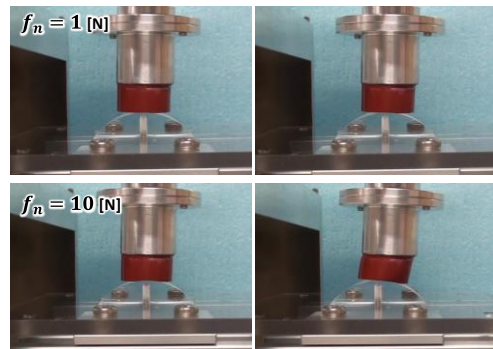


(b) S4 fingertip

Figure 14. Photo of side views of the fingertip using the R15 curved surface: initial states (left) and slip occurrence (right)



(a) S1 fingertip



(b) S4 fingertip

Figure 15. Photo of side views of the fingertip using the R25 curved surface: initial states (left) and slip occurrence (right)

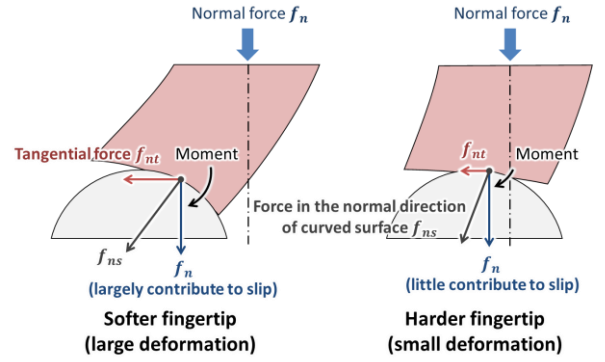


Figure 16. Schematic illustration of the states of softer and harder fingertips when pushing against a curved surface.

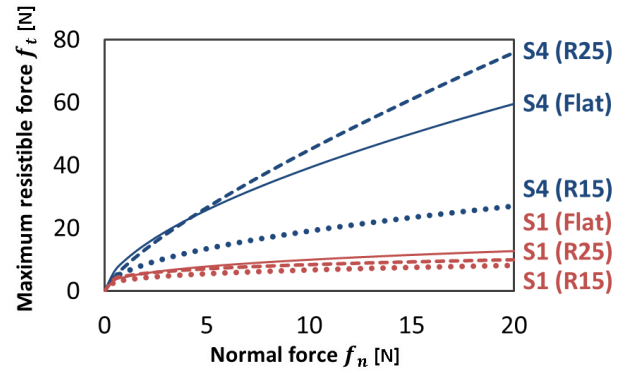


Figure 17. Comparison of maximum resistible force versus normal force for the two fingertips, S1 and S4, and the three contact surfaces: flat (solid lines), R15 (dotted lines), and R25 (dashed lines).

Other interesting points are that the ranges of the maximum resistible forces were very different and that the differences in the maximum resistible forces between S3 and S4 were small.

Fig. 17 illustrates the effect of the shape of the contact surface and shows the rearranged results for the S1 (softest) and S4 (hardest) fingertips. The results show that the softer fingertip was not greatly affected by the shape of the contact surface, while the harder fingertip was greatly affected. The maximum resistible force for the softer fingertip was not greatly affected by an increase in the normal force. As Fig. 16 shows, part of the original normal force can act as a tangential force because of large bending/shearing deformations in curved contact surfaces with softer fingertips. This might explain why the maximum resistible force does not increase much even when the normal force increases.

For hardest fingertip, the maximum resistible force for the R25 curved surface was the largest, while it was the smallest for R15. As Fig. 14 (b) and Fig. 15 (b) (at $f_n = 10$ [N]), part of the contact with the R15 surface occurred along the curved surface, and part of the original normal force can act as a tangential force in this area. This was not observed with the R25 surface (Fig. 15 (b)). These results indicate that there is a suitable curvature of the contact surface that maximizes the resistible force when a soft fingertip (with a relatively large stiffness) pushes against a curved surface.

IV. CONCLUSION

In this study, we experimentally investigated the effect of fingertip stiffness on the maximum resistible force produced when a cylindrical fingertip with a flat contact surface was in contact with a flat or curved surface. The maximum resistible force is defined as the maximum tangential force at which the fingertip can maintain contact when applying and increasing a tangential/shearing force. We include in the definition of this term the effect of fingertip deformation. The main findings are as follows.

1. Harder fingertips produce larger resistible forces, irrespective of the shape of the contact surface (flat or curved). The results for curved surfaces were somewhat different from those observed in our previous study [11]. When semispherical fingertip contacts with angled surfaces were tested in the previous study [11], softer fingertips were found to produce larger resistible force for a contact angle of 90 [degrees]. Although the experimental setups used in the two studies were different (for example, the magnitude of the normal force was fixed in [11] but varied in this study), as were the shapes of the fingertips, more detail investigations may be needed and will be conducted in our future research.
2. For harder fingertips, the maximum resistible force depends largely on the shape of the contact surface, while for softer fingertips, the shape has little effect. Of the three surfaces used in this study (one flat and two curved surfaces), the surface with the middle curvature resulted in the largest maximum resistible force for harder fingertips. How the magnitude of curvature affects the maximum resistible force will be examined in greater detail in our future research.
3. For softer fingertips, the magnitude of the resistible force changes little even when the normal force increases. This finding is very important from the perspective of grasp planning because conventional frictional coefficients cannot be used directly. The development of a new frictional model will also be a topic of our future research.

In addition to the future research needs identified above, investigation of frictional moments will be part of our future research. Both contact forces and contact moments can contribute to object grasping. Therefore, in grasp planning, both frictional forces and moments must be considered. Modeling and analytical investigations based on the experimental results will also be a part of our future work.

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