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FULL PAPER

Deformable Fingertip with a Friction Reduction System Based on Lubricating Effect for Smooth Operation under Both Dry and Wet Conditions

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For stable robotic grasping, a surface with high friction is required; thus, a soft surface is preferable. In contrast, a slippery surface is preferable for inserting fingers into a narrow space or placing a grasped object on a table. Additionally, in an environment involving humans, such operations are performed under dry and wet conditions. Hence, this study aims at developing a soft robotic fingertip with a friction control system in which the surface friction is actively controllable under dry and wet conditions, whereas the external effects on friction, such as wetness, are minimized. The basic concept involves achieving high friction under both conditions by using a slit surface texture, while friction is reduced with a lubricating system by utilizing capillary action. The experimental validation shows that the proposed lubricating system embedded in a robotic finger surface successfully reduces friction under both conditions. The releasing and grasping operations reveal the efficacy of the proposed system in an actual situation. Additionally, the mechanism of the lubricating method is confirmed by introducing the spreading coefficient.

Keywords: Grasping; Soft material robot; Contact modeling

1. Introduction

In robotic hands, surface friction plays an important role in grasping. A grippy surface with high friction is preferable for holding an object without dropping it. However, a grippy surface is not always preferable. A slippery surface is preferred in several situations such as inserting fingers in a narrow space, aligning the position and pose of an object on a table, and placing a grasped object on a table. Operations in a narrow working space, such as box packing or assembling objects inside a box, need to be performed with insufficient space for opening the fingers. In such a case, it is effective to slide and drop a grasped object for placing it without the need to open the fingers. Additionally, these operations are not always performed under dry conditions. Thus, this paper proposes a surface system for a robotic hand in which the surface friction is actively controllable under both dry and wet conditions.

1.1 *Robotic hand with a soft surface*

Supposing that a surface can be modeled by an aggregation of local spring models, a soft surface deforms more than a rigid surface when the same load is applied. This large deformation property

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provides high adaptability to the object shape and low contact impact in a grasping process. In soft surfaces, the friction increases with increasing apparent contact area [1–3], and a small grasping force can then provide a sufficiently large contact area or frictional force for stable grasping. These properties are effective in the delicate grasping of fragile objects. Therefore, several types of robotic hands with soft surfaces have been developed [4–20]. In this context, we developed a fluid fingertip that was composed of an elastic rubber bag filled with fluid. The inner soft material was a fluid, and thus, high adaptability to object shape was obtained. Thus, it was possible to grasp fragile objects such as potato chips and silken tofu. Additionally, we focused on the wet condition and proposed a surface structure composed of a silicone texture attached to the fluid fingertip. This surface structure provided a stable grasping under both dry and wet conditions [1]. However, the aim of the above described robotic hands with soft surfaces involved achieving high surface friction for handling various objects. The need of a slippery surface was not considered. From the investigation results of [2, 3], the frictional force (plus deformation) in soft surfaces is large even when the normal or grasping force is small. The effect of the adhesion force cannot be neglected, and the variation in the frictional force becomes large as the grasping force decreases. Hence, during the process of releasing an object, unexpected object motions including adhesion to a fingertip or falling at an unexpected time could occur. Therefore, the control of the releasing process of a grasped object is a significant issue with respect to soft robotic hands. The change from a grippy to a slippery surface can facilitate the release. Other examples of this need include exploring the surface of object and sliding on the surface to reach the desired grasping points.

1.2 *Friction control system for a soft surface*

The most important aspects when installing a friction control system in the soft surfaces of robotic hands are as follows. First, to embed the system in the fingertips or hands, a small and simple structure is preferable. Second, the system should not compromise the flexibility of the finger to maintain the abovementioned merits in soft surfaces. The change in fingertip stiffness provides not only a change in friction but also a change in the grasping forces. To keep a stable grasping, the control of both the frictional and grasping forces by opening or closing the fingertips is required, and the releasing process especially in a narrow space is difficult. The complexity of the control method owing to the nonlinear relationship among the friction forces, grasping forces, and stiffness is also a problem. Therefore, it is preferable that the system exhibits the high adaptation ability of the soft surface while the surface friction is independently controllable.

Several friction control systems for soft surfaces were already developed. Kim et al. [21] developed an adhesive in which the adhesion force is thermally controllable by utilizing adhesive polymers and shape memory polymers. Liu et al. [22] developed a fingerprint texture in which wrinkles appear under ultraviolet (UV) light exposure and disappear when the light is switched off. The friction of the texture is reduced due to the wrinkles when the UV light is switched on. Suzuki et al. [23] bonded a nylon textile sheet on a silicone rubber base and controlled the surface friction by compressing the silicone to selectively form wrinkles. Umedachi et al. [24] and Vikas et al. [25] proposed methodologies in which the part with high friction and the part with low friction were alternately grounded for moving/migrating mobile soft robots. The methods in [21, 22] require additional systems for controlling friction, and the applicable situations are limited. The method in [23] requires a change in the elasticity of the soft part to control friction. The methods in [24, 25] require large spaces, and it is difficult to apply them to soft robotic hands. Recently, Becker et al. [26] developed a simple system to control the surface friction of robotic hands. The surface was slippery and included several holes. An inflatable rubber bag with high friction was located at the inside of the surface. When the bag was inflated, the membrane was pushed out through the holes and the surface friction increased. However, the surface is basically rigid and its adaptability to the object shape is low.

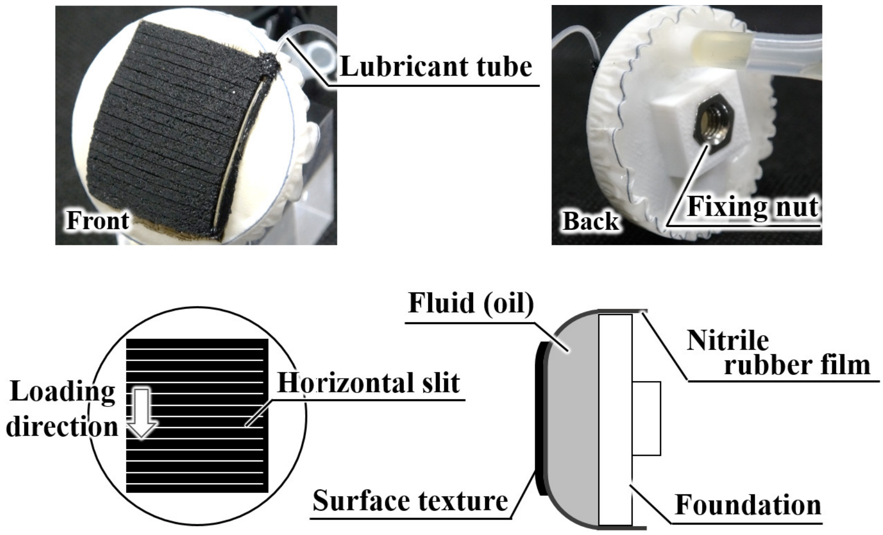

Figure 1. Deformable fluid fingertip with surface texture

1.3 *Contribution*

The present study proposes a novel friction reduction system by utilizing a lubricating effect to control the friction of an elastically deformable soft surface/fingertip with high friction. The utilization of the lubrication provides friction reduction without loss of deformability and softness. Based on the knowledge [1] of the relationship between a slit surface texture and friction under the wet condition, we develop a friction control system in which external effects on friction, including wetness, are minimized while the friction is actively controllable under both dry and wet conditions. The basic concept involves high friction under both conditions by a slit surface texture, while the friction is reduced by a lubricating system utilizing capillary action also under both conditions. The efficacy of the proposed system is experimentally investigated when the developed surface is in contact with several types of materials under both dry and wet conditions.

2. Structure of the developed fluid fingertip

2.1 *Structure of fluid fingertip*

We utilized the fluid fingertip shown in Figure 1 as the base for a deformable fingertip with a friction control system. The nitrile rubber film was bonded at the side of the fingertip foundation to create a space for the filling fluid. The foundation was rounded with a diameter of 45 mm to prevent fluid leakage. The inner fluid was chain saw oil (ISO VG100). The fingertip foundation included a hole connected to a pump and pressure sensor (Keyence AP-12S). The pressure of the inner fluid was 2 kPa, and this corresponded to the highest friction in a previous experiment [1].

2.2 *Surface texture*

A silicone texture was coated on the rubber film. The coated area was 30 $\times$ 25 mm. The material of the texture was a silicone sealant (Hapio seal pro, Kanpe Hapio) that deforms based on the expansion and contraction of the rubber film. In a previous study [1], we sub-optimized the texture to obtain a high maximum resistible force that is defined as the maximum tangential force at which the fingertip maintains contact while applying and increasing the tangential/shear force. It should be noted that the effects of surface deformation and friction force are considered

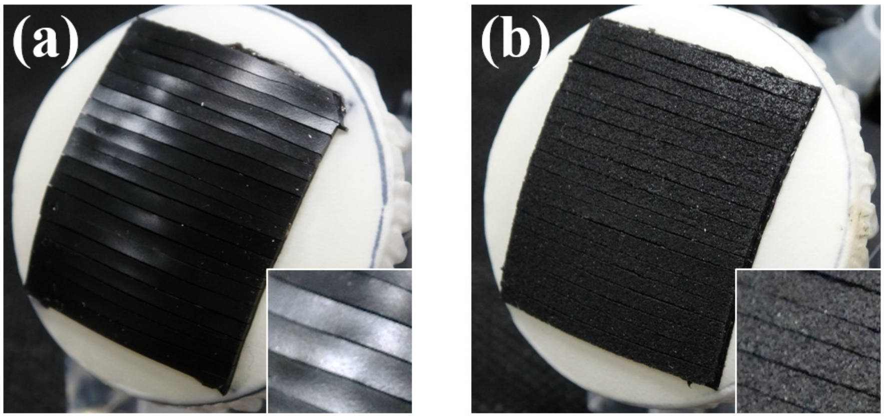

Figure 2. Difference in the surface; (a) smooth surface, (b) rough surface. The rough surface was used in all the following experiments.

at the maximum resistible force. The suboptimal texture corresponded to the hybrid texture of flats and slits, and the slit directions were orthogonal to the loading direction while the slit interval was 1.5 mm. However, its slit area provided sufficiently high friction for a practical usage. The aim of the study involved friction reduction with a lubricating effect, and it focused on performance under the wet condition. Thus, we selected and targeted the suboptimal slit texture pattern under the wet condition in [1].

The preliminary experiment indicated that a smooth flat surface utilizing the silicone sealant shown in Figure 2(a) is sticky. In practical situations, soil and dirt typically stick to the smooth surface. It is easy to pick up objects although it is difficult to release the grasped objects. This burdens the operation. We reduced the sticky property by creating micro holes on the surface. The fabrication process involves the following steps. Figure 2(b) shows the manufactured texture.

(1) A 30 × 25 × 1 mm frame built by a 3D printer was bonded on a plastic thin sheet by utilizing double-faced tapes.
(2) Powdered gelatin was dispersed on the double-faced tape inside the frame, and silicone sealant was subsequently applied on the tape.
(3) The frame was removed from the plastic sheet after hardening. The powdered gelatin was removed by boiled water.
(4) The silicone sealant was taken from the frame, cut to create slits with an interval of 1.5 mm, and the texture was obtained.
(5) The texture was bonded on the rubber film by utilizing the silicone sealant as a bond.

3. Lubricating system

There are several methods to control the surface friction, as described at Section 1.2, although those methods involve a space issue or decrease the deformability of the soft surface. Thus, this study proposes a new friction reduction system utilizing lubrication with liquid.

The effects of external factors to the surface condition of the target object should be minimized to actively control friction. The wet condition is considered as the state in which lubricants were already applied to the surface of the object, and it is not possible to ignore the effect of wetness on the friction. In [1], we successfully reduced the effect of wetness by using the surface texture. Hence, this study aimed at developing a system in which friction is reduced by an active lubricant action while the external lubricating factors are minimized by surface texture.

Table 1. Physical properties of liquids and materials [28–30].

	Viscosity [mPas]	Density [g/cm3]	Surface tension [mN/m]		
			Dispersion	Polar	Total
Water	1.00	0.998	21.8	51.0	72.8
Ethanol	1.20	0.789	18.8	2.6	21.4
Rubber	-	-	19.0	0.0	19.0
Polypropylene	-	-	31.1	0.0	31.1

Values at 20 °C

3.1 *Lubricant*

A chemically safe and easy to dry lubricant is preferred, and ethanol was subsequently selected as the lubricant. The effect of a solution of ethanol in water on rubber friction was investigated by Nishi et al. [27], and they indicated that both the static and kinetic frictional coefficients decrease with an increase in the density of ethanol in the solution. Subsequently, we selected an absolute ethanol with density exceeding 99.5 % (Kenei Pharmaceutical Corp.) to clearly distinguish the influence of the wetting of the object surface and the action of the lubricant.

3.2 *Structure of lubricating system*

We considered the method in which capillary action was utilized to place the lubricant inside the slits and to permeate the lubricant on the surface. Table 1 lists the viscosity, density, and surface tension of water and ethanol at 20 °C. There are slight differences in viscosity and density while the surface tension of ethanol is 1/3 of that of water. We introduce the spreading coefficient [27] to evaluate the wettability of the lubricant at the interface that is associated with capillary action and the degree of lubricant spreading. The spreading coefficient S is expressed as follows:

$$S = \gamma_{of} - (\gamma_{ol} + \gamma_{fl}) \tag{1}$$

$$\gamma_{ij} = (\sqrt{\gamma_i^d} - \sqrt{\gamma_j^d})^2 + (\sqrt{\gamma_i^p} - \sqrt{\gamma_j^p})^2 \tag{2}$$

where γ_{ij} denotes the surface tension of the interface between material i and material j, and γ_i^d and γ_i^p denote the dispersion and polar components of the surface tension, respectively. Note that the subscripts o, f, and l respectively denote object, fingertip, and lubricant. From (2), (2), and Table 1, it is observed that if a lubricant providing small surface tension on the interface is used, the spreading coefficient is large, and hence, the capillary action works well. This is another reason for the selection of ethanol as a lubricant. The slit structure shown in Figure 3 was adopted to permeate the lubricant on the entire area of the fingertip surface from the outside of the fingertip. The injection of lubricant was done by a syringe via a tube with a diameter of 1 mm. This method does not require any inner structures for the flow channel at the inside of the fingertip and can be applied to any type of fingertips without any changes in their inner structure. It is a valid method for a deformable fingertip to maintain its deformability and adaptability. Figure 4 includes photographs taken when observing the fingertip surface before and after injecting ethanol, with a blue lighting. The permeation of ethanol in the entire area of the slits is observed. The amount of the injection was 0.05 ml. A total time of 1.2 s was needed for the permeation of ethanol. If the fingertip surface after the injection contacts an object, the ethanol sweats out of the slits on the surface and works as a lubricant.

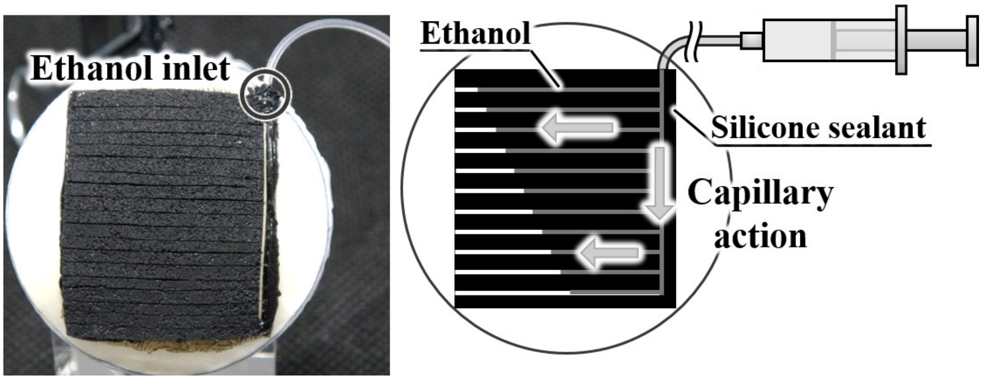

Figure 3. Lubrication mechanism using capillarity effect (please refer to the video clip).

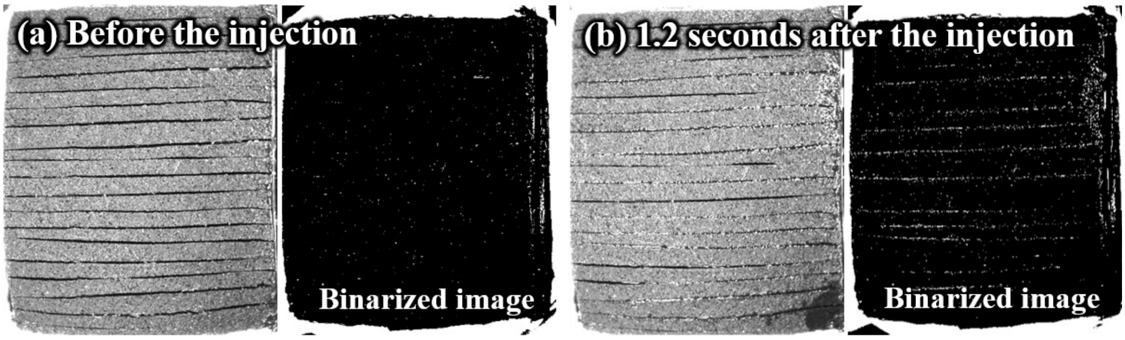

Figure 4. Fingertip surface before and after injecting ethanol (please refer to the video clip); (a) before the injection, (b) 1.2 s after the injection.

4. Evaluation of lubricating effect

4.1 *Procedure*

Figure 5 shows the experimental setup for the evaluation of the lubricating effect. First, the target material/object was placed on the table of the linear guide. Next, the fingertip was attached to the tip of the force gauge (IMADA DS2-50N) attached to the vertical automatic poisoning stage (IMADA MX2-500N), such that the slit direction is orthogonal to the pulling direction. It should be noted that, as mentioned above, this slit pattern provides suboptimal maximum resistible force under wet condition, based on the results in [1]. The value of the force gauge was set as 0 N when the fingertip was not in contact with anything. Subsequently, we pushed the fingertip against the target material with a pushing force of 0.3 N. The value of the pushing force was assigned based on preliminary studies so that the effects of contact area and deformation by the pushing force can be minimized. The fingertip surface is curved and only the convex part is then in contact with the object when the pushing force is too small. In this case, the effect of lubrication could be lost or limited. If the pushing force is too large, the fingertip surface deformed largely and the contact area and the slit texture could then be expanded. The expansion could cause unexpected spreading of the lubricant, and the lubricant ability could vary and be difficult to identify. Therefore, we carefully select the value of the pushing force. Given this state, the table of the linear guide was pulled by the horizontal automatic positioning stage (Oriental motor ELSM2XF30K) with a speed of 5 mm/s. The pulling force was measured by a force gauge (IMADA DS2-50 N). We measured the value of the pulling force when the fingertip started sliding. The pulling force value (f_s) divided by the pushing force (f_n) of 0.3 N was defined as the equivalent maximum static frictional coefficient (EMSFC) μ_E :

$$\mu_E = \frac{f_s}{f_n} = \frac{f_s}{0.3} \tag{3}$$

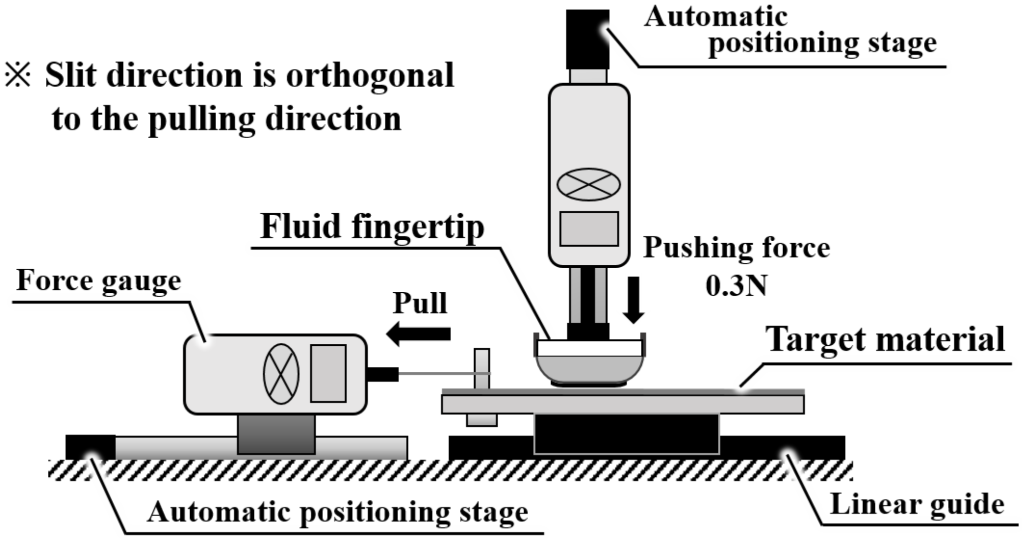

Figure 5. Schematic view of the experimental setup for the evaluation of the lubricating effect.

Table 2. Experimental conditions.

Experimental condition	Lubricant (Ethanol)	Timing of lubrication action	Target surface condition
(i)	Without	-	Dry
(ii-1)	With	Before the contact	Dry
(ii-2)	With	After the contact	Dry
(iii)	Without	-	Wet
(iv-1)	With	Before the contact	Wet
(iv-2)	With	After the contact	Wet
(v)	Without	-	Oily
(vi-1)	With	Before the contact	Oily
(vi-2)	With	After the contact	Oily

The volume of the injected lubricant was 0.05 ml.

The volume of the water and oil for the wet / oily condition, respectively, was 0.5 ml.

This corresponded to the evaluation target. Trials were conducted four times for each condition.

4.2 *Experimental condition*

The experimental conditions are presented in Table 2. We investigated the lubricating effect in the case when the target material object was dry and also the case when it was wet or oily. The target material was dry in the conditions (i) and (ii), the lubricant was not injected in (i), and it was injected in (ii). At (ii-1), the injection was performed prior to the contact between the material and fingertip while the injection was performed after the contact at (ii-2). Distilled water with a volume of 0.5 ml was used to wet the target material at (iii) and (iv) while chain saw oil with a volume of 0.5 ml was used to make the target material oily at (v) and (vi). The volume of the injected lubricant was 0.05 ml, which was determined so that the lubricant could work evenly at the whole contact area, i.e., in such a way that all slits include the lubricant; however, the lubricant does not flow out from the slits when nothing touches the surface.

4.3 *Lubricating effect on different materials*

The lubricating effect on different materials was investigated by conducting the experiments under conditions (i) and (ii). The target materials included a polypropylene sheet, a silicone sheet, an acrylic plate, paper (PPC paper Daio-Paper), stainless steel, porcelain plate, and glass

Table 3. Experimental results for different target materials.

Target material	(i)		(ii-1)		(ii-2)	
	EMSFC*	Standard deviation	EMSFC*	Standard deviation	EMSFC*	Standard deviation
Polypropylene	2.19	0.161	1.01	0.076	1.03	0.079
Silicone	2.30	0.143	1.30	0.024	1.26	0.064
Acryl	1.53	0.100	0.63	0.075	0.61	0.014
Paper	1.49	0.220	0.91	0.109	0.93	0.214
Stainless steel	2.28	0.132	1.83	0.213	1.82	0.248
Porcelain	2.44	0.166	1.80	0.097	1.83	0.122
Glass	2.03	0.125	1.13	0.233	1.16	0.106

* EMSFC denotes the equivalent maximum static frictional coefficient.

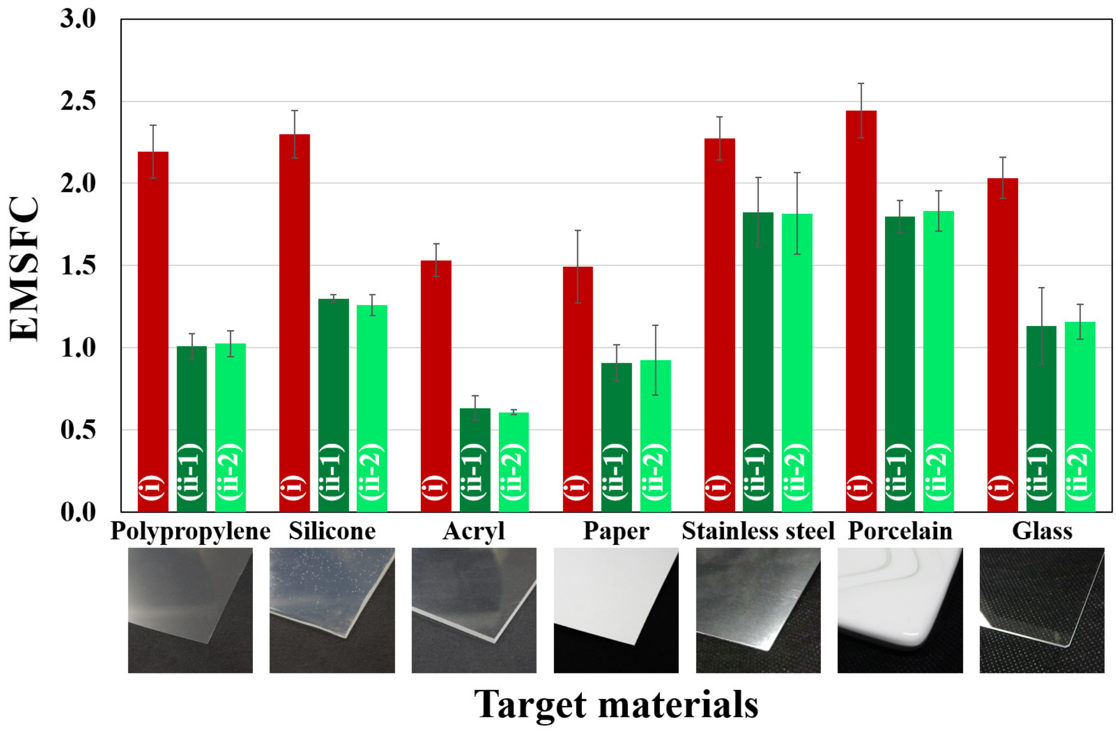

Figure 6. Equivalent maximum static frictional coefficient (EMSFC) for different target materials, without (red colored bar) or with a lubricant (green and light green colored bars).

plate. Among the everyday tasks, kitchen tasks are typical of those realized under a wet condition. The target materials were selected so that they can represent the typical kitchen utensil material. The results are presented in Table 3 and Figure 6. The injection of the lubricant reduced EMSFC to approximately 54 % for the polypropylene sheet, approximately 43 % for the silicone sheet, approximately 59 % for the acrylic plate, approximately 39 % for the paper, approximately 20 % for the stainless steel, approximately 25 % for the porcelain plate, and approximately 44 % for the glass plate. The friction reduction was observed in all the materials, although the levels of reduction were different. A clear difference between (ii-1) and (ii-2) was absent, and this revealed that the timing of the injection (i.e., if the injection occurs before or after the contact) did not affect the lubricating effect on EMSFC. The results indicate that the spreading of the lubricant was not prevented by the contact owing to the deformability of the fingertips, and the magnitude of the friction is controllable by the lubricating system even when the fingertip is in contact with a surface.

Table 4. Experimental result with the conditions in Table 2.

Experimental condition	Static frictional force [N]	EMSFC*	Standard deviation of EMSFC*
(i)	0.66	2.19	0.161
(ii-1)	0.30	1.01	0.076
(ii-2)	0.31	1.03	0.079
(iii)	0.69	2.31	0.269
(iv-1)	0.38	1.28	0.123
(iv-2)	0.39	1.30	0.047
(v)	0.22	0.72	0.055
(vi-1)	0.20	0.66	0.098
(vi-2)	0.19	0.63	0.085

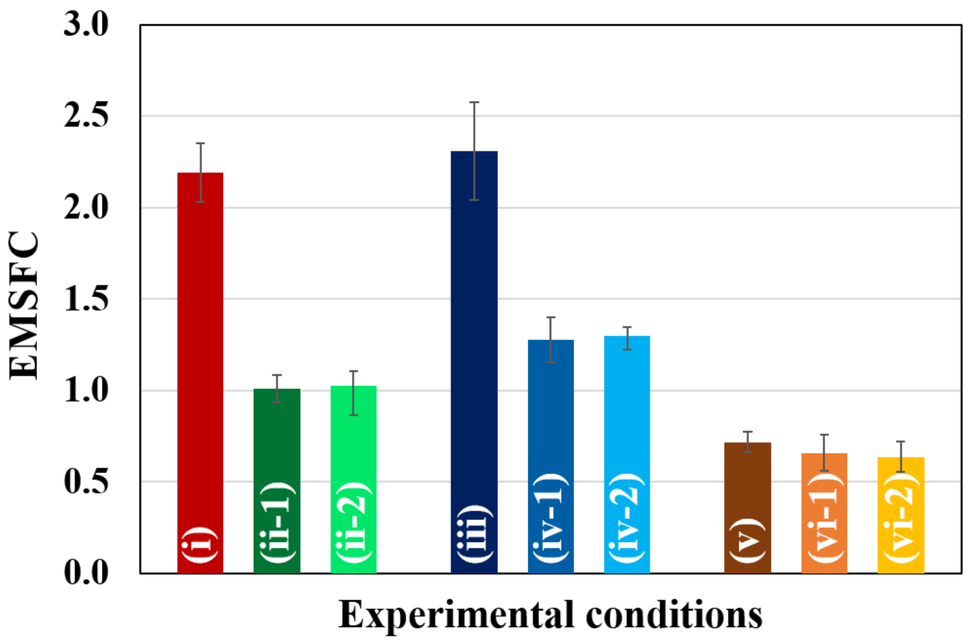

Figure 7. EMSFC at various experimental conditions presented in Table 2. The target material was polypropylene.

4.4 *Lubricating effect under wet and oily conditions*

The lubricating effect under wet and oily conditions was investigated by conducting the experiments under conditions (iii)∼(vi). The target material corresponded to a polypropylene sheet in which a high level of friction reduction was obtained in the previous experiment described in Section **??**, while the EMSFC at the nominal dry condition (i) was high. Table 4 and Figure 7 present the results.

The EMSFC at the oily condition (v) was approximately 33 % of the EMSFC at condition (i). As shown in the (vi-1) and (vi-2) results, a lower effect was observed with respect to the injection of ethanol. The lubricating effect by oil was dominant.

A comparison of the results at (i) and (iii) indicates that the wet condition results in a slight increase in friction (EMSFC). A clear difference in EMSFC was not observed. A comparison of the results at (iii) and (iv) indicates that the injection of ethanol reduced EMSFC to 45 %. The effect of wetness on friction was reduced/controlled (by the texture) while the friction reduction by the injection of lubricant (ethanol) was successful.

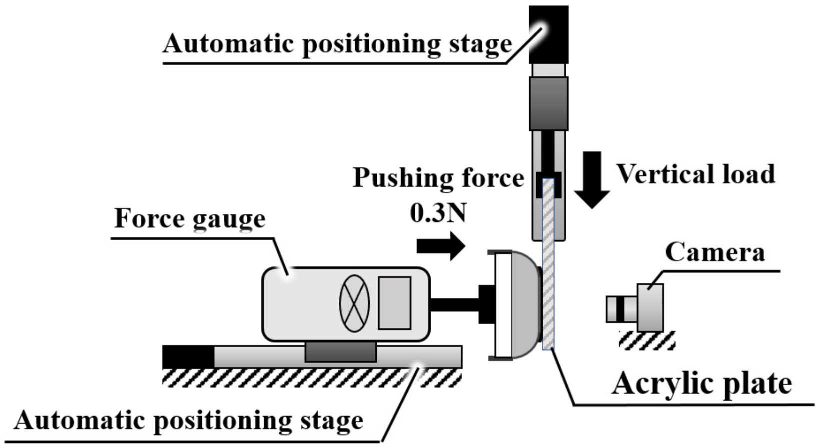

Figure 8. Schematic view of experimental setup for observing the contact area.

5. Observation of contact area

5.1 *Lubricating effect and spreading coefficient*

When the target material was wet by water, the texture prevented the friction reduction while the injection of ethanol reduced the friction. These were the desired results, but the reason why we obtained them is unclear. The reason was then discussed by observing the contact area when applying a tangential load with and without the lubricant. Fig. 8 shows the experimental setup for the observation. The fingertip was pressed against a transparent acrylic plate with a load of 0.3 N. In this state, a load in vertical direction (contact tangential direction) was applied, and the contact area was observed by using a camera. The experiment was performed under conditions (i), (ii-1), (iii), and (v). Figure 9 shows the observed contact area. At (i), it was observed that the texture was deformed, and the slits opened owing to the friction and loading. Comparing with the results at (i), we discuss the observation results at (ii-1), (iii), and (v) with the spreading coefficient given in (2). From the experimental results at [27], both the kinetic and maximum-static frictional coefficients decrease with an increase in the spreading coefficient. Focusing on the contact area at (ii-1), the injected ethanol located inside the slits permeated the wide contact area by the contact with the acrylic plate, and this indicates a high spreading coefficient. It is considered the reason for the decrease in the EMSFC (friction). Focusing on (iii), the area where water spread was small, and this indicates a low spreading coefficient. The high (polar) surface tension of water is considered to cause the low spread. As a result, water did not permeate the surface but it flowed into the slit, which reduced the wetting area. Therefore, the observed dry spots were wide. They are considered as the reason why EMSFC (friction) was high and close to that at (i). At (v), oil spread throughout the entire area of contact, and the degree of spreading was the highest among the three cases ((ii-1), (iii), and (v)). This is considered the reason why EMSFC (friction) was low.

We estimated the results at (iv) and (vi). The density of ethanol in the surface liquid is between the densities at (ii) and (iii). It is then estimated that the spreading coefficient at (iv) is between the values at (ii) and (iii), and its EMSFC is therefore between those at (ii) and (iii). Oil spread to each corner at (v), and subsequently, the lubricating effect by the injection of ethanol is estimated as low at (vi). Therefore, EMSFC at (vi) is estimated as close to that at (v). These estimations coincide with the results shown in Figure 7.

It should be noted that our previous study [1] showed that the slit texture provided an EMSFC under the oily condition close to that under the dry condition, although in these experiments, the EMSFC under the oily condition was smaller than that under the dry condition. The roughness of the surface shown in Figure 2(b) is considered the reason for the decrease in EMSFC.

5.2 *Durability of lubricating effect*

The lubricating effect does not work until the lubricant permeates the contact surface. Subsequently, we investigated the durability of the lubricating effect by considering the area in which the lubricant permeated as an evaluation criterion. The contact between the fingertip and target material was performed after the injection of ethanol (it corresponds to condition (ii-1)). The permeated area was evaluated with changes in time, from the time of injection to the time of contact. The permeated area was reduced to half after 30 s following the injection, and it was reduced to approximately 10 % after 90 s following the injection. The permeated area was almost zero after 120 s. In summary, the lubricating effect is reduced to half after 30 s following the injection, and the surface becomes dry after 120 s. The experiment did not include the effect of the reduction of lubricant by touching surfaces such as a target object. The aforementioned times would decrease after the touching. The time to become dry is considered as sufficiently rapid, considering the processing time for recognizing the target and surroundings.

6. Experimental evaluation of grasping and releasing

The efficacy of the proposed surface composed by the slit texture to obtain a high friction and the lubricating system for reducing friction was examined in the previous section. In this section, the developed friction reduction system was evaluated at the grasping and releasing operations.

6.1 *Grasping and releasing test*

Here, supposing that the tasks are performed in a narrow space, we investigated whether a grasped object can be released by controlling the friction, without changing the grasping configuration or pose. The target objects are shown in Figure 10 while the experimental setup is shown in Figure 11. A gripper in which the surface corresponds to the developed surface was utilized. The procedure is as follows. First, the target object on the stage was grasped by the gripper without injecting the lubricant with the grasping force listed in Table 5. Subsequently, the stage was removed and the weight with the value listed in Table 5 (approximately 30$\sim$40 % that of the target object) was placed on the top of the object to confirm the realization and stability of grasping. After removing the weight, the lubricant was injected without changing the grasping configuration to confirm friction reduction by examining whether the object slips down. If the object did not slip down, then the weight that was utilized for confirming the grasping stability was placed on the top of the object again to confirm whether the friction reduction was realized. The slipping indicated friction reduction if the object slipped down. The experiments were performed under both dry and wet conditions. In order to obtain the wet condition, we applied mist of 0.2 ml per 10 cm^2 distilled water to the object. Trials were performed four times for each condition.

Table 6 shows the success rate. Under the dry condition, the target objects were grasped stably while they slipped down owing to the injection of the lubricant, without changing the grasping configuration or pose. Under the wet condition, the friction reduction by the injection was not sufficient to cause the objects to slip down. Therefore, the weight was placed on the top of the objects to confirm the friction reduction. The results indicated that the friction was reduced. The level of the reduction was lower than that under the dry condition, and this coincides with the results shown in Figure 7. It should be noted that deformable fingertips did not obey Coulomb's law [2, 3]. Additionally, the deformation and subsequently the contact area of the deformable fingertips at the grasping and releasing tests differed from those in the experiments in Section 4 owing to the gravitational effect. Therefore, it is not possible to estimate the grasping force required for holding the objects at the grasping and releasing test from the EMSFC obtained in Section 4. The results validated the efficacy of the friction reduction system by lubricant injection under both dry and wet conditions.

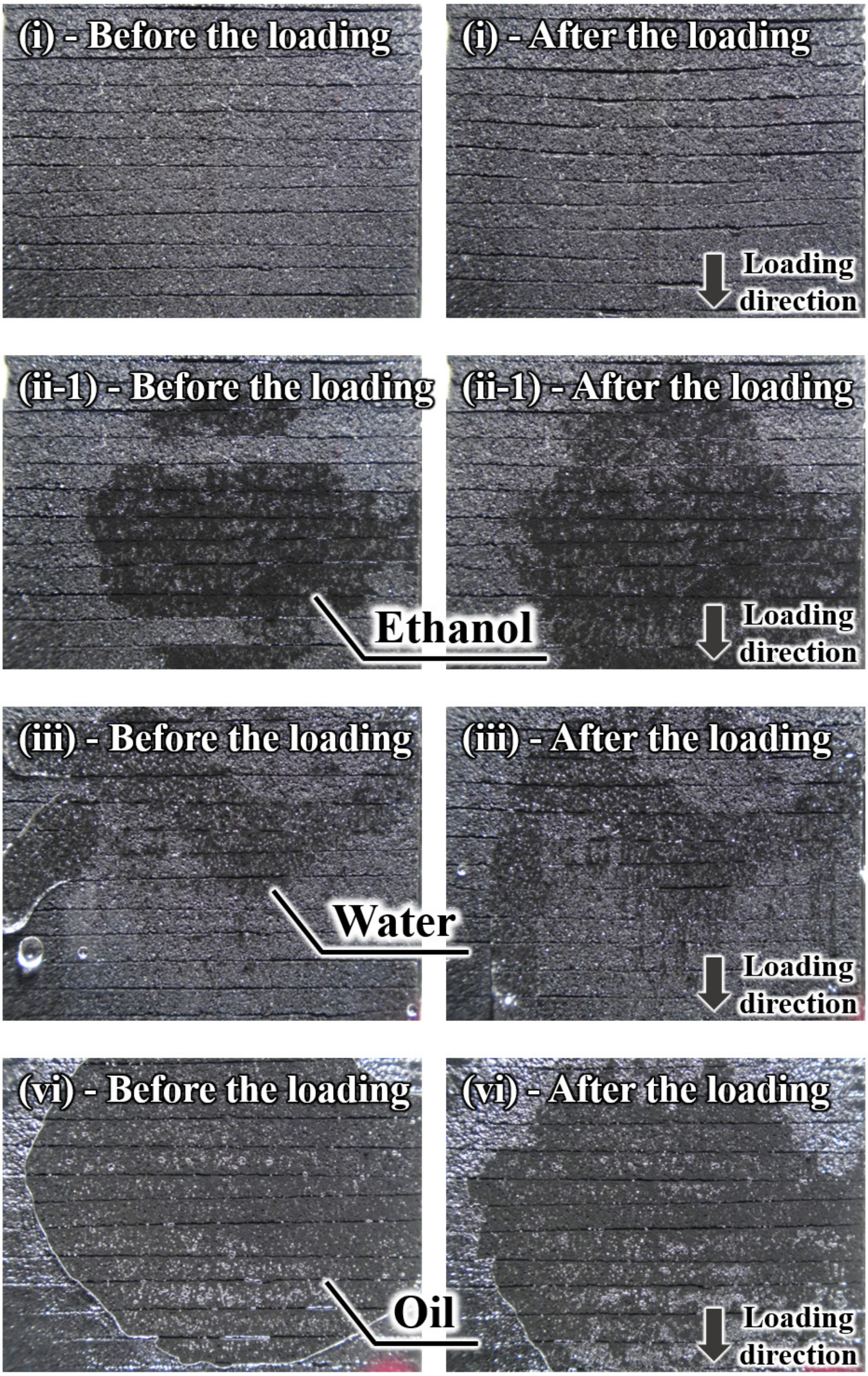

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Figure 9. Contact area at the various experimental conditions.

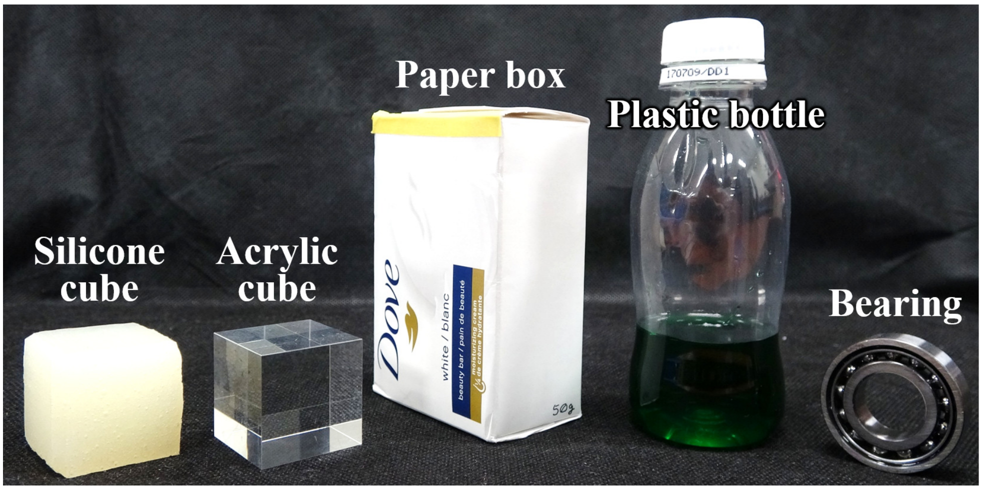

Figure 10. Target objects for the grasping and releasing test.

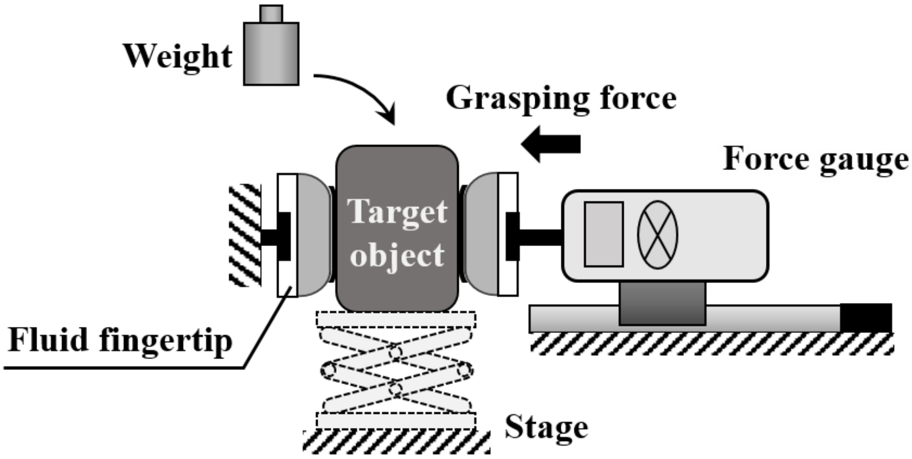

Figure 11. Schematic view of the experimental setup for the grasping and releasing test (please refer to the video clip).

Table 5. Conditions for the grasping and releasing test.

Target object	Weight of object [g]	Grasping force [N]	Weight value [g]
Silicone cube	30	0.35	10
Acrylic cube	31	0.3	10
Paper box	50	0.5	20
Plastic bottle	50	0.5	20
Bearing	40	0.4	10

6.2 *Box-packing simulating task*

An experiment simulating a box packing task under dry condition (in a narrow working space) was performed with the same procedures as those in the previous experiment described in Section 6.1. As shown in Figure 12, the task was successfully performed by releasing the box without changing the grasping configuration and without causing positional or postural misalignment, and this validated the proposed friction reduction system utilizing a lubricating effect.

6.3 *Time response of the friction reduction system*

Here, we investigated the time required for releasing the grasped object by injecting the lubricant without changing the grasping configuration. The target was the experiment presented in Section

Table 6. Success rate of the grasping and releasing test.

Target object	Success rate	
	Dry condition	Wet condition*
Silicone cube	4/4	3/4
Acrylic cube	4/4	4/4
Paper box	4/4	4/4
Plastic bottle	4/4	4/4
Bearing	4/4	3/4

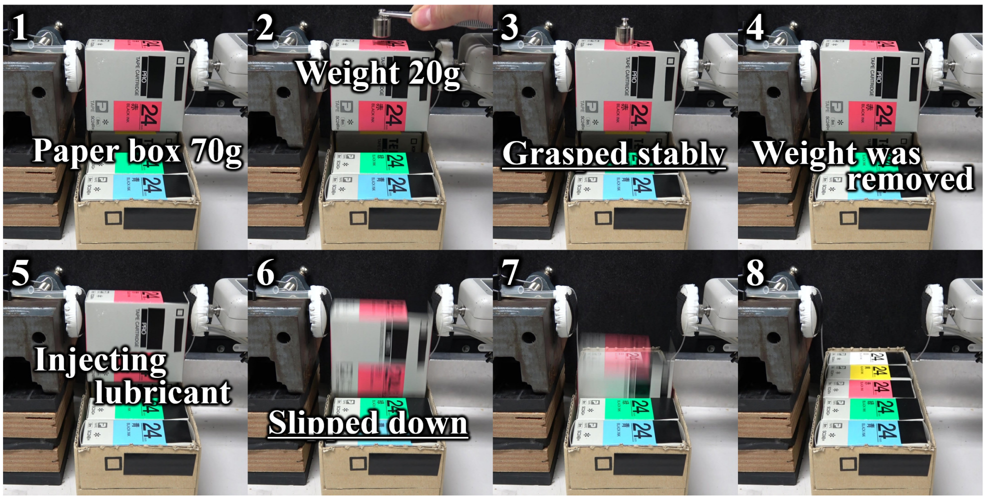

Figure 12. Overview of grasping and releasing operation simulating a box packing task (in a narrow working space) (please refer to the video clip).

Table 7. Time required for releasing the grasped object by injecting the lubricant (under dry condition).

Target object	Time required [s]
Silicone cube	4.0
Acrylic cube	2.3
Paper box	2.1
Plastic bottle	1.8
Bearing	2.4

6.1. The releasing of the object by using only the lubricant was observed under the dry condition, and thus, we only investigated the dry condition. Table 7 presents the results. Except for the case when the target was a silicone cube, the time required was short and less than 2.5 s. When the silicone was targeted, the time required was longer than the cases targeting the other materials. Because the fingertip surface was made of silicone, the contact between the same materials (silicone) could cause a close contact, and therefore, a longer time could be required to spread the lubricant. This is considered the reason why a longer time is required for the release. In summary, the time required for the release was within 4.0 s in any case, and it was short enough for performing everyday tasks by robots.

7. Conclusion

This study proposed a novel deformable fingertip with a friction control system, without loss of deformability and adaptability to both the environment and object shape. A slit surface texture with high friction under both dry and wet conditions was proposed in our previous study. This study subsequently produced a lubricating system embedded into the slit surface texture to reduce or control the friction. The lubricating system was based on capillary action and worked through the injection of lubricants. The aim of the proposed surface was to achieve high friction by its texture, under both dry and wet conditions, while displaying low friction owing to the lubricating system, also under both conditions. In the developed friction control system, the external effect of wetness on friction was minimized while the friction was actively controlled under both conditions. The results of the evaluation revealed that the friction reduction was realized under both conditions. Under the dry condition, a high reduction was observed. The grasped object is released by injecting the lubricant without changing the grasping configuration. This is effective for assembly tasks or for packing a box in a narrow space. The observation of the contact area confirmed the efficacy of the lubrication from the viewpoint of the relationship between friction and spreading coefficient.

Ethanol was used for the lubricant in this study given that it is chemically safe and easy to dry. A limitation of the proposed system is that the friction was not reduced under the oily condition. The lubricating effect was examined at the slit pattern providing a suboptimal maximum resistible force under the wet condition, based on the results [1]. From the results from contact area observation, it seems that the lubricant spread irrespective of the slit pattern, and the effect of directional patterns of the slit on the lubricating is low. However, only one type of lubricant was utilized, and the directional property could affect the spreading if other types of lubricant are used. The selection of lubricants and further examination of the directional properties of the slit are then future issues. The time required for releasing the grasped object was short enough for performing typical kitchen tasks by robots but not short enough for working at factories. The improvement in the time required is thus another future issue. The development of a robotic hand with the proposed friction reduction system, and the realization of several operations utilizing this robotic hand are also aspects for future research. The controlling of grasping force for appropriately functioning the system is also future issue. Our future works involve these issues along with extending the available range by examining the effect of varying amounts of various lubricants on different surfaces.

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