Effects of Surface Texture on Soft-Materials for Medical Applications

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We have studied the effects of a textured structures on soft-materials, mainly to reduce friction between body tissues and plastic components used in medical devices. For this purpose, we investigated changes in friction between the structure of grooves on plastic and rubber, which was considered as body tissue. Silicone oil was used for the purpose of lubrication, and the changes in friction were observed from the point of view of aspect ratio. The results indicated that a grooved surface exhibited lower friction compared to a non-textured surface. Furthermore, directional sliding perpendicular to the grooves was more effective in reducing friction than that parallel to the grooves. In addition, the results indicated that the kinetic friction was changed by pitch and depth even if the aspect ratio was similar in a direction perpendicular to the straight grooves. Furthermore, the results indicated that a higher aspect ratio resulted in a lower kinetic friction when the pitch was fixed and the depth was changed in a direction perpendicular to the straight grooves. In this study, the frictional materials used were soft-materials that simulated the softness of the human body and medical devices. Thus, from the results mentioned above, we can conclude that textured structures can reduce friction for soft materials.

Keywords: friction reduction, surface texture, lubrication, soft-materials, medical applications

1. Introduction

In order to improve the Quality of Life of patients, reducing the friction between medical devices and body tissues is urgently required in the medical field. For example, in the case of hemodialysis, patients undergoing dialysis are dialyzed approximately three times a week in Japan. Two indwelling needles are inserted into the patient's arm for performing dialysis. One of the needles sends blood from the patient's body to the dialyzer. The other needle sends filtered blood from the dialyzer to the patient's body. Thus, patients undergoing dialysis are frequently punctured with indwelling needles and they feel constant pains. In contrast to indwelling needles used for drip infusion, the friction generated on inserting an indwelling needle into a patient's arm for dialysis causes significant pain because the diameter of the needle is large. For effective dialysis, the needles have to ensure a sufficient quantity of blood flow. Thus, the diameter of the needle cannot be minimized to reduce the pain felt by the patient. Thus, a different solution is required that can reduce friction. Furthermore, in the case of endovascular treatment by

using a catheter, the friction between the catheter and the inner wall of a blood vessel, and the friction between the inner part of the catheter and medical devices, such as guide wire, decreases the operability of medical devices. For example, if there is friction, the medical device cannot reach the affected area, and, in the worst-case scenario, the inner wall of a blood vessel may be damaged.

To solve these problems, lubricants, such as silicone oil, have been used conventionally for indwelling needles and other medical devices. Moreover, chemically modifying the surface of a medical device, such as hydrophilicity, has been used conventionally for catheters and guide wires. Furthermore, many researchers have carried out basic research on reducing friction for medical device applications. For example, Ikeuchi *et al.* reported that poly (N, N, dimethylacrylamide) (DMAA) grafted on the surface of a urethral catheter reduced friction in water because of its hydrophilic nature [1]. Sunita *et al.* reported that poly (MPC-co-BMA) coated on the surface of polyurethane reduced friction in water more than non-coated polyurethane because of hydration [2]. Yoshinaka *et al.* reported that low frequency oscillation reduced the

Fig. 2 Friction direction: a) perpendicular to the straight grooves, b) parallel to the straight grooves

The specifications of the textured structure are shown in Tables (1,2). The pitch and depth of the straight grooves ranged between 25-100 μm and 2.5-20 μm respectively. Straight grooves with aspect ratios of 0.13, 0.10, and 0.08 were assumed as grooves with aspect ratio of 0.1, as the depth of grooves was not precisely controllable in our process. The surface of a plastic plate (Polypropylene, Hazaiya Co., Ltd., 15 mm $\times$ 15 mm $\times$ 1 mm) was processed to create a textured structure by pressing a metal mold (aluminum alloy) having a textured structure. Before processing the plastic plate was washed with

isopropyl alcohol (Wako Pure Chemical Industries, Ltd.). The textured structure was processed on the metal mold by using a shaper. The metal mold was pressed into the plastic plate by using a vice and a hot plate (EC Hotplate EC-1200N, AS ONE Corporation) under heated conditions for the purpose of texturing. The heat was set at 25-120°C depending on each textured structure. The textured structure on the surface of the plastic plate was confirmed using a confocal laser microscope (KEYENCE CORPORATION, VK-9510), as shown in Fig. 3, the textured samples were tested and compared

Table 1 Specifications of textured structure (Aspect ratio around 0.1)

Sample	P (Pitch μm)	D (Depth μm)	Aspect Ratio(D/P)
P100-D13-AR0.13	100	13	0.13
P50-D4-AR0.08	50	4	0.08
P25-D2.5-AR0.10	25	2.5	0.10
Non textured sample	-	-	-

Table 2 Specifications of textured structure (pitch was fixed 100 μm)

Sample	P (Pitch μm)	D (Depth μm)	Aspect Ratio(D/P)
P100-D20-AR0.20	100	20	0.20
P100-D13-AR0.13	100	13	0.13
P100-D4.8-AR0.05	100	4.8	0.05

Fig. 3 Textured structure (P: pitch; D: depth)

Fig. 4 Friction measurement system

with non-textured samples. The opposing material was silicone rubber (Kyowa Industries Inc, 5 mm × 10 mm, Shore hardness 10 degrees), which was used to simulate the softness of the human body. Silicone rubber was adhered to a circular metal jig (ϕ 10, half cylinder, S45C, MISUMI Corporation) in order to press on set load.

The frictional force between the textured surface and silicone rubber was measured using strain gauges attached to double parallel leaf springs (Fig. 4). The circular metal jig adhered to silicone rubber was fixed on the double parallel leaf springs. Vertical load was set at a constant value and controlled using a feedback controller (Texture Analyzer ©Texture Technologies Corp and by stable micro systems, Ltd). The range of vertical load was between 0.2-2.0 N. The samples were reciprocated using an automatic stage (SIGMAKOKI Co., Ltd). The length of the stroke was 5 mm. The sliding speed was set at 10 mm/s, and the number of friction cycles was 40. The lubricant used was silicone oil (Dow corning, MDX4-4159 50% medical grade dispersion). The viscosity of the silicone oil was 170 cst (170 mm²/s), and 10 ml of the lubricant was applied on the textured surface in the form of drops.

3. Results

3.1. Validation of results for constant aspect ratio (The first experiment)

We studied the samples that had an aspect ratio of 0.1. The samples had different depths and pitches. The kinetic friction was determined by the system and shown in Fig. 1. Figures 5,6 show the relationship between the kinetic friction and vertical load. Figure 5 shows the results for the friction direction perpendicular to the straight grooves. Figure 6 shows the results for the friction direction parallel to the straight grooves.

3.1.1 Friction along direction perpendicular to straight grooves

As shown in Fig. 5, a higher vertical load resulted in a

higher kinetic friction. The kinetic friction decreased in the following order: Non-textured surface > P25-D2.5-AR0.10 > P50-D4-AR0.08 > P100-D13-AR0.13 (As shown in Table 1. P: pitch, D: depth, AR: aspect ratio, and the rest are omitted). Every sample did not exhibit significant differences in kinetic friction until a vertical load of 0.8 N was applied. However, the samples were confirmed to have significant differences in kinetic friction when the vertical load exceeded 1.0 N; kinetic frictions of the non-textured sample, P25-D2.5-AR0.10, and P50-D4-AR0.08 increased significantly. Finally, when the vertical load was 2.0 N, which was the maximum value, kinetic frictions of the non-textured sample, P25-D2.5-AR0.10, and P50-D4-AR0.08 were 0.82 N, 0.56 N, and 0.36 N respectively. P25-D2.5-AR0.10 exhibited approximately 32% lower kinetic friction compared to that of the non-textured sample. P50-D4-AR0.08 exhibited approximately 56% lower kinetic friction compared to that of the non-textured sample. On the contrary, the kinetic friction of P100-D13-AR0.13 increased significantly when the vertical load exceeded 1.8 N. Finally, when the vertical load was 2.0 N, the kinetic friction increased to 0.15 N. P100-D13-AR0.13 exhibited approximately 82% lower kinetic friction

Fig. 5 Kinetic friction (Direction perpendicular to the straight grooves)

Fig. 6 Kinetic friction (Direction parallel to the straight grooves)

compared to that of the non-textured sample.

As a result, kinetic frictions of P25-D2.5-AR0.10, P50-D4-AR0.08, and P100-D13-AR0.13 decreased compared to the non-textured sample. The relationship trend between the kinetic friction and vertical load for P25-D2.5-AR0.10 was similar to that of P50-D4-AR0.08. P100-D13-AR0.13 had a low kinetic friction under a high vertical load. Therefore, P100-D13-AR0.13, which has a pitch of 100 μm and a depth of 13 μm , had the lowest friction in this study. These results show that kinetic friction depends on the size of grooves even if the aspect ratio is the same.

3.1.2 Friction along direction parallel to straight grooves

As shown in Fig. 6, a higher vertical load resulted in a higher kinetic friction, which is true in case the friction direction is perpendicular to the straight grooves. The kinetic friction decreased in the following order: Non-textured sample > P25-D2.5-AR0.10 > P50-D4-AR0.08 > P100-D13-AR0.13. Every sample did not exhibit significant differences in kinetic friction until a vertical load of 0.8 N was applied. However, all the samples were confirmed to have slight differences in kinetic friction when the vertical load exceeded 1.0 N. Finally, when the vertical load was 2.0 N, kinetic frictions of the non-textured sample, P25-D2.5-AR0.10, P50-D4-AR0.08, and P100-D13-AR0.13 were 0.83 N, 0.83 N, 0.76 N, and 0.76 N, respectively. Compared to the non-textured sample, kinetic frictions of the texture samples decreased. Nonetheless, a significant difference could not be confirmed between the samples.

As a result, kinetic friction in a direction parallel to the straight grooves did not decrease as significantly as the kinetic friction in a direction perpendicular to the straight grooves. In addition, it is assumed that kinetic friction decreased slightly in a direction parallel to the straight grooves compared to the non-textured structure mainly because the contact area between the textured structure and the opposing material decreased.

3.1.3 Comparison between direction perpendicular to straight grooves and direction parallel to straight grooves

As described in section 3.1.1, kinetic frictions of all textured samples were significantly lower than non-textured samples in a direction perpendicular to the straight grooves. In section 3.1.2, the kinetic frictions of all textured samples were slightly lower than the non-textured sample in a direction parallel to the straight grooves. Comparing the kinetic friction of P100-D13-AR0.13 in a direction perpendicular to the straight grooves to that in a direction parallel to the straight grooves under a vertical load of 2.0 N, it can be observed that kinetic friction in a direction perpendicular to the straight grooves was 0.15 N, and that in a direction parallel to the straight grooves was 0.76 N. Thus, kinetic friction in a direction perpendicular to the straight grooves exhibited approximately 80% lower compared to that in a direction

Fig. 7 Kinetic friction (different aspect ratios)

parallel to the straight grooves. Therefore, kinetic friction in a direction perpendicular to the straight grooves decreased more in comparison to that in a direction parallel to the straight grooves.

3.2. Comparison of different aspect ratios (constant pitch of 100 μm) (the second experiment)

As described in Section 3.1.1, kinetic friction at an aspect ratio of 0.13 (100 μm pitch, 13 μm depth) was lower than other samples in a direction perpendicular to the straight grooves. Therefore, a pitch of 100 μm had the potential to decrease kinetic friction. Thus, we tested samples with different aspect ratios (the pitch was fixed at 100 μm , the depth was 20 and 4.8 μm) (Shown in Table 2).

Figure 7 shows the relationship between the kinetic friction and vertical load (in a direction perpendicular to the straight grooves). The kinetic friction decreased in the following order: non-textured sample > P100-D4.8-AR0.05 > P100-D13-AR0.13 > P100-D20-AR0.20. As a result, samples having a bigger aspect ratio had a lower kinetic friction. The kinetic friction of P100D4.8-AR0.05 started to increase when the vertical load exceeded 1.2 N and increased to 0.20 N. The kinetic friction of P100-D13-AR0.13 started to increase when the vertical load exceeded 1.8 N and increased to 0.15 N. The kinetic friction of P100-D20-AR0.20, which changed slightly from 0.01 to 0.08 N, did not increase while the vertical load was in the range of 0.2–2.0 N. Hence, it can be observed that a higher aspect ratio resulted in a lower kinetic friction.

4. Discussion

We obtained mainly three results, which are described as follows;

- The kinetic friction in a direction perpendicular to the straight grooves decreased more in comparison to that in a direction parallel to the straight grooves.
- The kinetic friction changed for different values of pitch and depth even if the aspect ratio was the same in a direction perpendicular to the straight grooves.

Fig. 8 Textured metal

- When the pitch was fixed and the depth was changed, a higher aspect ratio resulted in a lower kinetic friction in a direction perpendicular to the straight grooves.

From the results, we observed that the kinetic friction in a direction perpendicular to the straight grooves was significantly lower than that in a direction parallel to the straight grooves. This trend had been observed in previous studies in machinery fields. For example, in a strip-drawing process, friction occurs between a metal strip and the two dies. Costa *et al.* studied the effects of a textured structure to reduce friction in a strip-drawing process. They reported that the frictional force of grooves, which were oriented in a perpendicular direction to the drawing direction, was considerably reduced compared to grooves oriented in a parallel direction [19]. In a fundamental study, Sihuan *et al.* reported that grooves perpendicular to the sliding direction had a better effect on friction reduction than that in a parallel orientation under a low contact pressure [20]. They studied the effect of a lubricated textured structure on friction for hard materials. In this study, we studied the effect of a lubricated textured structure on friction for soft-materials that are used in medical practice. Therefore, we studied the effect of textured structures for hard materials using the same conditions to determine if the effect of textured structure on reducing friction is the same for both hard and soft materials. We determined the frictional force between a metal (aluminum alloy), which was processed with straight grooves having a pitch of 100 μm and a depth of 25 μm (As shown in Fig. 8, similar to P100-D20-AR0.20), and another opposing metal (S45C, MISUMI Corporation) under lubricated conditions (under the same conditions used in the first and second experiments except that textured substrate and opposing material were different). Moreover, we determined the frictional force between a non-textured metal (aluminum alloy) and the textured metal (S45C).

The results are shown in Fig. 9. A significant difference could not be confirmed between the non-textured metal and textured metal. Thus, textured structures could not reduce friction in metals under

Fig. 9 Kinetic friction (soft materials vs hard materials)

these conditions (the shape of the textured structure, viscosity of the lubricant, and sliding speed). It was also confirmed that the kinetic friction between hard materials (the textured metal and another opposing metal) was higher than that between soft-materials (the textured polypropylene and the opposing silicone rubber). Finally, under a vertical load of 2.0 N, the kinetic friction between soft-materials was 0.08 N and that between hard materials was 0.22 N. The kinetic friction between soft-materials was approximately 66% lower compared to that between hard materials. Therefore, we assume that textured structures only reduce friction between soft-materials when the shape of the textured structure, viscosity of the lubricant, and sliding speed are considered. Therefore, we believe that these effects that reduce the friction between soft materials are specific only to soft materials.

In this study, we assume that the opposing material contacts a rib of the textured substrate, as shown in Fig. 10. As the opposing material is softer than the textured substrate, when a vertical load is applied, the opposing material deforms and presses into the grooves. The lubricant is held in the grooves. We believe that the following phenomena occurred when the opposing material slid on the textured surface under the conditions mentioned above:

- 1) The effect of hydrodynamic pressure
- 2) Scraping out lubricant by deformation of the

Fig. 10 Hypothesis

opposing material

- 3) The effect of soft EHL
- 4) Amount of lubricant in grooves
- 5) The effect of viscoelastic dissipation

4.1. The effect of hydrodynamic pressure

Hydrodynamic pressure is regarded as the most important effect of textured surfaces [20-23]. In this study, in the case where the sliding direction was perpendicular to the straight grooves, the cross-section of the grooves was an inverted triangle (As shown in Fig. 3). Therefore, the grooves were wedge-shaped in the direction of friction. The wedge shape is one of the most important factors to generate hydrodynamic pressure [8]. Nanbu *et al.* studied the effect of hydrodynamic action by using model-based virtual texturing and numerical simulation, and they observed that different hydrodynamic effects were produced depending on the texture of the bottom surface. They reported that the oil film forming performance was high when the bottom surface had a wedge-shaped texture. [8,24]. Thus, we believe that the hydrodynamic pressure is generated in the grooves in a direction perpendicular to the straight grooves. The behavior of kinetic friction depended on the shape of grooves (pitch and depth). We believe that a bigger cross-sectional shape results in a higher hydrodynamic pressure and this reduces friction. More studies describing the relationship between the shape of the grooves and the hydrodynamic pressure are required in the future.

In the case where the frictional direction is parallel to the straight grooves, the hydrodynamic pressure is not generated in the grooves. This is because the straight grooves are in the same direction as the frictional direction.

Thus, the kinetic friction in a direction perpendicular to the straight grooves was significantly lower than that in a direction parallel to the straight grooves, and there was no significant difference between non-textured samples and textured samples in a direction parallel to the straight grooves.

4.2. Scraping out lubricant by deformation of the opposing material

Both the opposing material and textured substrate were soft-materials. The Young's modulus of polypropylene used as the textured substrate was approximately 1.5×10^3 MPa. In contrast, the Young's modulus of silicone rubber used as opposite material was approximately 4.0 MPa. Thus, silicone rubber as the opposing material was softer than polypropylene as the textured substrate. Therefore, the opposing material was deformed by the vertical load and pressed into the texture grooves when the vertical load was applied.

When the opposing material slides on the textured surface in a direction perpendicular to the straight grooves, the opposing material pressed into grooves scraps out the lubricant existing in a groove. Consequently, this phenomenon results in lubricating other grooves. Thus, the lubricant is constantly held in grooves (As shown in Fig. 10).

When the opposing material slides on the textured surface in a direction parallel to the straight grooves, the opposing material does not scrap out the lubricant existing in a groove because the straight grooves are in the same direction as the frictional direction. Thus, the lubricant is not provided to other grooves. Thus, oil starvation occurs easily compared to that in a direction perpendicular to the straight grooves. Therefore, as shown in Figs. 5,6, as well as described in section 4.1, the kinetic friction in a direction perpendicular to the straight grooves was significantly lower than that in a direction parallel to the straight grooves.

4.3. The effect of soft EHL

As described in sections 4.1 and 4.2, in case the sliding direction is perpendicular to the straight grooves, hydrodynamic pressure is generated in the grooves, and the opposing material scraps out lubricant existing in the textured grooves; therefore, lubricant is provided to other grooves. In addition, we believe that soft EHL generated at contact areas between the opposing material and the textured surface at the ribs had an effect on friction reduction [25]. Silicone rubber was softer than polypropylene. We believe that when the opposing material slides on the textured surface, the opposing material deforms at the contact areas because the hydrodynamic pressure is generated in the grooves. The hydrodynamic pressure increases as the area to flow lubricant narrows [8,24-25]. Thus, the hydrodynamic pressure increases most at the lubricant inlet of a rib. Thus, the opposing material deforms most at the lubricant inlet of the rib. We believe that when the opposing material deforms, the lubricant is held in the deformed place at a microscopic level; thus, the lubricant is held at the contact areas (As shown in Fig. 10). If this effect does not occur, the lubricant flows laterally as the lubricant cannot flow forward, and lubricant cannot be provided at the contact areas in the rib. Thus, oil starvation occurs. However, the kinetic friction

decreased in this study. Therefore, we believe that the effect of soft EHL may also reduce friction. However, we did not study the above phenomenon experimentally. To discuss this mechanism in detail, we need to study the above effects by using visualization experiment in the future.

4.4. Amount of lubricant in grooves

As described in sections 3.1 and 3.2, in case the friction direction is perpendicular to the straight grooves, the kinetic friction changed for different values of pitch and depth even if the aspect ratio was the same, and a larger pitch resulted in a lower kinetic friction. We also observed that when the pitch was fixed and the depth was changed, a higher aspect ratio resulted in a lower kinetic friction. We think that these results are related to the amount of lubricant in the grooves. Thus, we tried to compare the amount of lubricant in grooves (As shown in Fig. 11 and Table 3). In the first experiment, compared to the oil groove cross-sectional area having a width of 280 μm , the cross-sectional area of P100-D13-AR0.13 was 1083 μm^2 and that of P50-D4-AR0.08 was 363 μm^2 (third part of P100-D13-AR0.13). The area of P25-D2.5-AR0.10 was 311 μm^2 (third point fifth part of D100-D13-AR0.13). As shown in Fig. 5, when the vertical load was 2.0 N, the kinetic frictions of P25-D2.5-AR0.10 (311 μm^2), P50-D4-AR0.08 (363 μm^2), and P100-D13-AR0.13 (1083 μm^2) were 0.56 N, 0.36 N, and 0.15 N, respectively. The kinetic friction decreased with increasing oil groove area. This result was also confirmed in the second experiment. As shown in Table 4, the area of the oil groove increased with increasing the depth of the groove. Compared to the oil groove cross-sectional area having a width of 280 μm , the cross-sectional areas of P100-D20-AR0.20, P100-D13-AR0.13, P100-D4.8-AR0.05 were 1815 μm^2 , 1083 μm^2 , and 826 μm^2 , respectively. As shown in Fig. 7, when the vertical load was 2.0 N, the kinetic frictions of P100-D4.8-AR0.05 (826 μm^2), P100-D13-AR0.13 (1083

μm^2), and P100-D20-AR0.20 (1815 μm^2) were 0.20 N, 0.15 N, and 0.08 N, respectively. The kinetic friction also decreased with increasing oil groove area. Thus, textured samples, which are processed with a large oil groove area, have a low kinetic friction in order to maintain fluid film lubrication. Oil starvation is generated easily in textured samples processed with a small oil groove area when the vertical load increases because the opposing material deforms and scraps out lubricant in the grooves based on the vertical load. As a result, it was observed that the kinetic friction varied based on the depth and pitch even if the aspect ratio was the same. Furthermore, when the pitch was fixed and the depth was changed, a higher aspect ratio resulted in a lower kinetic friction.

On the other hand, we believe that, except the amount of lubricant, the pitch and depth of the textured structure (shape of the textured structure), and the deformation volume of the opposing material are also related to the hydrodynamic pressure (section 4.1). Thus we think it is necessary to set an optimal pitch and depth

Fig. 11 Comparison of oil grooves

Table 3 Lubricant area comparison of lubricant's cross-section area for 280 μm (Aspect ratio around 0.1)

Sample	Aspect ratio	Depth (μm)	Pitch (μm)	Lubricant Area (Range 280 μm) (μm^2)
P100-D13-AR0.13	0.13	13	100	1083
P50-D4-AR0.08	0.08	4	50	363
P25-D2.5-AR0.10	0.10	2.5	25	311

Table 4 Lubricant area comparison of lubricant's cross-section area for 280 μm (pitch was fixed 100 μm)

Sample	Aspect ratio	Depth (μm)	Pitch (μm)	Lubricant Area (Range 280 μm) (μm^2)
P100-D20-AR0.20	0.20	20	100	1815
P100-D13-AR0.13	0.13	13	100	1083
P100-D4.8-AR0.05	0.05	4.8	100	826

in view of the hydrodynamic pressure, amount of lubrication, and deformation volume of the opposing material. More detailed studies are required in the future.

4.5. The effect of viscoelastic dissipation

As the opposing material used in this study was rubber, viscoelastic dissipation should be discussed. Viscoelastic dissipation affects friction more effectively when the opposing materials directly contact the textured substrate without a lubricant. However, on the application of a lubricant, friction is reduced compared to that with viscoelastic dissipation. Thus, we believe that other effects (section 4.1-4.4) mainly affect friction compared to viscoelastic dissipation. However, we believe that the effect of viscoelastic dissipation is also important; therefore, we need to study it in more detail in the future.

We believe that the effects mentioned above interact in a complex manner and reduces the kinetic friction by acting simultaneously when a material is slid on another. Apart from these effects, there may be other effects also that may affect the kinetic friction of sliding materials. Thus, more studies are required to understand the effect of textured structures on reducing friction between soft materials.

In this study, we confirmed that the kinetic friction between silicone rubber that simulated the softness of the human body and polypropylene used for medical devices was reduced by processing a textured structure. Therefore, we believe that a textured structure has the potential to reduce friction caused between medical devices and body tissue in the future. In addition, this study contributes to a fundamental study of soft EHL.

5. Conclusion

Our findings are summarized as follows:

- The kinetic friction in a direction perpendicular to the straight grooves decreased more compared to that in a direction parallel to the straight grooves.
- The kinetic friction changed for different values of pitch and depth even if the aspect ratio was the same in a direction perpendicular to the straight grooves.
- When the pitch was fixed and the depth was changed, a higher aspect ratio resulted in a lower kinetic friction in a direction perpendicular to the straight grooves.
- The kinetic friction between soft-materials was lower compared to that between hard materials.
- We believe that these effects that reduce the friction between soft materials are specific only to soft materials.

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