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RESEARCH ARTICLE

# Softness Perception Interfered by Friction in Gliding Virtual Surfaces

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**ABSTRACT** Recent studies have shown that surface friction affects softness perception when objects are slid over using fingers. This study examines whether this phenomenon extends to interactions with virtual objects using a stylus-based haptic interface, which independently controls friction and object stiffness. In Experiment 1, we investigated how kinematic friction coefficients influence perceived stiffness. Results showed that surfaces with minimal friction (coefficient $= 0$) were perceived as stiffer than those with higher friction ($\geq 0.2$). For instance, a surface with a stiffness of 500 N/m at minimal friction was perceived as equivalent to 581.7 N/m at a friction coefficient of 0.4. However, the perceived stiffness was not different under frictional conditions, with coefficients ranging from 0.2 to 0.6. Experiment 2 evaluated participants' ability to discriminate stiffness levels (400 N/m vs. 500 N/m and 500 N/m vs. 600 N/m) under three friction conditions (0, 0.25, and 0.5). Discrimination accuracy declined with increasing friction. These findings provide valuable insights for designing haptic interfaces and virtual reality applications, enabling developers to optimize user experiences by accounting for the interplay between friction and perceived softness.

**INDEX TERMS** Stylus, kinetic friction, softness, stiffness, sliding, gliding.

## I. INTRODUCTION

Softness is one of the most prominent haptic properties [1], [2], [3], and it is largely determined by mechanical stiffness, such as spring coefficient and elastic modulus [4], [5], [6], [7], [8], [9], [10], [11]. Recently, in a setting where actual object surfaces were slid over using fingers [12], surface friction was found to influence softness judgment, providing insights relevant to the fields of cosmetics and coating [13], [14]. Researchers compared synthetic skins made of rubber with several types of powdery lubricants [12]. The surfaces with less frictional lubricants were judged softer. In natural contexts, sliding motions are employed as frequently as pressing motions to evaluate softness [15], [16]. Nonetheless, earlier researchers have primarily studied softness perception through pressing motions.

Until now, except for the study by [12], only a few studies have investigated the perception of object softness during sliding [17], [18], where the perceptual effects of different surface profiles were discussed using actual specimens. Hence, the effects of surface friction on softness judgment have not been thoroughly studied. The objective of this study is to test the influence of friction on softness judgment, involving objects with different stiffness and friction, whereas the previous study [12] compared objects of the same stiffness but different friction. For this purpose, we employ virtual surfaces rendered by a commercial force feedback device. Such devices allow us to easily control object stiffness and friction. If the surface friction of an object influences its softness judgment during interaction with virtual objects, then developers of virtual reality applications need to be aware of this effect because the perceived stiffness of a virtual object can vary solely by changing the surface frictional property.

Furthermore, it is meaningful to compare the effects of friction on softness judgment between the bare-finger condition and the kinesthetic condition. Several researchers [4], [19], [20] agree that when objects are pressed, both tactile

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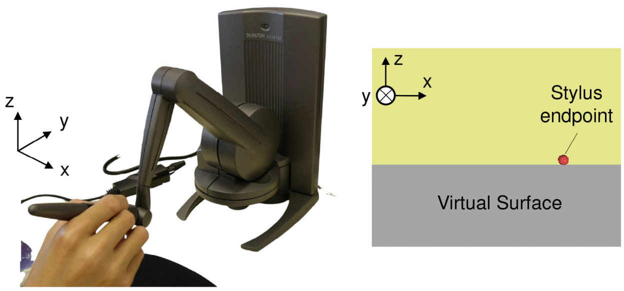

**FIGURE 1.** **Force feedback device used in the experiments. Participants held the stylus of the device and slid it horizontally over virtual surfaces to explore their stiffness.**

and kinesthetic cues play important roles through studies where available cues for softness judgment were controlled. A similar comparison also needs to be performed for sliding conditions in softness judgment. This study provides additional insights into the literature on studies involving bare fingers and styluses.

The comparison between kinesthetic and bare finger or tactile conditions has often been treated as a comparison between point contact and surface contact. When considering the contact between a fingertip and an object, simulating adhesive friction, which depends on the contact area [21], [22], the contact area is explicitly considered [23], [24], [25]. In contrast, haptic simulations using commercial haptic displays primarily involve interaction through a rigid tool [26], [27], [28]. Under these conditions, based on rigid body assumptions, changes in the contact area are typically not computed. To present softness, the effectiveness of combining tactile displays with kinesthetic force display devices has been demonstrated [7], [29].

When a finger slides over a compliant surface, both the restoring force of the deformed surface and friction forces are generated. If the resultant force is not correctly decoupled, accurate stiffness judgment becomes difficult [12]. This interference of friction with stiffness perception can occur in two ways: altering perceived stiffness due to friction (Experiment 1) and impairing the accuracy of stiffness judgment (Experiment 2). This study consists of two experiments. In Experiment 1, we explore pairs of stimuli that are perceived as equally soft despite differences in stiffness and friction. The results reveal the relationship between the spring coefficient and the coefficient of friction in an interchangeable manner. In Experiment 2, we investigate how friction affects the process of softness judgment, experimentally demonstrating that the presence of large friction prevents correct judgment of stiffness. These experiments extend the authors' previous works [30], [31], which used limited stimulus levels and simplified experimental protocols. This study complements our previous research in a more general and robust manner.

## II. METHODS COMMON FOR EXPERIMENTS 1 AND 2

### A. APPARATUS: FORCE DISPLAY DEVICE

As shown in Figure 1, we used a commercial haptic device, Phantom Touch X (SensAble Technologies Inc., MA, USA), to simulate virtual planes with varying levels of stiffness and friction. These virtual planes were arranged parallel to the tabletop. The device enables interaction with virtual objects using a stylus, providing the user with a three degrees-of-freedom force feedback experience. The nominal maximum force output is 7.9 N in each direction. The control frequency was set to 1 kHz. Participants interacted with the device while seated comfortably at a table, with the haptic device positioned directly in front of them.

### B. COMPLIANT AND FRICTIONAL PLANE

Virtual stimuli—elastic plates with surface friction—were designed by using OpenHaptics (3.5.0, SensAble Technologies Inc., MA, USA). The stiffness of the virtual plane was modeled using Hooke's law, characterized by a spring constant $k$ (N/m). The reaction force perpendicular to the plane was proportional to the penetration of the stylus's tip into the virtual plane along the z-axis ($\delta$ (m)), and was calculated by:

$$f_z = k\delta. \tag{1}$$

The plane did not deform; hence, the stiffness of the plane could not be visually judged.

The kinetic friction force was modeled using the following equations:

$$(f_x, f_y)^\top = -\frac{\boldsymbol{v}}{|\boldsymbol{v}|}\mu(\boldsymbol{v})f_z, \tag{2}$$

$$\mu(\boldsymbol{v}) = \mu_0\left(\frac{2}{\pi}\right)\mathrm{Tan}^{-1}\left(\frac{|\boldsymbol{v}|}{0.05}\right), \tag{3}$$

where $\boldsymbol{v} = (v_x, v_y)^\top$ (m/s) is the two-dimensional sliding velocity of the stylus over the plane, with $|\bullet|$ representing the $L^2$ norm. The nominal value of the friction coefficient is $\mu_0$. An arctangent function was employed to eliminate discontinuities in the frictional force near zero velocity, a standard strategy to maintain continuity in friction forces [32]. The denominator in the arctangent function defines the velocity range over which the kinetic force transitions smoothly. This velocity threshold, set at 0.05 m/s, was determined through preliminary tests to ensure stable frictional forces without noticeable vibrations. Static friction, which can induce disruptive vibrations known as stick-slip phenomena [33], [34], was not simulated. Consequently, this study focuses on examining the effects of kinetic friction on softness perception.

### C. EXPLORATORY PROCEDURES

At the beginning of the experiment, each participant familiarized themselves with the haptic device and the interaction with the virtual planes for a few minutes. They were instructed to glide along the mediolateral (x-axis) direction. Gliding velocities were monitored, and participants were encouraged to maintain an average speed exceeding 50 mm/s. None of the participants had difficulty maintaining this speed.

During the main sessions, participants slid the stylus across the surface of each plane to assess the level of stiffness.

Stiffness was defined as follows: the stiffer the object, the greater the force required to displace the surface along the vertical direction. They were instructed to maintain a consistent and comfortable speed and load while exploring different objects. The normal force and gliding velocity were continuously monitored by the experimenters, and participants received instructions as needed. For example, if excessive force caused unintended vibrations in the haptic device, participants were prompted to use less force. Additionally, participants were instructed not to press down on the plane without incorporating lateral sliding motion.

Participants used their dominant hand to control the stylus and their non-dominant hand to control a mouse. The experimental task was a paired-comparison, where a reference and test stimulus were contrasted. Switching between the test surface and the reference surface was conducted by clicking the left and right mouse buttons, allowing for direct comparison. The allocation of the two surfaces was random for each trial.

### D. ETHICAL STATEMENT

The study protocol was approved by Institutional Review Board, Hino Campus, Tokyo Metropolitan University (H22-031).

## III. EXPERIMENT 1: SOFTNESS PERCEPTION ALTERED BY FRICTION

### A. PROCEDURES

The experiment was designed to determine the subjective equality of perceived stiffness under different friction coefficient $\mu_0$ values. For this purpose, we utilized the dynamic staircase method [35] in conjunction with the two-alternative forced choice task.

Participants were allowed to freely compare the reference (500 N/m or 250 N/m) and test stimulus (varying stiffness) at each trial. The coefficients of friction were different for the test and reference stimuli. The initial stiffness value of the test stimulus was either 300 N/m or 700 N/m for the reference of 500 N/m, and 100 N/m or 400 N/m for the reference of 250 N/m. These initial values were randomized in a counterbalanced manner for each individual. The highest reference stiffness was set to 500 N/m, as it was sufficiently smaller than 700 N/m, considering the discrimination threshold for stiffness in force displays [8]. Additionally, we limited the number of reference stiffness levels to two, based on findings by Cholewiak et al. [36], which reported that 2–3 stiffness levels could be reliably identified using a force display device with a maximum output of 5.0 N.

After exploring the surfaces at each trial, participants judged which surface felt stiffer. The reference surface had fixed stiffness, whereas as shown in Fig. 2, the stiffness of the test surface was adjusted either upwards or downwards by a step size, depending on the participant's judgment, such that the perceived stiffness of the test surface gradually approached that of the reference surface. The experiment continued until four shifts in the direction of participant responses were observed. The step size was halved after two shifts. The initial step size was 100 N/m and 50 N/m for the reference stiffness of 500 N/m and 250 N/m, respectively.

### B. STIMULI

With the experimental setup in this study, the coefficient of friction could be stably increased up to 0.6. The $\mu_0$ values greater than 0.6 tended to cause vibratory behavior of the stylus and were not employed in the study. We set four friction levels to investigate how perceived stiffness varied with the friction level. Hence, six combinations of the coefficients of friction ($\mu_0$) for the reference and test stimuli were adopted. They were designed as follows:

1) Test surface: $\mu_0 = 0.2$ and reference: $\mu_0 = 0$
2) Test surface: $\mu_0 = 0.4$ and reference: $\mu_0 = 0$
3) Test surface: $\mu_0 = 0.6$ and reference: $\mu_0 = 0$
4) Test surface: $\mu_0 = 0.4$ and reference: $\mu_0 = 0.2$
5) Test surface: $\mu_0 = 0.6$ and reference: $\mu_0 = 0.4$
6) Test surface: $\mu_0 = 0.6$ and reference: $\mu_0 = 0.2$

Each of these six cases was conducted twice with different initial stiffness values of the test stimuli. In total, there were 24 series (two reference stiffness levels × six friction cases × two initial stiffness values) for each participant.

This experiment aimed to examine how the perceived stiffness of surfaces with nonzero friction coefficients ($\mu_0 \neq 0$) differs from that of a surface with zero friction ($\mu_0 = 0$). In principle, three stimulus comparison pairs—such as pairs (0, 0.2), (0, 0.4), and (0, 0.6)—are sufficient to estimate the relative stiffness at each friction level. However, including additional pairs enables the use of a least squares method, which helps to reduce the influence of observational noise and ensures consistency across the estimated stiffness values for different $\mu_0$ conditions.

### C. PARTICIPANTS

Twenty university students (11 males and 9 females; average age: 23.3 years) in their 20s participated in the study. The purpose of the study was not disclosed to the participants before the experiment. All participants provided written informed consent prior to the experiment.

### D. DATA ANALYSIS

To determine the point of subjective equality, the mean stiffness at the last two reversal points was calculated for each experimental series. These points were then averaged across two series with different initial stiffness values for individual participants.

We solved the following simultaneous equations to determine the subjectively equal stiffness values under different

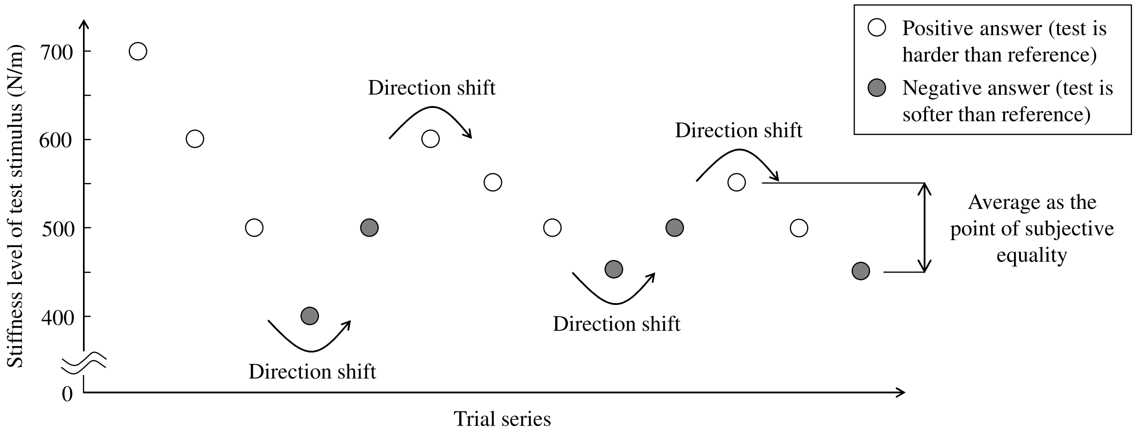

**FIGURE 2.** Illustration of the staircase method in a descending series, where the test stimulus starts at 700 N/m and decreases. The stimulus presentation order shifts four times before completing a single task. After two shifts, the step size of stiffness adjustment is halved from 100 N/m to 50 N/m, as shown in this example with the reference stimulus of 500 N/m.

$\mu_0$ values. Here, the analytical model is formulated as:

$$\begin{cases} \bar{k}_0 = k_{0.2}^{(1)} + \Delta k_{0\text{-}0.2} \\ \bar{k}_0 = k_{0.4}^{(2)} + \Delta k_{0\text{-}0.4} \\ \bar{k}_0 = k_{0.6}^{(3)} + \Delta k_{0\text{-}0.6} \\ k_{0.4}^{(4)} - \bar{k}_{0.2} = \Delta k_{0\text{-}0.2} - \Delta k_{0\text{-}0.4} \\ k_{0.6}^{(5)} - \bar{k}_{0.4} = \Delta k_{0\text{-}0.4} - \Delta k_{0\text{-}0.6} \\ k_{0.6}^{(6)} - \bar{k}_{0.2} = \Delta k_{0\text{-}0.2} - \Delta k_{0\text{-}0.6} \end{cases} \tag{4}$$

where $\bar{k}_0$, $\bar{k}_{0.2}$, and $\bar{k}_{0.4}$ are the spring constants of reference stimuli presented at $\mu_0 = 0$, 0.2, and 0.4, respectively: 500 or 250 N/m. $k_\mu^{(i)}$ is the stiffness perceived as equal to the reference stiffness in N/m at $\mu_0 = \mu$ for the $i$-th test condition described in Section III-B. $\Delta k_{\mu_i\text{-}\mu_j}$ is the perceived difference in stiffness between different $\mu_0$ values. The three $\Delta k$ values are unknown variables and were determined as the least-squares solutions of the six equations.

For example, consider the case where the reference stiffness is 500 N/m. For the first test condition ($i = 1$), refer to the first equation in (4). In this condition, the reference and test stiffness were presented at $\mu_0 = 0$ and 0.2, respectively. The reference stiffness at $\mu_0 = 0$ is $\bar{k}_0 = 500$ N/m. Assume that 500 N/m at $\mu_0 = 0$ is subjectively equal to 570 N/m at $\mu_0 = 0.2$ for a participant, thus $k_{0.2}^{(1)} = 570$. The difference between these stiffness values is $\Delta k_{0-0.2} = -70$ N/m. Similarly, assume that $\Delta k_{0-0.4}$ is determined from the second test condition ($i = 2$), for example, $\Delta k_{0-0.4} = -100$ N/m.

In the fourth condition ($i = 4$), the difference in perceived stiffness at two friction levels, $\mu_0 = 0.2$ and 0.4, is also investigated. If 500 N/m at $\mu_0 = 0.2$ is subjectively equal to 530 N/m at $\mu_0 = 0.4$, then the left side of the fourth equation is $k_{0.4}^{(4)} - \bar{k}_{0.2} = 530 - 500 = 30$. This is balanced by the right side, i.e., $\Delta k_{0-0.2} - \Delta k_{0-0.4} = -70 - (-100) = 30$. However, when using the results of the experiment, the fourth equation may not hold exactly due to the variation in test results. In such cases, the $\Delta k$ values are determined by minimizing the errors for each equation in (4).

For each participant, we calculated the $\Delta k$ values. Finally, for each coefficient of friction, that is, $\mu_0 = 0.2, 0.4$, and 0.6, the stiffness subjectively equal to 500 or 250 N/m at $\mu_0 = 0$ was calculated as follows:

$$k_{0.2} = \bar{k}_0 - \Delta k_{0-0.2} \tag{5}$$

$$k_{0.4} = \bar{k}_0 - \Delta k_{0-0.4} \tag{6}$$

$$k_{0.6} = \bar{k}_0 - \Delta k_{0-0.6}. \tag{7}$$

These values were averaged across participants, and a repeated-measures analysis of variance (ANOVA) was conducted to compare the effects of different $\mu_0$ values. Following a significant ANOVA result, pairwise $t$-tests were performed with a Bonferroni correction factor of six to account for multiple comparisons.

Before conducting the statistical tests, the normality of the samples was assessed using Shapiro-Wilk tests. For all pairs of $\mu_0$ values, the assumption of normality was not rejected at the 0.05 significance level for either reference stiffness value.

### *E. RESULTS*

Fig. 3 shows the results of Experiment 1 for each of the two levels of reference stiffness.

When the reference stiffness was 500 N/m, the omnibus ANOVA revealed a significant difference among the four perceived stiffness values ($F(3, 57) = 11.38$, $p < 0.001$). The average perceived stiffness $k_{0.2}$ for $\mu_0 = 0.2$ was 602.2 N/m, with a 95% confidence interval (CI) of ±65.1 N/m. This stiffness value is barely greater than the reference stiffness $k_0 = 500$ N/m ($t(19) = 2.98$, $p = 0.046$). Under the condition of $\mu_0 = 0.4$, the average $k_{0.4}$ was 585.5 N/m, which is also greater than the reference (95% CI $= \pm 50.5$, $t(19) = 3.12$, $p = 0.027$). The average $k_{0.6}$ was 562.1 N/m (95% CI $= \pm 40.7$, $t(19) = 2.85$, $p = 0.061$). For $\mu_0 = 0.2$, 0.4 and 0.6, the surfaces were perceived barely softer than those for $\mu_0 = 0$, although the $p$-value was greater than 0.05 for $\mu_0 = 0.6$ with the Bonferroni correction

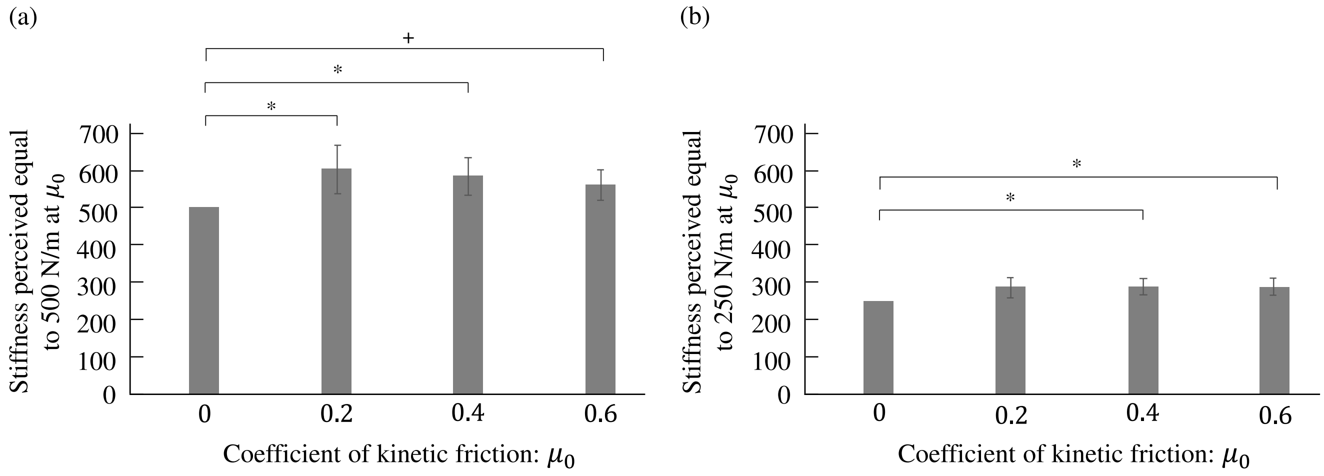

**FIGURE 3. Mean stiffness values subjectively equal to (a) 500 and (b) 250 N/m at $\mu_0 = 0$ for different $\mu_0$ values. Error bars are the standard errors among the participants.* and + indicates significant difference at $p < 0.05$ and 0.10, respectively, with Bonferroni correction of factor six.**

applied. Conversely, the stiffness values were not different among the three frictional conditions: $\mu_0 = 0.2, 0.4$, and 0.6.

When the reference stiffness was 250 N/m, the ANOVA exhibited a significant difference across the perceived stiffness values ($F(3, 57) = 11.16$, $p < 0.001$). The average $k_{0.2}$ was 289.0 N/m (95% CI = ±27.3). This stiffness value is not significantly different from 250 N/m ($t(19) = 2.50$, $p = 0.13$). The average $k_{0.4}$ was 290.3 N/m and greater than the reference (95% CI = ±22.1, $t(19) = 3.59$, $p = 0.012$). The average $k_{0.6}$ was 287.4 N/m (95% CI = ±22.8, $t(19) = 3.00$, $p = 0.044$). Among the three frictional conditions, the differences in perceived stiffness were not observed.

## IV. EXPERIMENT 2: SOFTNESS PERCEPTION DETERRED BY FRICTION

Following the observations from Experiment 1, where participants reported difficulties in comparing surfaces with different stiffness values at high coefficients of friction, we aim to investigate the effects of friction on the accuracy of stiffness judgments. We hypothesize that an increase in friction reduces the accuracy of stiffness judgments.

### A. PARTICIPANTS

Two different groups of thirteen university students participated in the tasks comparing 400 N/m vs. 500 N/m (10 males, 3 females; mean age: 23.2 years) and 500 N/m vs. 600 N/m (9 males, 4 females; mean age: 23.1 years), respectively. All participants provided written informed consent prior to the experiment. The objectives of this experiment were not explained to the participants in advance.

### B. STIMULI

Two pairs of stiffness values were employed for the discrimination task: $k = 400$ N/m vs. 500 N/m and 500 N/m vs. 600 N/m. In a preliminary study involving the authors and their colleagues (who did not participate in the main experiment), the mean correct answer proportion was approximately 0.75 for discerning these paired stiffness values, indicating a moderate level of difficulty. Furthermore, the experiment incorporated three distinct nominal coefficients of friction: $\mu_0 = 0, 0.25$, and 0.5. It is noted that two stiffness values were compared at the same $\mu_0$ value in a single trial.

### C. PROCEDURES

Prior to the main experiment, participants underwent a two-stage training process to accommodate those with limited experience using force feedback devices.

The first stage involved familiarization with the operation of the force feedback device. Participants slid the stylus on frictional surfaces with coefficients of friction set at 0.25 and stiffness values at 350 N/m and 500 N/m, presenting a difference of 150 N/m, which exceeds the difference used in the main experiment. Participants were allowed to slide and explore the two surfaces for as long as they desired. Participants then identified the stiffer surface. Feedback regarding the accuracy of each selection was provided. Once participants made correct judgments five times in a row, they progressed to the second stage.

In the second stage, using the same stimulus parameters as the first stage, participants slid over each surface twice before selecting the one they perceived as stiffer. The main difference between the first and second stages was the number of sliding motions designated. Participants who made five consecutive correct choices progressed to the main experiment.

In the main experiment, participants compared the stiffness values of 400 N/m and 500 N/m or 500 N/m and 600 N/m under three frictional conditions: frictionless ($\mu_0 = 0$), low friction ($\mu_0 = 0.25$), and high friction ($\mu_0 = 0.5$). Under each frictional condition, 20 trials were conducted per participant. The sequence of friction conditions was randomized to avoid order effects. Similar to the second training stage, participants were allowed to slide each surface only twice before making a judgment.

### D. DATA ANALYSIS

For the comparison between 400 N/m and 500 N/m, one male participant was unable to advance to the second stage as he failed to meet the criterion even after 20 attempts. In total, twelve participants proceeded to the main experiment.

The proportions of correct judgment were compared for every pair of friction conditions by using Wilcoxon signed-rank test with the Bonferroni correction of factor three.

### E. RESULTS

Fig. 4 presents the proportions of trials in which individual participants correctly identified the stiffer surface. Panel (a) corresponds to the comparison between 400 N/m and 500 N/m, while panel (b) shows the results for the comparison between 500 N/m and 600 N/m.

In the comparison between 400 N/m and 500 N/m (Fig. 4(a)), the stiffer surface was correctly identified in 0.78 ± 0.019 (mean ± standard error) of trials under the frictionless condition ($\mu_0 = 0$). This proportion was 0.74 ± 0.020 for $\mu_0 = 0.25$, and 0.67 ± 0.015 for $\mu_0 = 0.5$. The difference between $\mu_0 = 0$ and $\mu_0 = 0.25$ was not statistically significant ($T = 9.5$, $z = 1.49$, $p = 0.41$). In contrast, significant differences were observed between $\mu_0 = 0$ and $\mu_0 = 0.5$ ($T = 0$, $z = 2.91$, $p = 0.011$), as well as between $\mu_0 = 0.25$ and $\mu_0 = 0.5$ ($T = 1$, $z = 2.69$, $p = 0.021$).

In the comparison between 500 N/m and 600 N/m (Fig. 4(b)), the correct response proportions were 0.86 ± 0.027, 0.76 ± 0.026, and 0.67 ± 0.023 for $\mu_0 = 0, 0.25$, and 0.5, respectively. The proportions at $\mu_0 = 0$ were significantly higher than those at $\mu_0 = 0.25$ ($T = 8$, $z = 2.47$, $p = 0.041$) and $\mu_0 = 0.5$ ($T = 0$, $z = 3.49$, $p = 0.0015$). Additionally, performance at $\mu_0 = 0.25$ was significantly better than at $\mu_0 = 0.5$ ($T = 2.5$, $z = 2.81$, $p = 0.015$).

These results collectively indicate that increased kinetic friction impaired participants' ability to accurately judge the stiffness of surfaces during sliding, with performance declining under higher-friction conditions.

During the task comparing the 500 N/m and 600 N/m surfaces, we recorded the maximum pressing force in the $z$-direction for each participant. The mean values and standard errors across participants were $1.43 \pm 0.25$ N, $1.57 \pm 0.27$ N, and 1.50 ± 0.28 N for surfaces with $\mu_0 = 0$, 0.25, and 0.5, respectively. A two-way repeated measures ANOVA, with friction and stiffness levels as within-participant factors, revealed no significant effect of friction ($F(2, 24) = 1.25$, $p = 0.30$) or stiffness ($F(1, 12) = 1.18$, $p = 0.30$) on the pressing force.

## V. DISCUSSION

As described in Section I, previous studies on softness perception demonstrated that surfaces with higher friction coefficients are perceived as stiffer when rubbed by fingers [12]. This phenomenon is referred to as the paradox of softness perception because physically stiffer objects produce smaller friction forces.

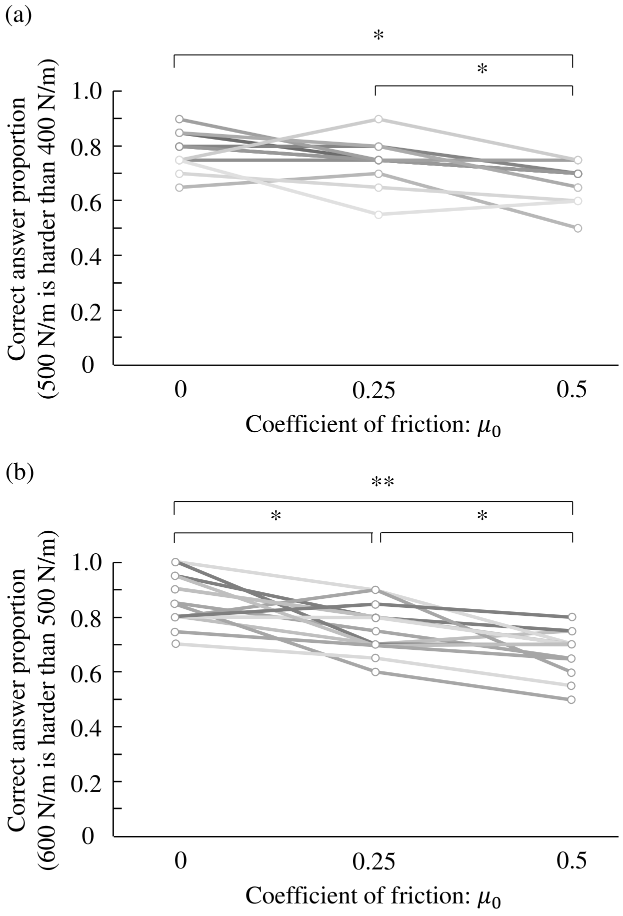

**FIGURE 4.** Accuracy of the thirteen participants in judging the stiffness of two planes with different stiffness values ((a) 400 vs. 500 N/m, (b) 500 vs. 600 N/m) under three different friction conditions ($\mu_0$ = 0, 0.25, and 0.5).* and ** indicates the significant difference at $p < 0.05$ and 0.01, respectively, with the Bonferroni correction of factor three.

However, our results in Experiment 1 revealed a different aspect: perceived stiffness was unaffected by the friction coefficient, except for $\mu_0 = 0$. Under this condition, the surface was perceived as stiffer compared to conditions where $\mu_0$ ranged from 0.2 to 0.6.

One possible explanation for the discrepancy between our findings and those of Arakawa et al. [12] lies in the perceptual cues available for softness judgment. While Arakawa et al. [12] primarily focused on tactile sensations, our study emphasized proprioceptive (or kinetic) feedback through stylus-mediated exploration. We speculate that the perceptual paradox of softness is attributable to tactile force perception at the finger skin, as opposed to the mechanical force perception employed during stylus use. Arakawa et al. [12] hypothesized that the paradox stems from the incorrect decoupling of normal and frictional forces applied to the skin. In contrast, during stylus-based exploration, mechanical receptors in the finger and wrist joints may more effectively decouple these forces, outperforming tactile-based perception. While this explanation remains speculative and requires further investigation, our findings offer new insights into the underlying mechanisms of the perceptual paradox of softness and friction.

The paradox of softness perception [12] was not observed in the setup of this study; however, surface friction influenced the stiffness judgment in the task using a force display device. The object was perceived as stiffer at $\mu_0 = 0$ than at $\mu_0 \geq 0.2$. To the best of our knowledge, such observations have not been previously reported. Although we have no clear explanation for this effect, one possibility is the influence of an internal model about the relationship between friction and stiffness. The adhesion and deformation friction increase as the elastic modulus of the object decreases, i.e., the softer the object, the more frictional it is [21], [37], and [38]. This physical relationship may be intuitively understood by people, suggesting that they may estimate more frictional objects as softer. An example of such internal models' effect on haptic perception is weight perception [39], [40], [41], [42].

It should be noted that the results of this study do not fully align with our earlier study [31], in which frictional planes were perceived as stiffer than less frictional ones when assessed using the magnitude estimation method. The earlier study utilized the same equipment as the present study, with the primary difference being the psychophysical method employed. The magnitude estimation method is typically applied when only a single type of quantity in stimuli changes [43], suggesting unclear validity toward our experimental condition where both friction and stiffness varied. In such cases, it cannot be entirely dismissed that participants may not have clearly differentiated between the stiffness and friction of the object surfaces because they relied on a descriptive criterion, i.e., "how stiff is this stimulus?" In contrast, in this study, participants directly compared referential and test stiffness in a paired comparison approach, where each judgment was made using a two-alternative forced choice task. This process is believed to yield more reliable results.

In Experiment 2, the increased friction made it more difficult to discern subtle differences in surface stiffness. This could be because frictional or tangential forces might have obscured the perception of the normal or restoring forces of the virtual surfaces made by linear springs. When the friction force is minimal, the perception of the normal force is less likely to be affected by friction forces. However, when the friction force is significant, judging the normal force requires the consideration or separation of two-axial forces, which could introduce cognitive load. A similar phenomenon was observed with the use of a tactile display [44], where the normal and tangential vibrations of the touch panel heightened the absolute perceptual thresholds for each other. That is, orthogonal physical quantities impeded the perception of each
other.

One potential explanation for the results in Experiment 2 is the masking effect. In our setup, both the restoring force of the compliant virtual object in the normal direction and the tangential frictional force are simultaneously produced. When both forces are applied to the stylus, accurately judging each force cue independently can be challenging. For example, physically correct force and additional moment cues presented by a haptic display can be naturally integrated rather than being recognized separately in presenting object stiffness [45]. However, the masking effect does not explain the results of Experiment 1. Moreover, if the masking effect interfered with softness judgment, it would be unreasonable for humans to frequently use rubbing motions when evaluating object softness [15], [16].

Another aspect of Experiment 2 is the force-constancy rule. According to [46], people tend to apply constant forces when sliding a stylus over virtual surfaces. If participants unconsciously maintained a constant resultant force while comparing different stiffness levels, the normal force component would have been relatively smaller at higher friction than at lower friction conditions. As suggested by [47], if small forces are inadequate for distinguishing between adjacent stiffness levels, participants may have experienced difficulties in discriminating stiffness when normal forces were low under high friction conditions. However, as reported in Section IV-E, we did not observe any significant differences in the normal forces across the various friction conditions.

This study is subject to several limitations, including variations in stimuli due to the equipment's capabilities and a limited pool of participants. The most significant limitation is that the experiment was conducted solely using a haptic device. Similar experiments need to be conducted using actual specimens and compared with the results of this study. We temporarily attempted to establish the experimental setup using actual specimens and a stylus; however, the manipulation of friction occasionally led to frictional vibrations [34], [48], [49], [50], which were not preferred for our objectives. Nevertheless, such comparative studies are necessary to draw general conclusions about the effect of surface friction on softness judgment. Additionally, the underlying mechanisms of the interaction between friction and perceived softness remain to be elucidated in future research.

A key takeaway from this study, as well as the previous work by [12], is that the same rendering or perceptual principles cannot always be applied equally to kinesthetic and tactile conditions. Although this caution has been raised by several researchers (e.g., [11], [51]), our study provides new insights into the sliding exploration of surfaces. Additionally, further studies on the interactions between softness and friction are needed, despite the tendency of researchers to speculate that mechanical stiffness properties are perceptual determinant of softness judgment [1], [2], [3].

## VI. CONCLUSION

This study examined the effects of friction on softness perception during interactions with virtual surfaces using a stylus-based haptic interface. Experiment 1 showed that surfaces with minimal friction ($\mu_0 = 0$) were perceived as stiffer than those with higher friction coefficients, despite identical stiffness. Experiment 2 revealed that increased friction reduced the accuracy of stiffness discrimination.

These findings highlight the importance of considering friction in the design of haptic interfaces and virtual reality applications, as it can significantly alter perceived softness and user experience. Future work should investigate these effects in real-world settings and further explore the interaction between tactile and proprioceptive cues in softness perception.

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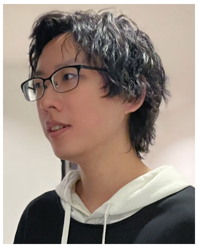

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