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Textural Feelings of Simulated Stick-Slip Phenomena via Stylus

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***Abstract*—Friction is a key factor in determining surface texture, but the influence of frictional vibrations or stick-slip phenomena on texture perception remains insufficiently explored. This study simulated virtual surfaces inducing stick-slip phenomena using a stylus-based commercial haptic interface. Virtual surfaces with varying static and dynamic friction coefficients were evaluated by 12 participants, who rated the friction, roughness, stickiness, hardness, and pleasantness of the surfaces using the Semantic Differential method. Multiple regression analysis, with friction parameters as explanatory variables and subjective ratings as response variables, revealed the following insights: An increase in the static friction coefficient significantly enhanced perceived friction, roughness, and stickiness while reducing the pleasantness experienced when sliding across the surfaces. An increase in the kinetic friction coefficient influenced only roughness perception, leading to a decrease in roughness ratings. Interestingly, an increase in kinetic friction did not enhance the perception of friction or stickiness during stick-slip vibration. The difference between static and kinetic friction coefficients significantly increased roughness ratings. These findings indicate that while the static friction coefficient primarily influences the evaluation of virtual surface textures, the kinetic friction coefficient and the difference between the two coefficients also contribute to determining certain perceived surface characteristics. This study enhances our understanding of the perceptual effects of dynamic frictional vibrations.**

***Index Terms*—friction, static, kinetic, Semantic Differential method, roughness, stickiness, pleasantness**

I. Introduction

Friction plays a crucial role in texture perception and is one of the primary perceptual dimensions [1]–[4]. When surface roughness is the dominant factor generating friction, roughness and friction perception are often confused and not clearly separated [5]. However, friction perception is also believed to originate from a distinct perceptual dimension that allows the assessment of surface adhesive properties [6], [7]. Humans' ability to perceive surface friction characteristics contributes to both conscious and unconscious grasping strategies for stable object manipulation [8], [9]. Additionally, it plays a role in material affinity to the skin [10], the perception of liquid purity [11], [12], textural discrimination [13]–[15], and the assessment of skin condition [16]–[20].

When a finger or stylus slides over a surface, shear resistance provides a cue for perceiving the frictional properties of the surface. In scenarios where a bare finger interacts with a surface, under static friction or stable kinetic friction conditions, the frictional force quasi-statically stretches the skin of the fingertip. The intensity of this stretching primarily determines friction perception [21], [22].

Friction exhibits dynamic behavior, with one of the most notable examples being the stick-slip phenomenon. This phenomenon arises due to the difference between static and kinetic friction, leading to high-frequency oscillations where two contacting objects alternate between sticking and slipping as they attempt relative motion [23]. In elastic bodies such as human fingers, an intermediate state known as partial slippage occurs between full adhesion and full slippage [24]–[26], contributing to the perception of contact conditions [8], [9].

However, how humans infer material texture properties from stick-slip phenomena has been scarcely investigated. One intriguing study reported that this phenomenon is used to distinguish the purity of a liquid—whether it is clean water or contains impurities such as oil [11]. This suggests that dynamic friction phenomena may serve as a criterion for evaluating water cleanliness. Furthermore, frictional vibrations may have an equal or greater influence on the perception of surface tactile quality compared to the average friction level [27]–[30]. For example, Kawazoe and Miki reported that the variation in friction force plays a dominant role in judging surface moisture levels [30]. Conversely, smaller fluctuations are associated with a more preferable fabric texture [29].

Thus, the stick-slip phenomenon has a certain impact on the perception of surface friction conditions. However, previous studies have not systematically investigated this influence. One reason for this is that the occurrence of stick-slip phenomena depends on sliding velocity, normal load [23], [31], and the sliding direction relative to the fingertip [32], [33], making it difficult for participants to consistently experience and evaluate the phenomenon when rubbing a material with a bare finger [34]. In this study, we use a commercial haptic display to control the frictional properties of a virtual surface and simulate the stick-slip phenomenon. Participants evaluate these simulated stick-slip stimuli. To determine which types of textural properties are influenced by the stick-slip phenomenon, we examine the relationship between the friction coefficients that govern this phenomenon and the perceived intensities of multiple surface attributes—roughness, friction, hardness, and pleasantness—using the Semantic Differential (SD) method.

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Fig. 1. Apparatus. A commercial haptic interface (Phantom Touch X) was used to implement stick-slip stimuli on a virtual plane.

To the best of our knowledge, no prior study has investigated the perception of controlled stick-slip stimuli. This research serves as a foundation for addressing this gap in the field of haptics.

II. Methods

A. Apparatus

In our experiment, we used a commercial haptic device (Phantom Touch X, 3D Systems Inc., MA) with three-dimensional force feedback to simulate the stick-slip phenomenon, as shown in Fig. 1. The device enabled interaction with virtual objects through a stylus. Thus, our study focuses on sliding friction under a point-contact condition. Participants sat facing the haptic device, which was placed on a table, and operated it with their dominant hand.

B. Simulated stick-slip stimuli

The stick-slip phenomenon is caused by the difference between the coefficients of static and kinetic friction [35]. In this experiment, we presented different stick-slip stimuli by controlling these coefficients at multiple levels on a virtual plane. While maintaining a balance between the stability of the haptic interface and the realism of the friction phenomenon, several models for switching between the static and kinetic friction have been proposed by many researchers [36]. In this study, as the simplest implementation method, we used the *setFriction* function from the OpenHaptics Toolkit (3.5.0, 3D Systems Inc., MA). This function determines the coefficients of static friction (μ_s) and kinetic friction (μ_k) on the surface of virtual objects. However, since the *setFriction* function is an undocumented builtin function, it should be noted that the exact implementation algorithm for static and kinetic friction is not fully known.

Table I shows the combinations of μ_s and μ_k used in this experiment. By varying the values of μ_s and μ_k, we created ten types of stimuli. The values of μ_s and μ_k were divided into four levels, including 0, to make the changes in the stick-slip phenomenon on the virtual plane. Additionally, due to the constraints of the *setFriction* function, μ_s was set to be greater

TABLE I
COMBINATION OF THE COEFFICIENTS OF STATIC AND KINETIC FRICTION.

Stimulus no.	Static friction μ_s	Kinetic friction μ_k
1	0	0
2	0.15	0
3	0.15	0.15
4	0.3	0
5	0.3	0.15
6	0.3	0.3
7	0.45	0
8	0.45	0.15
9	0.45	0.3
10	0.45	0.45

than μ_k. The maximum values for both μ_s and μ_k were set to 0.45 in order to maintain the stability of the haptic device.

Figure 2 presents examples of rapid changes in friction force over a 200 ms interval under the stimulus conditions used in the experiment. These forces were recorded using the *getForce* function from the OpenHaptics Toolkit, without the use of any external measurement instruments.

Figs. 2(a) and 2(b) show tangential forces where μ_s and μ_k were set to 0.45 and 0, respectively, but with different sliding speeds and normal loads. The zigzag patterns in the force profiles reflect the alternating stick and slip phases of the stylus on the virtual surface. The resistance increased during the stick phase of the stylus and decreased when transitioning to the slip phase. Comparing (a) and (b), the frictional vibration (force and frequency) varied depending on the normal force and sliding speed. Fig. 2(c) shows the friction force when μ_s and μ_k were set to 0.3 and 0.15, respectively. In these figures, the frequencies of the frictional vibrations were approximately 80, 90, and 100 Hz, indicating that the frequencies depend on both the frictional parameters and the operators' manipulation.

C. Participants

Twelve university students (6 females, 6 males; aged 21–24 years) participated in the experiment. They were unaware of the experiment's purpose beforehand and provided written informed consent prior to participation.

D. Ethical statements

This study protocol was approved by the institutional review board of Hino Campus, Tokyo Metropolitan University (Approval No. H22-031).

E. Procedures

During the training phase preceding the main experiment, participants familiarized themselves with the operation of the haptic interface. They were guided by the experimenter on how to maintain a stable interaction with the device. This phase lasted approximately one minute.

In the main experiment, combinations of friction coefficients, as shown in Table I, were randomly assigned to the virtual surfaces. Participants rubbed each surface within a one-minute time limit with no restricted exploratory motion and completed a questionnaire at the end of each trial. Details of

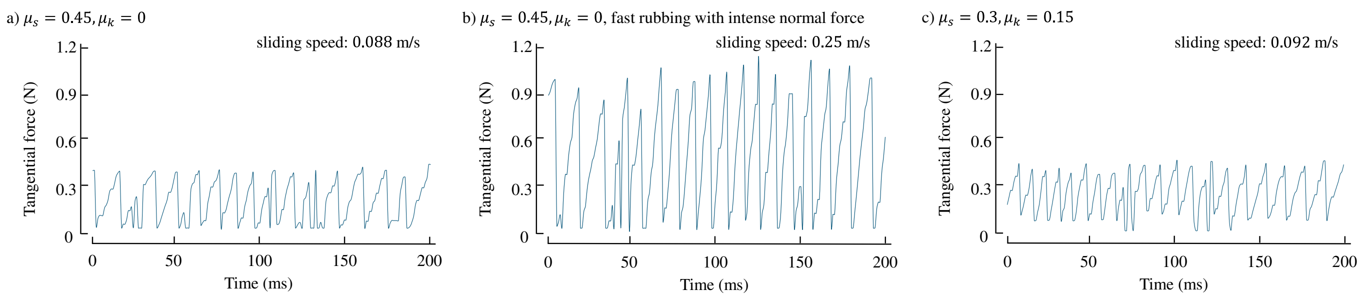

Fig. 2. Tangential force and sliding speed measured by the haptic device. (a) $\mu_s = 0.45$, $\mu_k = 0$ with natural contact force and sliding speed. (b) $\mu_s = 0.45$, $\mu_k = 0$ with intense contact force and fast speed. (c) $\mu_s = 0.3$, $\mu_k = 0.15$ with natural contact force and sliding speed.

the questionnaire are provided in Section II-F. Each participant experienced each stimulus condition twice in a randomized block design, resulting in a total of 20 trials.

F. Questionnaire items for Semantic Differential method

The primary objective of this study is to investigate the types of textural properties humans perceive from stick-slip phenomena. To achieve this, we employed the Semantic Differential (SD) method [37] to examine differences in impressions arising from varying friction parameters. In this method, participants rated multiple adjective dyads on a scale of 9 points with the central point representing a neutral response. We used five dyads: frictional–not frictional, rough–not rough, sticky–not sticky, hard–soft, and pleasant–unpleasant.

To select the five evaluation items, we referred to studies on haptic dimensions [3], [4], [38]. The five items cover those frequently used in previous research on material texture perception, excluding those related to thermal sensations. Additionally, to examine the impressions induced by friction parameters in greater detail, the items frictional and sticky were separately rated. Friction was defined as the level of difficulty in sliding over the surface or the magnitude of resistance forces encountered during sliding. Stickiness was defined as the intensity of effort required for the stylus to overcome stuck states. Furthermore, as friction is a preferential factor [10], [29], we included the item pleasantness in the evaluation.

G. Data analysis

Subjective scores were normalized for each item using z-scores to account for individual differences. The normalized scores for each evaluation item were used as the dependent variable, with μ_s and μ_k as the independent variables, and multiple linear regression analysis was applied. Additionally, a separate regression analysis was performed with μ_s and $\delta = \mu_s - \mu_k$ as the independent variables. This is because one of the main factors causing the stick-slip phenomenon is the difference between the two friction coefficients [23], [35], and this difference may affect the surface tactile sensation. It is noted that these two types of analyses are statistically equivalent, as only two of the three parameters (μ_s, μ_k, and δ) are free parameters. Furthermore, for each subjective item, the correlation between the subjective scores and μ_s, μ_k, and δ was calculated.

III. RESULTS

Table II presents the correlation coefficients between each friction parameter (μ_s, μ_k, and δ) and the subjective scores, along with the results of the test for no correlation.

The static friction coefficient μ_s showed strong correlations with the friction and stickiness scores (friction: $r = 0.77$, stickiness: $r = 0.72$). Additionally, μ_s exhibited a moderate negative correlation with pleasantness ($r = -0.40$). The correlation coefficient for roughness was $r = 0.35$, indicating a weak correlation, while a marginal correlation was observed with hardness ($r = 0.19$).

The kinetic friction coefficient μ_k showed weak correlations with the friction, stickiness, and roughness scores (friction: $r = 0.31$, stickiness: $r = 0.27$, roughness: $r = 0.18$). No significant correlation was found with the other evaluation terms (hardness: $r = 0.11$, pleasantness: $r = -0.13$).

The difference between static and kinetic friction coefficients, δ, showed moderate correlations with friction, roughness, and stickiness (friction: $r = 0.46$, roughness: $r = 0.48$, stickiness: $r = 0.45$). Additionally, a weak negative correlation was found with pleasantness ($r = -0.27$), while no correlation was observed with hardness ($r = 0.082$).

We are particularly interested in the δ values, as they are the primary cause of stick-slip phenomena. Therefore, we present scatter plots of subjective scores against δ, as shown in Fig. 3.

Table III shows the results of regression analysis with subjective scores as the dependent variables and μ_s and μ_k as the independent variables. For all dependent variables except for hardness, μ_s had a significant effect (friction: $p = 3.7 \times 10^{-22}$, roughness: $p = 7.4 \times 10^{-17}$, stickiness: $p = 4.9 \times 10^{-19}$, pleasantness: $p = 1.0 \times 10^{-5}$). On the other hand, for hardness, $p = 0.089$, indicating that the effect of μ_s was not significant. The only dependent variable for which μ_k had a significant effect was roughness ($p = 0.012$). For the other dependent variables, μ_k did not have a significant effect (friction: $p = 0.16$, stickiness: $p = 0.097$, hardness: $p = 0.87$, pleasantness: $p = 0.35$).

Table IV shows the results of regression analysis with subjective scores as the dependent variables and μ_s and δ as

TABLE II

CORRELATION COEFFICIENTS BETWEEN EACH FRICTION PARAMETER (μ_s, μ_k, AND δ) AND THE SUBJECTIVE SCORES, ALONG WITH THE RESULTS OF THE TEST OF NO CORRELATION.

Friction parameter	Statistics	Friction	Roughness	Stickiness	Hardness	Pleasantness
μ_s	r	0.77	0.35	0.72	0.19	-0.40
	t-values	13	4.0	11	2.1	-4.8
	p-values	1.5×10^{-24}	9.5×10^{-5}	1.7×10^{-20}	0.038	5.1×10^{-6}
μ_k	r	0.31	0.18	0.27	0.11	-0.13
	t-values	3.6	-2.0	3.0	1.2	-1.5
	p-values	5.3×10^{-4}	0.048	3.0×10^{-3}	0.24	0.15
δ	r	0.46	0.48	0.45	0.082	-0.27
	t-values	5.6	6.0	5.5	0.90	-3.0
	p-values	1.6×10^{-7}	2.8×10^{-8}	2.2×10^{-7}	0.37	2.8×10^{-3}

TABLE III

REGRESSION COEFFICIENTS OF μ_s AND μ_k TO EXPLAIN SUBJECTIVE FRICTION, ROUGHNESS, STICKINESS, HARDNESS, AND PLEASANTNESS SCORES. MEANS AND 95% CONFIDENCE INTERVALS.

Predictor	Objective valuable (subjective score)				
	Friction	Roughness	Stickiness	Hardness	Pleasantness
μ_s	5.8 ± 0.96 ($p = 3.7 \times 10^{-22}$)	5.6 ± 1.1 ($p = 7.4 \times 10^{-17}$)	5.5 ± 1.0 ($p = 4.9 \times 10^{-19}$)	1.0 ± 1.2 ($p = 0.089$)	-2.6 ± 1.1 ($p = 1.0 \times 10^{-5}$)
μ_k	-0.69 ± 0.96 ($p = 0.16$)	-1.5 ± 1.1 ($p = 0.012$)	-0.87 ± 1.0 ($p = 0.097$)	0.10 ± 1.2 ($p = 0.87$)	0.52 ± 1.1 ($p = 0.35$)
R^2	0.59	0.46	0.52	0.020	0.15

TABLE IV

REGRESSION COEFFICIENTS OF μ_s AND δ TO EXPLAIN SUBJECTIVE FRICTION, ROUGHNESS, STICKINESS, HARDNESS, AND PLEASANTNESS SCORES. MEANS AND 95% CONFIDENCE INTERVALS.

Predictor	Objective valuable (subjective score)				
	Friction	Roughness	Stickiness	Hardness	Pleasantness
μ_s	5.2 ± 0.96 ($p = 7.8 \times 10^{-19}$)	4.1 ± 1.1 ($p = 5.9 \times 10^{-11}$)	4.7 ± 1.0 ($p = 4.3 \times 10^{-15}$)	1.1 ± 1.2 ($p = 0.060$)	-2.0 ± 1.1 ($p = 3.7 \times 10^{-4}$)
δ	0.69 ± 0.96 ($p = 0.16$)	1.5 ± 1.1 ($p = 0.012$)	0.87 ± 1.0 ($p = 0.097$)	-0.10 ± 1.2 ($p = 0.87$)	-0.52 ± 1.1 ($p = 0.35$)
R^2	0.59	0.46	0.52	0.020	0.15

TABLE V

CORRELATION TABLE AMONG THE FIVE TYPES OF SUBJECTIVE SCORES.

	Roughness	Stickiness	Hardness	Pleasantness
Friction	0.87	0.84	0.15	-0.44
Roughness	–	0.89	0.15	-0.42
Stickiness		–	0.11	-0.42
Hardness			–	-0.07

the independent variables. For all dependent variables except for hardness, the independent variable μ_s had a significant effect (friction: $p = 7.8 \times 10^{-19}$, roughness: $p = 5.9 \times 10^{-11}$, stickiness: $p = 4.3 \times 10^{-15}$, pleasantness: $p = 3.7 \times 10^{-4}$). On the other hand, for hardness, $p = 0.060$, indicating that the effect of μ_s was not significant. The only dependent variable for which δ had a significant effect was roughness ($p = 0.012$). For the other dependent variables, δ did not have a significant effect (friction: $p = 0.16$, stickiness: $p = 0.097$, hardness: $p = 0.87$, pleasantness: $p = 0.35$).

Table V presents the correlation coefficients between the five types of subjective scores. The high correlation coefficients among friction, roughness, and stickiness suggest that these three assessments are qualitatively similar in the context of this study.

IV. DISCUSSION

This study investigated the effects of simulated stick-slip stimuli on tactile perception. While numerous studies have discussed the role of stick-slip phenomena in perception [11], [27]–[30], [34], no prior research has systematically examined this effect by directly controlling friction parameters, as done in this study.

Experimental results revealed that μ_s significantly influenced textural assessments, including friction, roughness, stickiness, and pleasantness. The increase in μ_s leading to higher friction and stickiness scores is intuitively understandable. The effect of μ_s on roughness scores can be attributed to the strong correlations among friction, roughness, and stickiness (Table V), suggesting that these properties were regarded qualitatively similar in our study. A high μ_s likely caused the stylus to experience stronger sticking phases, which may have evoked an impression of engagement or interlocking with surface asperities, despite the virtual surface being flat.

Furthermore, the negative correlation between μ_s and pleasantness can be interpreted in terms of material affinity to the skin. Materials with higher friction tend to exhibit lower physical affinity with the skin [10], [29], [39].

On the other hand, the effects of μ_k and δ on textural evaluations were limited. These parameters significantly in-

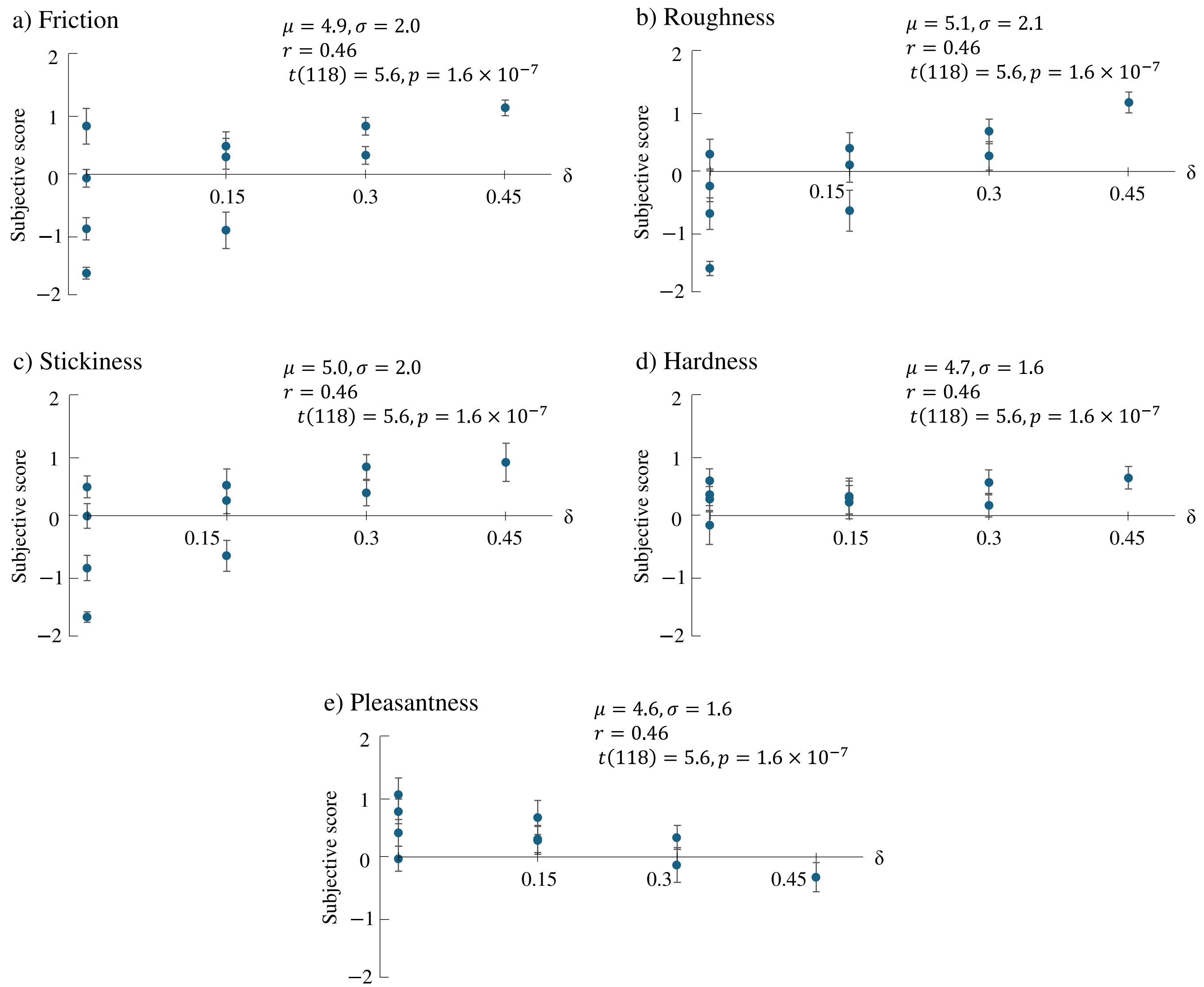

Fig. 3. Scatter plots of the relationship between the mean questionnaire scores and the difference, δ, between the static and kinetic friction coefficients. Error bars indicate the standard errors. Scores for (a) friction, (b) roughness, (c) stickiness, (d) hardness, and (e) pleasantness. The mean score of each stimulus is shown for visual clarity; however, the correlation coefficient and corresponding t and p-values are based on all the samples.

fluenced only roughness perception (Tables III and IV), in a manner where smaller μ_k values and greater δ values led to stronger roughness sensations. This result suggests that frictional vibrations, induced by the difference between μ_s and μ_k, contribute to the perception of roughness. Although surface roughness was not explicitly simulated in this experiment, vibrotactile stimuli are generally associated with the impression of roughness caused by surface irregularities [5], [40], [41].

One might find it unexpected that an increase in μ_k did not lead to higher perceived friction. In this experiment, stick-slip vibrations continuously occurred during the relative motion of the stylus, preventing a stable kinetic friction state from being maintained. Under such conditions, an increase in μ_k acts to suppress frictional vibrations rather than enhance friction perception. Interestingly, despite an increase in the average friction force with increasing μ_k, the perceived friction did not increase. This finding aligns with insights in previous researches [27], [28], [30], suggesting that friction perception is influenced more by variations in friction force rather than by its absolute magnitude.

As shown in Fig. 3, the correlation coefficients suggest that δ pertains to all textural evaluations except for hardness. However, this correlation is likely a spurious relationship caused by the confounding between μ_s and δ. In contrast, multiple regression analysis, although not perfectly, separates the effects of μ_s and δ. As shown in Table IV, δ does not exhibit a significant direct effect on tactile perception and pleasantness, except for roughness.

Despite these results, we suspect that δ may have a more direct or statistically clear influence on friction perception. If our experiment failed to reveal the potential effects of δ, the primary reasons are likely as follows.

First, there is the issue of the stimulus set. Under the constraint $\mu_s \geq \mu_k$, μ_s and δ are inevitably confounded, making it difficult to separate and discuss their individual effects. Therefore, it is recommended to design a stimulus set that minimizes this confounding as much as possible.

Second, there is a fundamental difference between using a stylus and a bare finger. Previous studies demonstrating the perceptual effects of frictional vibrations [11], [27], [28], [30] were based on conditions in which a bare finger slid over a material, a scenario that includes partial slippage phenomena [24]–[26]. In contrast, this study presented simulated stick-slip stimuli through a stylus, where only two distinct states—sticking or slipping—were present. Under such conditions, the vibration of the stylus may be more perceptually salient. Therefore, it is certain that the effects of δ differ between bare finger and stylus conditions.

Furthermore, the discrepancy between the simulated and actual stick-slip stimuli may have contributed to obscuring the effects of δ. Additionally, the definition of all the evaluation items were not clearly provided to participants in this study, which may not have fully captured the influence of δ. These factors should be carefully considered in future studies to further investigate the textural perception of stick-slip stimuli.

V. Conclusion

This study investigated the effects of simulated stick-slip stimuli on tactile perception by systematically controlling friction parameters. The results demonstrated that the static friction coefficient μ_s strongly influenced the assessment of friction, roughness, stickiness, and pleasantness, with higher μ_s increasing friction, stickiness, and roughness while reducing pleasantness.

In contrast, the kinetic friction coefficient μ_k and the difference δ between static and kinetic friction had limited effects, influencing only roughness perception. The increase in δ led to greater roughness sensations, implying that frictional vibrations contribute to roughness perception even in the absence of explicit surface roughness. It is noted that during stick-slip phenomena, the increase in μ_k does not intensify the feelings of friction and stickiness.

These findings provide new insights into the perceptual effects of stick-slip phenomena and contribute to the development of haptic interfaces incorporating friction-based feedback.

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