Kinetic Friction Deters Softness Judgment during Sliding Motion

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***Abstract*—We explored the impact of friction on hardness perception during sliding interactions, an aspect not commonly examined in earlier studies that primarily focused on hardness perception during compression. Using a commercial force display, we simulated virtual surfaces with two levels of stiffness, 400 and 500N/m, and coefficients of kinetic friction of 0 and 0.5. Eight participants engaged in a user study and selected the harder one among two virtual surfaces with different hardness while sliding their surfaces. The correct answer proportion was 0.77 on average under the frictionless condition; however, it significantly decreased to 0.66 under the frictional condition. These findings indicate the importance of friction in conveying haptic softness in consumer electronics, where haptic interfaces are popular communication interfaces between humans and computers.**

***Index Terms*—hardness, haptic interface, friction**

I. INTRODUCTION

Haptic interfaces are valuable communication channels between humans and computers in consumer electronics. Among haptic information delivered by such interfaces, the hardness or softness of the virtual objects is a fundamental cue. Earlier studies have discussed how well such information can be presented when virtual objects are pressed or tapped without a sliding motion (e.g., [1]–[4]). However, humans employ both pressing and sliding motions equally frequently in investigating softness quality in their daily lives [5], [6]. Recently, Arakawa et al. have found that human criteria for softness judgment differ between pressing and sliding motions, and that friction influences softness perception in the latter case [7].

Nonetheless, in an earlier study that investigated the effect of friction on softness perception during stroking exploration [7], only rubber and human skin with the same hardness were explored using bare fingers. The effects of friction on softness perception should also be examined using specimens with different hardness values and via exploratory methods that are different from direct touch by bare fingers so as to generalize the influence of friction on softness perception. Hence, in this study, we employed a haptic interface in which virtual objects are touched via a stylus, and through which the hardness and friction of the objects can easily be controlled. This study contributes a new aspect to the literature on haptic communication between humans and computers.

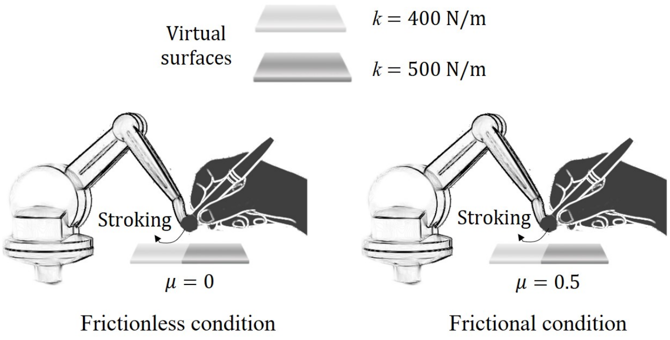

Fig. 1. Experiment to investigate the effect of friction on softness judgment during sliding motions using a commercial haptic interface. Assessors stroked the surfaces of virtual objects using a stylus to judge the harder one among the two objects with different degrees of stiffness. The tests were conducted under two friction conditions, i.e., minimum and moderate kinetic friction.

II. METHODS

A. Stimuli

We employed a Phantom Touch X force display (SensAble Technologies Inc., MA, USA) to depict virtual planes with varying levels of hardness and friction. The virtual planes were positioned parallel to the desktop.

The hardness was instrumented using Hooke's law, that is, a linear spring with stiffness coefficient k. When the pressing depth of the stylus into the plane is d, the reaction force normal to the plane is determined as follows:

$$f_z = kd. \tag{1}$$

The stiffness values used in this experiment were $k = 400$ N/m and 500 N/m. These values were selected for two main reasons. First, these values are challenging to be discriminated such that the mean success proportion would be approximately 0.75. Second, these specific values are within the device's maximum output capability of 7.9 N, ensuring regular operation without exceeding force limits.

The virtual objects were not visually deformed while interacting with the stylus of the haptic interface such that the hardness difference could not be judged from visual cues.

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The kinetic frictional force was defined as follows:

$$f = -\mathrm{sgn}(v)\mu f_z \quad (2)$$

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

where $\mathrm{sgn}(v)$ indicates the sign of v, and v (m/s) is the sliding velocity of the stylus on the plane, and f_z (N) is the load normal to the plane. The nominal value of the friction coefficient is μ_0. An arctangent function was used to eliminate any discontinuities in the frictional force at zero velocity. This ensures a seamless transition of the kinetic friction force near zero speed. The denominator of the arctangent function provides the range over which the kinetic force undergoes a gradual change. The denominator of the velocity was determined through preliminary tests to maintain the stability of the frictional force without evident sensible vibrations. Because static friction leads to frictional vibrations that disrupt the smooth stroking motion, it was not rendered. Therefore, the focus of this study was to investigate the effects of kinetic friction. Two nominal coefficients of friction were used: $\mu_0 = 0$ and 0.5.

B. *Participants*

The experiment involved a group of nine individuals (eight males and one female; mean age, 23.0 years). The aims of the study were not disclosed to the participants before the experiment. Written informed consent was obtained from all the participants before the experiment commenced.

C. *Procedures*

Before the main experiment, the participants underwent a training session divided into two stages. The first stage involved familiarizing themselves with the manipulation of the force feedback device. Participants stroked the surfaces of two planes with friction coefficients of 0.25 and hardness of 350 N/m and 500 N/m. Note that their difference was 150 N/m, which was greater than that of the main experiment. They could continue their exploration for as long as they wanted. Two planes were randomly assigned to each side of the screen. The participants then selected the harder one. The accuracy of each selection was returned to the participants. Once the participants made correct judgments five times in a row, they progressed to the second stage.

In the second stage, the participants stroked each plane twice and selected the harder plane. Once they made five correct judgments consecutively, they proceeded to the main experiment. This stage ensured that the participants could understand the difference in hardness using only the two sliding motions. One male participant did not pass the second stage; therefore, eight participants participated in the main experiment.

In the main experiment to compare the two hardness values, i.e., $k = 400$ N/m and $k = 500$ N/m, the participants conducted 20 trials under each of the frictionless ($\mu_0 = 0$) and frictional ($\mu_0 = 0.5$) conditions. Two frictional conditions were presented in randomized order.

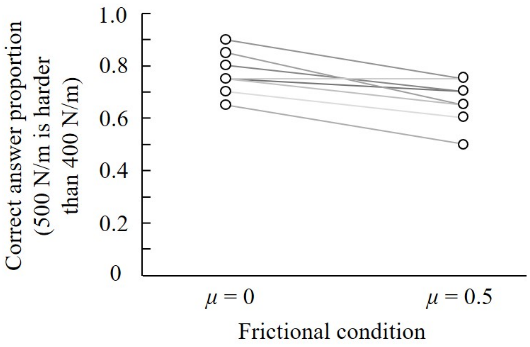

Fig. 2. Accuracy of the eight participants in judging the two planes with different stiffness (400 and 500 N/m) under two different friction conditions μ_0 (0 and 0.5). Error bars indicate the standard errors. ** indicates a significant difference at $p < 0.01$.

D. *Data analysis*

The difference in accuracy proportions between the two friction conditions was calculated for each participant. Subsequently, a one-sample t-test was employed to test the mean difference among all the participants so as to investigate the effect of friction on the ability to judge hardness.

III. RESULT

Under the frictionless condition, that is, $\mu = 0$, the hardness of the two virtual planes was correctly determined as 0.77 ± 0.026 (mean ± standard error). However, when $\mu_0 = 0.5$, the proportion decreased to 0.66 ± 0.028. Friction significantly lowers the proportion of correct judgements ($t(7) = 5.15$, $p = 0.0013$). The kinetic friction affected the participants' ability to judge the stiffness of the planes while sliding their surfaces.

IV. CONCLUSION

Earlier studies have primarily investigated humans' ability to judge hardness when objects are being pressed. Hence, they did not undergo any evident sliding motion. This study investigated the effects of sliding friction on hardness judgment while sliding objects' surfaces. A user study revealed that participants' judgment was less accurate with greater kinetic friction. This suggests that frictional conditions should be considered when humans interact with soft objects. In the future, tests should be conducted to determine whether similar effects can be observed using actual compliant materials. Finally, this paper pertains to our another study [8] demonstrating that the virtual objects with kinetic friction are perceived harder than those with little friction.

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