Frictional Planes are Felt Harder through a Force Display Device

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***Abstract*—An earlier study demonstrated that when two surfaces of equal hardness were stroked, the surface with higher friction felt harder. This tribological paradox was the focus of our experiment. We used a force display device to stroke objects with varied stiffness (300–700 N/m) and kinetic friction coefficient (0–0.6). The device primarily involved proprioceptive cues, limiting tactile cues. Participants used the device's stylus to explore objects and reported perceived hardness using the magnitude estimation method. Their motion was restricted to stroking with comfortable force. Results indicated that surfaces with lower friction were perceived as softer. These findings enhance our understanding of hardness presentation using haptic interfaces that is a popular communication tool between man and computers in consumer electronics.**

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

I. INTRODUCTION

Humans can judge objects' softness by sliding their fingers on them which is a common behavior in our daily lives [1]. They do not necessarily press or tap objects to test their softness whereas pressing and tapping are typical exploratory motions for judging hardness [2]–[5]. Sliding motions give rise to friction between a fingertip and an object's surface. Hardness and friction perception are both major haptic qualities and are considered perceptually independent [6], [7]. However, recently, these two types of qualities have been found to be perceptually dependent. In a study conducted by Arakawa et al. [8], urethane rubbers that had been lubricated to be less frictional felt softer than those with more frictional surfaces when their surfaces were rubbed.

Earlier studies [8], [9] tested only one type of rubber object with the same hardness, which raises the first question. That is, whether the effect of friction on softness perception holds for a wide range of object hardness. The second question is whether the effect of friction on softness holds true when using haptic interfaces, through which objects are touched via a probe. It is possible that hardness is perceived differently between the two types of contact modes, i.e., bare finger and prove. Thus far, no earlier studies have investigated either of these research questions. The findings of this research will provide guidance for presenting softness by using force display devices that are popular man-machine interfaces in consumer electronics.

II. METHODS

A. Stimuli

We used a commercial force display, Phantom Touch X (SensAble, Inc., CA), to render virtual planes with different degrees of hardness and friction. The virtual planes are located parallel to the table. The virtual surface hardness, that is, the spring constant k (N/m) and kinetic friction μ were adjustable variables.

Stiffness is defined by a spring constant following Hooke's law. When the stylus is pressed to a depth of d, an upward reaction force is generated by

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

The simulated kinetic friction force is defined as follows:

$$\begin{aligned} F &= \mu f_z & (2)\\ \mu &= \mu_0 \left(\frac{2}{\pi}\right) \mathrm{Tan}^{-1}\left(\frac{-v}{0.05}\right) & (3) \end{aligned}$$

In this study, v (m/s) and f_z (N) represent the sliding velocity of the stylus and the load normal to the planes, respectively. The coefficient of friction was set by μ_0. We used the arctangent function to prevent any discontinuity in the friction force at zero speed, ensuring a continuous kinetic friction force.

As outlined in Section II-C, we used a psychophysical method of magnitude estimation where perceived hardness of a stimulus is reported by using a number referring to a reference stimulus. For the reference stimulus, parameters were set to $k = 500$ N/m and $\mu_0 = 0.3$, with a hardness magnitude of 10. The nine test stimuli were derived from combinations of three k values (300, 500, and 700 N/m) and three μ_0 values (0, 0.3, and 0.6).

B. Participants

Seven participants (six men and one woman; average age: 23.0 years) were recruited for this experiment. The objectives of this study were not explained to the participants before the experiments. All the participants provided signed informed consent prior to the experiment.

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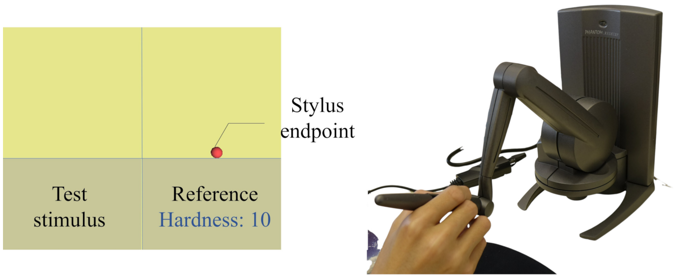

Fig. 1. Experimental setting. Participants judged the hardness of test virtual planes in compared with that of reference.

C. Procedures

Participants underwent brief training to acclimate to the force-feedback device by stroking a virtual plane with limited force. As shown in Fig. 1, two virtual planes were allocated on either side of a visualization window: a reference plane and a test plane. The planes did not exhibit visual deformation, preventing visual assessment of their hardness. Participants used a stylus to stroke the virtual surface and reported perceived hardness using the magnitude estimation method.

Magnitude estimation is a method that measures the subjective strength of a perceived stimulus, requiring participants to compare a standard stimulus with the test stimulus. They reported the ratio of subjective intensity of each test stimulus to the modulus using a numerical value.

Nine test stimuli were presented in a random order in a single set. Three sets of measurements were performed for each participant, resulting in 27 trials for each individual.

D. Data Analysis

For each test stimulus, the three magnitude values of perceived hardness acquired from each participant were geometrically averaged. Then, we used a two-way (stiffness k × coefficient of friction μ_0) repeated measures analysis of variance (ANOVA) to evaluate the statistical effects of stiffness and friction on the perceived hardness.

III. RESULT

The geometric means of the subjective hardness for all the nine stimuli are shown in Fig. 2. The results from the ANOVA reveal significant effects of stiffness ($F(2,54) = 5.59$, $p = 0.0062$, $\eta^2 = 0.062$) and friction ($F(2,54) = 53.27$, $p = 1.67 \times 10^{-13}$, $\eta^2 = 0.61$) on subjective hardness. There was no significant interaction observed between stiffness and friction ($F(4,54) = 0.76$, $p = 0.55$, $\eta^2 = 0.017$). Therefore, the virtual surface was perceived harder with a larger kinetic friction coefficient μ_0, irrespective of the stiffness values of the plane.

IV. DISCUSSION

Previous studies demonstrated that surfaces with greater friction coefficients were perceived harder when rubbed by fingers [8]. We designed an experiment using a haptic interface involving different stiffness values, close to those of human tissues [10], [11]. The participants judged the perceived hardness when rubbing stimuli generated by the force display device. The results suggest that the smaller the friction coefficient, the softer the perception.

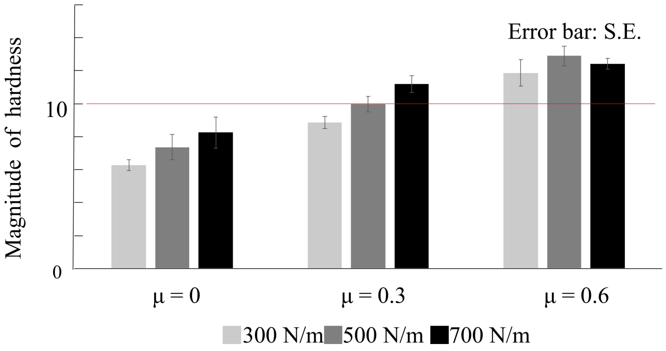

Fig. 2. Mean magnitudes of perceived hardness acquired from seven participants on three stiffness planes (300, 500 and 700 N/m) with three coefficients of friction μ_0 (0, 0.3 and 0.6). The red line is the hardness of the reference stimulus with $k = 500$ N/m and $\mu_0 = 0.3$. Its magnitude of hardness was defined as 10. Error bars indicate the standard errors.

The main effect of stiffness was significant; hence, the participants could distinguish between different stiffness values. However, this trend was not clear for the stimuli with $\mu_0 = 0.6$ as shown in Fig. 2. In a post-hoc manner, we applied a one-way ANOVA for the $\mu_0 = 0.6$ condition. The effect of stiffness was not significant ($F(2,18) = 0.69$, $p = 0.51$, $\eta^2 = 0.071$), indicating that the perceptual effect of friction masked the difference in stiffness.

V. CONCLUSION

We explored the influence of friction on hardness perception in a virtual environment, using a range of stiffness and friction coefficients. Participants assessed surface stiffness using a stylus and a force display device. They were not allowed to press surfaces without sliding motion. Subjective hardness values were collected using the magnitude estimation method. Results showed that surface friction significantly impacts hardness perception. Lower surface friction led to softer surface perception. This contributes to our understanding of perceived softness through haptic interfaces with practical applications in virtual reality and gaming. This study has limitations to be solved in the future, including variations in stimuli and a small number of participants. These may have resulted in the weak statistical significance in the analyses. Finally, this paper pertains to our another study [12], where two virtual objects with different stiffness values are less correctly discriminated with larger kinetic friction. Collectively considering this study and [12], kinetic friction influences softness judgment while sliding over virtual objects through a stylus.

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