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Sliding Friction Provides Cues to Judge Object Compliance: Evidence through Comparison among Sliding, Rolling, and Pressing Exploration by Using Shaft Bearing

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***Abstract*—Pressing motions have traditionally been regarded as the most effective method for discerning object compliance. However, recent studies suggest that humans adopt sliding motions just as frequently as pressing motions for this purpose. Sliding exploration inevitably induces friction, which is in part determined by material softness. This study demonstrates that friction provides crucial cues for judging softness.**

To investigate the role of sliding friction in compliance judgment, this study compares three tactile exploration methods—sliding, rolling, and pressing—using a shaft ball bearing. Participants assessed the softness of seven rubber materials through the bearing under controlled conditions. In the sliding mode, the outer ring of the bearing slid over the materials, generating significant friction. In the rolling mode, the inner ring was held stationary while the outer ring rolled over the material surfaces, minimizing friction. In the pressing mode, participants applied only vertical force using the bearing, with sliding and rolling motions prohibited. Consistent force application was ensured using a balance scale, and participants ranked the materials by perceived compliance for each method.

Results indicate that sliding provides the most reliable cues for judging physical compliance, followed by pressing, while rolling produces lower accuracy. These findings highlight the instrumental role of friction in accurately perceiving compliance during tactile exploration.

***Index Terms*—friction, softness, hardness, rubber**

I. Introduction

Researchers in the field of haptics have long studied pressing or pinching motions as a means for humans to discriminate objects with different hardness (e.g. [1]–[4]). In this context, the involvement of both cutaneous and kinesthetic sensations has been well documented [5]–[7]. The integration of these sensory modalities contributes to the perception of softness. For example, Bergmann Tiest and Kappers [8] compared human softness perception under conditions where only cutaneous or kinesthetic information could be effectively used, as well as conditions where both were available. They suggested that when the hardness of objects is around 1–2 MPa, cutaneous and kinesthetic information are integrated in a ratio of approximately 9:1. The relative dominance of these sensory modalities likely varies depending on object hardness, as indicated by the findings of Friedman et al [6]. Softer objects are expected to enhance the dominance of cutaneous sensations. In cutaneous sensation, the relationship between contact force and contact area has been identified as a particularly important cue for humans [9]–[13].

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Recently, however, studies have reported that humans often use sliding motions, similar to pressing motions, to evaluate the softness of objects [14]–[16]. For instance, when prompted to assess the softness of facial skin, humans frequently use both pressing and sliding motions. Sliding motions inherently involve friction, which depends on the elastic modulus of the object [17], [18]. As the elastic modulus decreases, indicating softer materials, both adhesion and deformation (hysteresis) friction increase. Adhesion friction is proportional to the contact area, which is larger in softer materials, resulting in higher overall friction. Deformation (hysteresis) friction depends on the volume of material deformed during relative motion, with softer materials exhibiting greater deformation friction. This suggests that humans might infer the softness of objects from the friction experienced during sliding. Indeed, examples of friction influencing softness perception have been reported [19]–[22]. For instance, Arakawa et al. [19] demonstrated the effect of friction on softness perception using rubber specimens with identical elastic moduli but different surface lubrication conditions.

The aim of this study is to complement the findings of Arakawa et al. [19] and demonstrate the importance of frictional information from a new perspective. In their experiments, Arakawa et al. tested specimens with identical hardness but differing surface friction. In our experiments, participants distinguish specimens with different physical hardness under conditions where prominent frictional information is either available or unavailable. Specifically, we compare two conditions: sliding and rolling. In both conditions, participants do not press the surfaces in the normal direction, but instead move their hands over the surfaces to judge the hardness of the material. The sliding condition generates greater friction than the rolling condition [23], [24]. When smooth and dry rubber specimens are tested, sliding or adhesion friction is approximately four times greater than rolling or deformation friction [23]. This ratio can be even large for human skins: approximately, 50:1 [24]. Thus, the sliding condition provides more prominent frictional cues than the rolling condition. It should be noted that both types of friction depend on the elastic modulus of the objects [17], [23], [25], [26].

If the results demonstrate that hardness judgments are more accurate or align more closely with physical hardness under the sliding condition than the rolling condition, it would strongly suggest that frictional information plays a significant role in hardness perception. Conversely, if there is no significant difference in hardness judgment accuracy between the sliding and rolling conditions, the influence of friction on hardness perception may be considered negligible. It is noted that it remains possible that humans use subtle frictional cues, such as those from rolling friction, for hardness judgments.

We achieve the comparison between sliding and rolling conditions using a shaft bearing, which is a mechanical component designed to minimize friction. As described later, participants perform hardness judgment tasks on rubber specimens using a shaft bearing, which facilitates the comparison between sliding (frictional) and rolling (frictionless) conditions during haptic exploration. To the best of our knowledge, this experimental approach is novel and constitutes a unique aspect of this study.

Additionally, as a reference, we compare hardness judgments made via pressing motions to those made via sliding and rolling motions. To date, no study has compared pressing and sliding motions—where cutaneous contact is minimized and kinesthetic information is primarily used—in terms of hardness perception. Understanding which motion condition is superior for hardness judgment will contribute to our understanding of the mechanisms underlying human hardness perception.

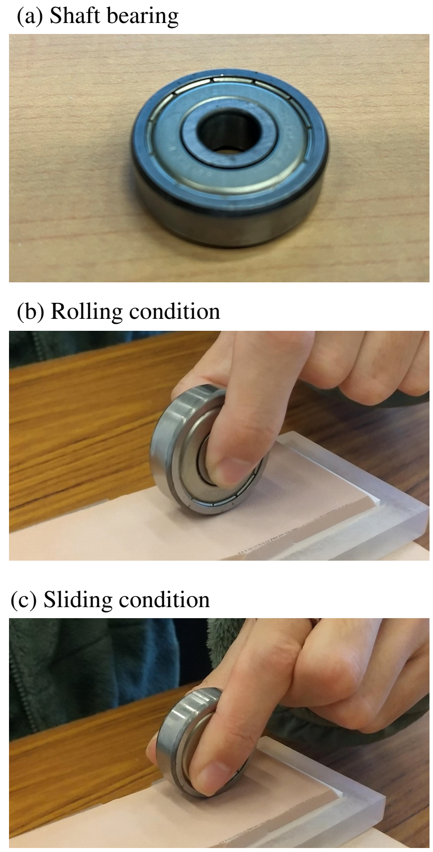

Fig. 1: Shaft ball bearing and grabbing methods. (a) Shaft ball bearing used in the experiment as a medium for participants to interact with the artificial skin. (b) Only the inner ring was held by fingers in the rolling condition. (c) Both the inner and outer rings were held by fingers in the sliding and pressing condition.

II. Methods

A. Ethical Statement

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

B. Participants

The experiment involved a group of 14 individuals (six females and eight males; mean age of 23.0 years). The aim of the study was not disclosed to the participants before the experiment. Written informed consent was obtained from all the participants before the experiment commenced.

C. Apparatus

We used a shaft ball bearing (6300ZE, NACHI-FUJIKOSHI Corp., Tokyo, Japan; external diameter of 35 mm, inner diameter of 10 mm; 53 g) as the medium for participants to indirectly interact with rubber materials, as shown in Fig. 1. The bearing is a compact, circular component comprising an outer ring and inner ring separated by internal rolling balls, which allow for frictionless rotation between the two rings.

Participants could manipulate the bearing in two distinct ways to explore the softness of the materials. In the rolling condition, as shown in Fig. 1 (b), the inner ring was held to allow the outer ring to roll over the material with little friction. In the sliding condition, as shown in Fig. 1 (c), the outer ring was held and slid over the rubber specimen, yielding notable friction.

In this experiment, as shown in Fig. 2, a balance scale [21] was employed to help participants apply consistent normal force during each trial. One side of the scale was loaded with a 345 g counterweight. This weight includes the weight of the material and its holder (45 g); hence, the net hand force plus the bearing mass balancing the weight was 300 gf. This specific weight was selected to ensure that it provides sufficient force for most participants to discern the softness differences of the experimental samples. With the lighter counterweight, the judgment of softness is more challenging in any exploratory condition.

While the use of a balance enables approximate control of the contact force, the reaction normal force may fluctuate

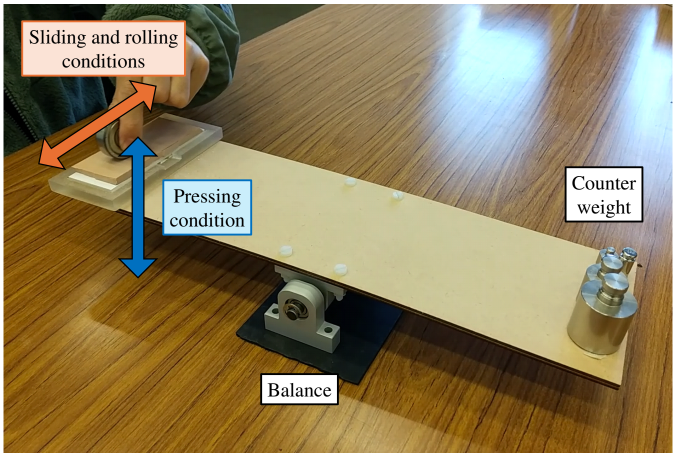

Fig. 2: Balance scale used to apply consistent normal force during the experiments. A counterweight of 345 g was used on one side to ensure participants applied 300 gf force while exploring the samples.

TABLE I: Young's moduli (E) and Shore AO hardness of rubber specimens. Adapted from [9].

Hardness level	Shore AO Hardness	E (kPa)
1	3.2	69.4
2	7.8	74.2
3	9.6	79.6
4	11.0	85.2
5	16.9	122.4
6	18.0	131.7
7	19.1	141.8

around 300 gf during dynamic exploration. Given the limited availability of practical methods for maintaining consistent force under such conditions, we consider the balance-based approach to be one of the most feasible and effective solutions currently available.

D. Compliant Material

This experiment used seven types of artificial skin materials (Bioskin, Beaulax Ltd., Saitama, Japan) as compliant stimuli, as shown in Table I. It comprised composite rubber layers with surface roughness equivalent to that of human skin. Its thickness was 5 mm. Each material was characterized by its Shore AO hardness or Young's modulus (E), which varied across different hardness levels to simulate various softness properties. Before the experiment, the material surfaces were cleaned by using industrial paper cloth with alcohol.

E. Procedures

Seven rubber samples, which were randomly presented, with varying degrees of hardness were evaluated. Participants were instructed to explore the hardness of each sample using a shaft ball bearing rather than directly touching the samples. Three types of exploratory procedures were employed: pressing, rolling, and sliding. Each participant used one of these methods in each session to rank the hardness of the seven samples.

To control the normal force applied by the participants, each sample was placed on one side of a balance scale weighted with a 345 g counterweight, as shown in Fig. 2. This balance took an equilibrium position when the participant applied the normal force of 300 gf on the material sample. They were tasked with maintaining balance on the scale while ranking the samples according to their perceived hardness. The hardness was defined as the difficulty of specimens to be deformed. The participants wore sunglasses covered with opaque tape to prevent them from judging material softness based on visual deformation.

In the pressing mode, participants assessed the hardness of the sample by pressing down on it with a shaft ball bearing. They carefully restricted their movements to ensure that the ends of the balance did not come into contact with the desktop. Thus, the participants could apply slight acceleration and deceleration while pressing the specimens, ensuring that the normal force remained approximately 300 gf.

In the rolling mode, the participant rolled the shaft ball bearing across the surface of the sample, causing the outer wheel of the shaft ball bearing to rotate along with the movement. Participants were instructed to maintain a stable level of pressing force during the process without causing significant vertical motion of the balance.

In the sliding method, the participant slid the shaft ball bearing across the surface of the sample without causing the outer wheel to rotate, allowing for the assessment of frictional resistances. Participants were also required to maintain a steady normal force and avoid abrupt up-and-down movements of the balance in the normal direction.

Participants were permitted to re-explore previously ranked samples if they were uncertain and adjusted the ranks of the samples accordingly.

Participants underwent a practice session to familiarize themselves with the three exploratory modes and the balancing requirements. During this session, they were allowed to compare all the specimens with disclosed information about their physical hardness and were encouraged to identify exploratory speeds that suited their ability to accurately judge hardness. This process ensured that participants would likely employ near-optimal exploration strategies in the subsequent main session. Once participants felt confident with the tasks—a process that typically took 10–15 minutes—they proceeded to the main session after a 10-minute break.

In the main session, the three exploratory modes were tested in random order and the assessment of all the specimens in one mode took approximately eight minute for the individuals. Their exploratory motions were monitored by the experimenter, that is, the authors, to ensure that they employed only designated motions.

F. Data Analysis

The perceived hardness rankings provided by each participant were compared to the rankings of the materials' mechanical hardness using Spearman's correlation coefficient. These

TABLE II: Results of paired t-tests comparing the correlation coefficients between two exploratory modes. The coefficients were transformed into Fisher's Z-scores. p-values were adjusted by Holm method of the maximum factor three.

Comparison	t-value	p-value
Sliding vs. Rolling	5.91	1.54×10^{-4} $(5.14 \times 10^{-5} \times 3)$
Sliding vs. Pressing	2.64	0.020 (0.020×1)
Rolling vs. Pressing	3.38	0.0098 (0.0049×2)

TABLE III: Results of F-tests comparing the variances of Z-scores among the exploratory conditions. The degrees of freedom for both the numerator and denominator are 13.

Comparison	F-value	p-value
Sliding vs. Rolling	1.69	0.53 (0.178×3)
Sliding vs. Pressing	0.99	1.00 (0.490×3)
Rolling vs. Pressing	1.68	0.54 (0.182×3)

correlation coefficients were subsequently transformed into Fisher's Z-scores to facilitate parametric statistical analyses.

Paired t-tests were conducted on the Fisher's Z-scores to compare the tactile discrimination accuracy among the three exploratory methods: pressing, rolling, and sliding. These paired comparisons evaluated whether significant differences in ranking accuracy existed between the methods. The p-values obtained from the hypothesis tests were adjusted using the Holm method (maximum adjustment factor of three) to account for multiple comparisons.

Additionally, to examine differences in the variability of Fisher's Z-scores across the three exploratory methods, F-tests were performed to compare the variances of the Z-scores.

III. Results

The experimental results are summarized in Fig. 3, which illustrates the individual correlation coefficients (Spearman's rank correlation) across the three interaction methods: sliding, rolling, and pressing. The line connects the results of the same participant.

The sliding method exhibited the highest mean correlation of 0.67 with the standard error (SE) of 0.050. In contrast, the pressing method showed a moderate mean correlation of 0.44 with the SE of 0.053. Lastly, the rolling method exhibited the lowest mean correlation being 0.12 and SE of 0.072, indicating low accuracy in judging mechanical hardness levels.

To analyze the differences among the three methods, paired t-tests were conducted to compare the consistency of hardness rankings. The results are presented in Table II.

The sliding condition produced significantly higher correlation coefficients compared to the rolling condition ($t(13) = 5.91$, $p = 1.54 \times 10^{-4}$), indicating superior softness discrimination accuracy for the sliding method. The pressing condition demonstrated intermediate performance, with correlation coefficients greater than those observed in the rolling condition ($t(13) = 3.38$, $p = 0.0098$). A marginal difference was found between the sliding and pressing conditions ($t(13) = 2.64$, $p = 0.020$).

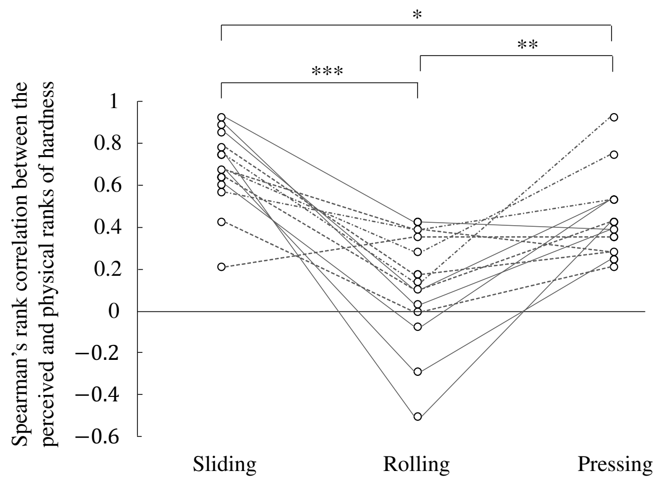

Fig. 3: Spearman's correlation coefficients between the physical hardness and perceived hardness for individual participants. Changes across three exploratory conditions: sliding, rolling, and pressing modes. The same participant shares the same line type.

These findings underscore the influence of the interaction method on participants' ability to rank material hardness. Collectively, the sliding method provides the highest accuracy for assessing the mechanical hardness of samples, followed by pressing, while the rolling method results in less precise hardness judgments.

Table III presents the results of variance comparisons of the Z-scores across the exploratory conditions. No significant differences were observed, indicating that the variability of the correlation coefficients was comparable between conditions. As no significant difference was found for the pair with the smallest p-value (sliding vs. rolling), the null hypotheses for the other pairs were also not rejected.

IV. Discussion

The sliding condition, which provided prominent frictional information, enabled participants to make more accurate judgments of physical hardness compared to the rolling condition, where frictional information was limited. One possible interpretation of these findings is that humans explicitly utilize frictional information during sliding motions to assess hardness. Although pressing motions were prohibited during the sliding condition to avoid confounding factors, participants could have incorporated subtle pressing movements while sliding. If this were the case, similar accuracy in hardness judgments would be expected across all three conditions. Therefore, the results of this study support the active involvement of frictional information in hardness perception. This aligns with previous reports that humans naturally adopt sliding motions when judging material hardness [14]–[16].

The results suggest that friction originating from surface softness contributes to the ability to discern variations in material compliance. Specifically, sliding friction appears to aid in hardness judgments. Since smaller elastic moduli (softer material) produce greater friction [25], [26], humans may make use of this relationship between the softness and friction in judging material softness.

However, this effect disappears when material compliance (elastic modulus) and surface friction are independently manipulated. Arakawa et al. [19] demonstrated that when bare fingers were used to slide over rubber specimens with identical elastic moduli but varying lubrication levels, samples with higher friction were perceived as harder. This perceptual effect of friction on softness judgment contradicts the previously mentioned physical correlation between softness and friction. Similarly, Wang and Okamoto [20] found that higher friction conditions impaired the accuracy of hardness judgments in a point-contact condition, where a force-feedback device was used to independently control virtual object hardness and kinetic friction. These findings suggest that frictional information contributes to hardness perception only when compliance and friction are interrelated. To date, no unified principle explains these observations. Further research is necessary to develop a theoretical understanding of how sliding friction influences hardness perception.

For the pressing condition, the mean correlation coefficient between the physical and perceived hardness was 0.44. Anecdotally, when participants use their bare fingers to press materials while maintaining the same setup as in this experiment, they can almost perfectly discern differences in physical hardness. This suggests that the absence of cutaneous sensations substantially reduces accuracy. These findings highlight the importance of cutaneous information in hardness discrimination during pressing motions, consistent with prior studies. For example, Srinivasan and LaMotte [5] experimentally demonstrated that discrimination of compliant objects is significantly hindered when cutaneous cues are unreliable.

A potential limitation of this study is the lack of strict control over sliding and rolling velocities, although participants were encouraged to adopt their preferred exploratory strategies. Rolling motions inherently involve lower friction, allowing faster hand movements. Some participants exhibited this tendency, feeling that faster motions suited hardness discrimination. However, the actual impact of velocity on discrimination accuracy remains unclear and requires further investigation.

We used a counterweight of 300 gf in the experiment. When a smaller weight was used, the resulting sliding friction was reduced, making it more difficult for participants to distinguish between specimens of different elasticity. The appropriate weight likely depends on the coefficient of friction between the specimens and the shaft bearing. The minimum required difference in frictional force or coefficient of friction for reliable softness discrimination remains an open question for future investigation.

V. Conclusions

This study investigated the role of sliding friction in material hardness perception by comparing three exploratory methods: sliding, rolling, and pressing. The results revealed that the sliding condition, which offers prominent frictional cues, facilitated more accurate hardness judgments compared to the rolling condition, where frictional information was minimized. These findings underscore the importance of frictional cues in tactile perception, particularly when material softness and friction are interrelated.

Future work should explore the theoretical principles governing the interaction between friction and compliance perception and investigate the impact of exploratory velocity on hardness discrimination.

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