What is the Hardness Perceived by Tapping?

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Abstract. A human can perceive the hardness of an object by tapping its surface. We compared the ranked subjective hardness values and physical properties of objects, including their stiffness, viscosity, density, and Shore hardness, and the frequencies and time constants of the natural vibrations caused by tapping. The stiffness, frequency, and viscosity exhibited a relatively strong positive correlation with the perceived hardness. The results show that the viscosity influences the hardness perceived by tapping, as well as the stiffness, whereas the stiffness and elasticity are considered to be major factors in the hardness perceived by pinching or pushing.

Keywords: Hardness perception · Damped natural vibration · Real object

1 Introduction

Hardness is an important characteristic of an object, which humans typically perceive by pinching or pushing the object. Thus far, many researchers have studied how humans perceive the hardness and softness of objects. For example, cutaneous and proprioceptive cues were found to be integrated for the perception of softness [2,3,10]. Because the maximum human force is limited, hardness perception based on the reaction force and deflection of an object caused by pinching or pushing is limited. Indeed, human hardness perception is saturated and less sensitive for harder objects [4]. Similarly, hardness perception using the deformation of a fingertip when contacting an object's surface is not effective for an object that is substantially harder than the fingertip. Hence, humans make use of tapping and the resultant vibrotactile signal to estimate the hardness of an object, for which the perceptual strategy based on the deformation of the object or fingertip is not effective.

Hardness perception by tapping has not yet been thoroughly studied. Okamura et al. [8,9] reported that the frequency and attenuation of the damped natural vibration caused by tapping influence the material perception. This finding has been exploited to allow force display devices with limited output forces to deliver hardness values greater than the device is capable of expressing in a quasi-static manner [6,7]. These studies agree that higher vibratory frequencies lead to the perception of greater hardness. However, few researchers have

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reported the exact physical properties of objects that humans perceive by tapping. In other words, a question is raised about how accurately the hardness perceived by tapping corresponds to the physical hardness.

In a former study, we researched the effects of the mass, viscosity, and stiffness of virtual objects on hardness perception by tapping [5]. The result suggested that an increase in stiffness and decrease in mass lead to the greater perceived hardness. We assume that these parameters are also effective for hardness perception in the case of real objects.

In this study, we investigated the correlations between the hardness perceived by tapping and representative physical parameters related to an object's hardness, including its stiffness, viscosity, density, and Shore hardness, and the frequency and time constant of the natural vibration caused by tapping. Understanding the characteristics of hardness perception by tapping will help us to develop materials or object structures that feel hard or soft, along with a method to render object hardness for virtual reality systems. It can be also linked with a hardness test for industrial products by tapping or hammering.

2 Experiment: Ranking of Perceived Hardness by Tapping

Participants tapped the surfaces of objects and ranked their hardness based on their damped natural vibrations. All of the experimental procedures were approved by the internal review board of the School of Engineering in Nagoya University (#15-12).

2.1 Specimens

We performed an experiment using two types of specimens: spring-damper specimens and material specimens. All of the specimens were hard enough that we could not judge their hardness by pushing on them with a finger. As shown in Fig. 1, the spring-damper specimen was composed of two aluminum plates, a linear spring, and a shock absorber (EMACN1212A, B, and C, MISUMI, Japan). Each aluminum plate was 80×80 mm in size, and the upper and lower plates were 3 mm and 5 mm thick, respectively. Three types of springs and shock absorbers

Table 1. Stiffness and viscosity of spring-damper structures

Sample	Stiffness [N/m]	Viscosity [Ns/m]
I	15700	0.047
II	7830	0.024
III	24700	0.047
IV	15700	0.026
V	15700	0.078

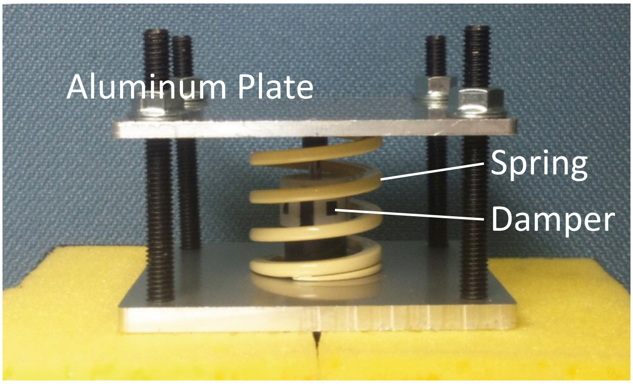

Fig. 1. Spring-damper structure

with different strengths could be used. Thus, as listed in Table 1, there were five types of specimens. The details of the vibration properties of each specimen are described in Sect. 3.

The material specimen was a block formed of a single material (60 × 60 × 30 mm). We used eight types of materials, including wood, nitril rubber, urethane rubber, modeling wax (ZW-200, Roland DG), ABS resin, acryl, stainless steel, and aluminum. The densities of these specimens are shown in Fig. 2. The density of stainless steel was remarkably higher than those of the other materials. There was a trend for the metal to have a high density and the wood to have a low density. However, there were no significant differences among the others.

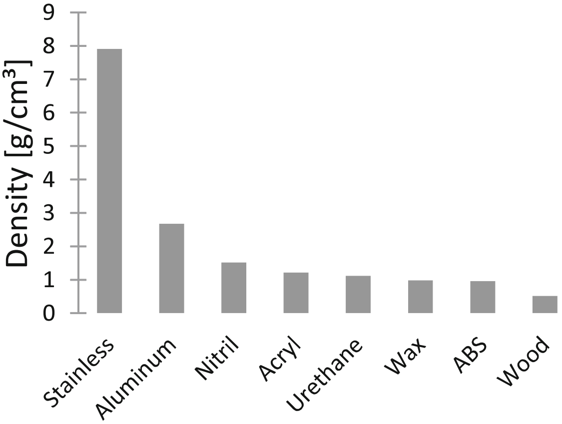

Fig. 2. Ranks of densities of material specimens.

2.2 Tasks and Participants

The participants separately ranked the hardness of each of the five spring-damper specimens and eight material specimens. They evaluated the hardness of a specimen by tapping its surface with the index finger of their dominant hand. It was stressed to the participants that they should tap the specimens with the same speed as much as possible and keep their finger touching a specimen while it was vibrating. The participants could tap each material as many times as they wanted. They ranked the perceived hardness of each specimen, and the same rank could be assigned to multiple specimens. They wore foggy glasses and headphones playing pink noise to block out visual and audio cues. The specimen was placed upon a buffer component, and its vibration was isolated from the ambient environment. They repeated the same task three times at intervals of a few minutes. The participants were five naive outsiders from the research group, who were males in their twenties.

2.3 Results

Figures 3 and 4 show the medians and 25th and 75th percentiles of the perceived hardness ranks. Friedman tests indicated that these ranks significantly varied among the specimens at a significance level of 0.05. In a post hoc manner, we tested the rank differences for all the pairs of specimens using Wilcoxon's rank sum tests, and the results are shown in the figures. As shown in Fig. 3, specimen V, which had a greater viscosity, was ranked first, and specimen III, which had a greater stiffness, was ranked second. Specimen I, which had medium stiffness and viscosity ranks, had a medium rank of perceived hardness. As shown in Fig. 4, the aluminum and stainless steel were ranked first, and the nitril rubber was ranked last among the material specimens. There were no significant differences among the ABS resin, acryl, urethane, modeling wax, and wood.

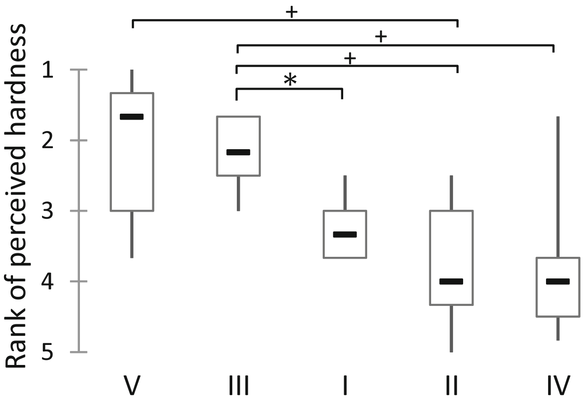

Fig. 3. Perceived hardness ranks of spring-damper specimens, where * and + indicate $p < 0.05$ and $p < 0.10$, respectively.

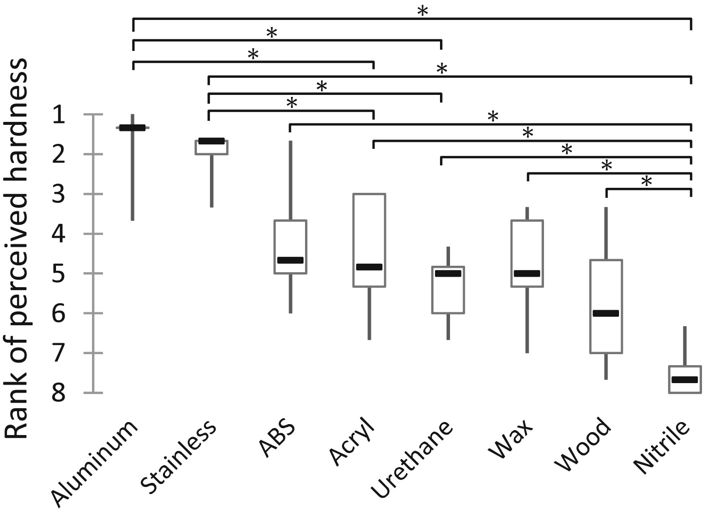

Fig. 4. Perceived hardness ranks of material specimens, where * indicates $p < 0.05$.

3 Physical Characteristics of Hardness Specimens

3.1 Characteristics of Natural Vibration

We tapped the spring-damper specimens and measured their damped natural vibration. An accelerometer (ADXL335, ANALOG DEVICES) was attached to the center part of the upper surface of a specimen. The measurement was repeated 10 times for each specimen with a sampling rate of 10 kHz. The specimen was placed on a buffer component, and its vibration was isolated from the ambient environment, including the table and floor. We specified the main frequency of the damped natural vibration by computing the fast Fourier transform (FFT) of the acceleration signals. The vibration waveform was then band-pass-filtered so as to include the natural frequency to determine the time constant. The time constant was obtained as the time until the amplitude of the filtered waveform was damped to 37 % of the maximum amplitude.

We assumed that the damped natural vibration of a spring-damper specimen was the impulse response of the one-degree-of-freedom spring-mass-damper system. In this assumption, the time constant τ and natural frequency f of the vibration are described as follows:

$$\tau = \frac{2m}{c} \tag{1}$$

$$f = \frac{1}{2\pi}\sqrt{(1-\zeta^2)\frac{k}{m}} \simeq \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{2}$$

where m, c, k, and ζ represent the mass, viscosity, stiffness of the system, and the damping ratio of the vibration, respectively. The stiffness k was defined

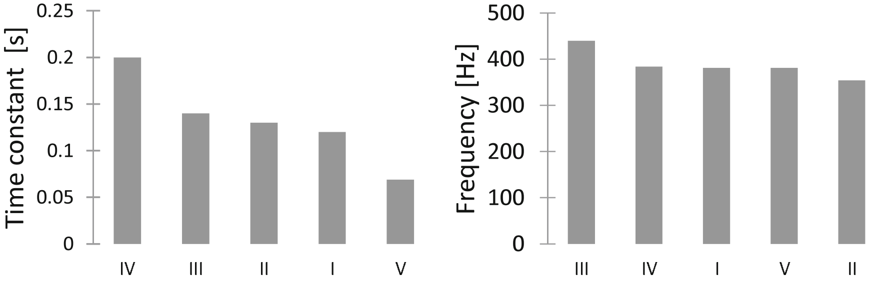

Fig. 5. Time constants and frequencies of vibrations of spring-damper specimens.

as the sum of the spring constants of the spring and damper composing the specimen. The viscosity c listed in Table 2 was obtained by substituting τ and f into Eqs. (1) and (2), respectively.

The time constants and natural frequencies of the damped natural vibrations of the specimens are shown in Fig. 5. The deviations of these values in repeated measurements were negligibly small. Specimens with greater spring constants exhibited greater natural frequencies. In addition, specimens with greater damping ratios had smaller time constants.

We also analyzed the vibration waveform of the material specimens by the same procedure. However, the waveforms contained multiple significant frequency components, which deviated from the damped natural vibration containing a single natural frequency component. Hence, we did not specify the vibration characteristics of the material specimens.

3.2 Shore Hardness

We measured the hardness of each specimen using a method based on the Shore C hardness test. In the original Shore C hardness test, a diamond hammer is dropped on an object, and its rebound height is measured. The Shore hardness is evaluated based on the ratio of the rebound height to the drop height. The Shore hardness may align with a human's hardness perception because both are affected by the physical properties of the object in a momentary contact state. In this experiment, we used a small ball made of hard rubber instead of the diamond hammer to avoid any possible damage to the specimens.

We fixed the specimen in a vise and dropped a rubber ball with a diameter of 22 mm from right above it. The position and initial height of the rubber ball were controlled using a guide frame. We tested each specimen five times, and recorded the drop and rebound heights using a high-speed camera (RX10II, SONY, Japan). We then derived the average rebound ratio for each specimen.

The ranks of the rebound ratios are shown in Fig. 6. Specimen III, which had a greater spring constant, exhibited the highest rebound ratio. Moreover, a specimen with a smaller viscosity had a greater rebound height. Among the material specimens, urethane was ranked first, and nitril rubber was ranked

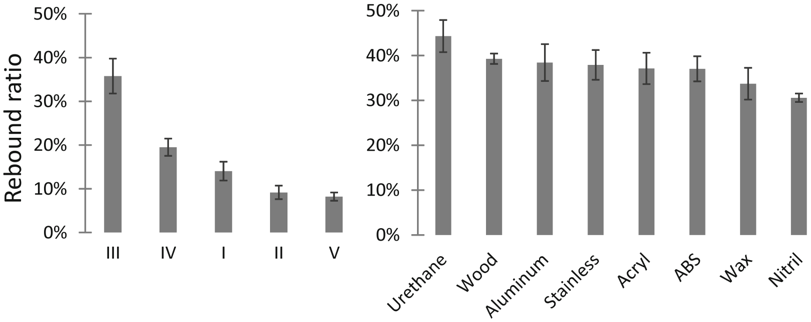

Fig. 6. Percentage of rebound height against falling height. Error bars indicate standard deviations. Left: spring-damper specimens. Right: material specimens.

last. There were no significant differences in the rebound heights of the wood, aluminum, stainless steel, acryl, ABS resin, and modeling wax.

4 Discussion: Comparison Between Perceived Hardness and Physical Characteristics Related to Hardness

We researched the relationships between the hardness perception by tapping and the representative parameters related to hardness. We calculated Spearman's correlation coefficient for the perceived hardness ranks and physical characteristics. The average perceived hardness rank among the participants was used in the calculation. Specimens with physical characteristics with no significant differences or differences that were too small to discriminate were ranked as the same level. Tables 2 and 3 show the ranks of the physical characteristics and their correlation coefficients with the perceived hardness.

It was found that the stiffness and viscosity of an object, and the frequency of the damped natural vibration, exhibited relatively strong correlations with the perceived hardness. Following these parameters, the density of a material and

Table 2. Ranks of physical characteristics of spring-damper specimens and Spearman's correlation with perceived hardness

Parameter	I	II	III	IV	V	Correlation
Stiffness	3	5	1	3	3	0.77
Viscosity	2.5	5	2.5	4	1	0.82
Frequency	3	5	1	3	3	0.77
Time constant	4	2.5	2.5	1	5	0.08
Rebound height	3	4.5	1	2	4.5	0.45
Perceived hardness	3.23	3.77	2.2	3.73	2.13	-

Table 3. Ranks of physical characteristics of material specimens and Spearman's correlation with perceived hardness

Parameter	Alum.	SST*	ABS	Acryl	Ure.	Wax	Wood	Nitril	Correl.
Density	2	1	6.5	4.5	4.5	6.5	8	3	0.58
Rebound height	4.5	4.5	4.5	4.5	1	4.5	4.5	8	0.50
Per. hardness	1.73	2.07	4.2	4.57	5.37	4.87	5.73	7.47	-

*SST indicates stainless steel

its rebound hardness were moderately correlated with the perceived hardness ($\rho > 0.5$). Here, we discuss the interpretation of these results, although any correlations in the results were insignificant because of the small number of samples.

Stiffness and Frequency. The perceived hardness ranks had a strong correlation with those of the stiffness and the frequency of the damped natural vibration of the specimens. It was experimentally proved that a human has the ability to discriminate the stiffness of an object by tapping. To the best of our knowledge, very few studies have attempted to examine this perceptual mechanism. It was assumed that the effect of the frequency was similar to that of the stiffness because they are related by the vibration property, as shown in Eq. (2). The result, the positive effect of the frequency on the perceived hardness, matches past conclusions on presenting the hardness of a virtual object through vibration stimuli [5,7–9].

Viscosity. The viscosity was found to be correlated with the perceived hardness as strongly as the stiffness, indicating that the viscosity was not a secondary factor for the perceived hardness. Note that the stiffness and viscosity were fairly independent of each other in our setup, with the correlation between these two types of values being 0.35. The viscosity has a role as important as the stiffness in restraining the amplitude of the vibration caused by tapping. Although the viscosity influences the hardness perception by pushing a compliant virtual object [1], the effect of the viscosity on the hardness perceived by tapping real objects was first confirmed in this study to the best of our knowledge. Because these two types of hardness perception are based on different perceptual mechanisms, we should not simply translate the effect of the viscosity between the hardness perception by pushing and that by tapping.

Density. The density of a material specimen had a moderate correlation with the perceived hardness. Note that the density and mechanical hardness of a material do not necessarily correspond to each other. For example, the hardness of a certain kind of urethane rubber can be changed, while its volume and mass are maintained by changing the ratio of the curing agent. We assumed that this correlation was caused by a change in the vibration properties as a result of a change in the density. The density of an object affects its vibration properties, including the amplitude, time constant, and frequency. The cause of the correlation would become clear by examining the effect of the density on the hardness perception with changes in the vibration properties.

Time Constant. There was no significant correlation between the time constant of the damped natural vibration and the hardness perception. As shown in Eq. (1), the time constant has a relationship with the viscosity. As previously mentioned, the viscosity exhibited a positive correlation with hardness perception. Thus, it seems natural that the time constant may have a negative one. Nonetheless, we are still uncertain about the contribution of the time constant to the perceived hardness, because in another study [5], the time constant of a simulated damped natural vibration influenced the perceived hardness. The effect of the time constant should be examined considering its interaction with other physical parameters and the human ability to discriminate the time change of vibration stimuli in future works.

Rebound Ratio. The rebound ratio was also found to be a secondary parameter affecting the hardness perception. According to the definition of Shore hardness, a harder object exhibits a higher rebound ratio as a result of the lower energy dissipation in the elastic deformation. An object with a higher stiffness whose energy dissipation is lower exhibits a higher rebound ratio. On the other hand, an object with a higher viscosity whose energy dissipation is higher exhibits a lower rebound ratio. Therefore, the hardness based on the rebound ratio has positive and negative correlations with the stiffness and viscosity of the object, respectively. However, as previously mentioned, the hardness perception has positive correlations with both the stiffness and viscosity. It is speculated that the rebound ratio is inferior to the individual use of the stiffness or viscosity as an index of perceived hardness by tapping.

5 Conclusion

We investigated the physical parameters that affect hardness perception based on the tapping of real objects. Through psychophysical experiments and mechanical tests, we compared the hardness perception ranks and six physical properties, including the stiffness, viscosity, density, and Shore hardness values of objects, and the frequencies and time constants of the natural vibrations caused by tapping. Our results suggested that the stiffness and viscosity of an object and the frequency of its damped natural vibration had correlations with the perceived hardness. In contrast with the quasi-static hardness perception by pinching or pushing, the viscosity was also found to be an effective factor, indicating that we should not assume that the perceived hardness is entirely related to the actual hardness of an object. The result suggests that viscosity can compensate for the perceived hardness of objects instead of increasing the stiffness. The findings can be applied to, for example, rendering a hard virtual object by using the powerless displays or the material design of industrial products.

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