Hardness Perception Through Tapping: Peak and Impulse of the Reaction Force Reflect the Subjective Hardness

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Abstract. Humans can judge the hardness of an object by tapping its surface. To investigate physical indicators for estimating subjective hardness, we analyzed the short-time reaction force caused by tapping various types of objects. We focused on five indicators in the time domain, including the peak force value, peak time, duration, maximum increase rate, and impulse of the reaction force. A strong correlation was observed between the peak force value, peak time, duration, and maximum increase rate. We found that subjective hardness can be predicted by combining the peak force value and impulse of the reaction force. Results suggest that the hardness involving stiffness and damping factor of objects can be estimated from the reaction force caused by tapping objects. Especially, the former and latter are, respectively, associated with the peak force value and impulse of the reaction force.

Keywords: Hardness perception · Reaction force · Impulse

1 Introduction

Humans can judge the hardness of an object by tapping or pushing its surface. Hardness perception through tapping is characterized by a much shorter contact time with an object compared with pushing. Additionally, in the case of tapping, dynamic phenomena are dominant whereas pushing is based on quasi-static phenomena. In previous studies, hardness perception through tapping was investigated by focusing on two types of dynamic phenomena: vibration of objects and reaction force caused by tapping. However, it has yet to be fully studied how humans judge mechanical properties of objects.

Vibration induced by tapping an object was reported as the cue of hardness perception. Okamura et al. reported that vibration properties, including amplitude, damping rate, and frequency of natural vibration caused by tapping, influenced material perception [13]. The effect of vibration frequency has been especially well-tested and confirmed by multiple studies [1,5,9,10,13]. They agree

D. Prattichizzo et al. (Eds.): EuroHaptics 2018, LNCS 10893, pp. 366–375, 2018.
https://doi.org/10.1007/978-3-319-93445-7_32

that the greater frequency leads to the greater subjective hardness. Additionally, hardness perception based on natural vibration caused by tapping object surfaces has been studied in relation to the mechanical properties of objects such as stiffness and viscosity [6–8].

Regarding the reaction force, which we focused on in this research, some physical indicators affecting hardness perception have been investigated in previous studies. For example, a greater magnitude and higher increase rate of the reaction force were observed when tapping harder real objects [11]. Hence, the increase rate of the reaction force was proposed as the indicator of hardness perception presented on the haptic display [2,12]. As investigated in the studies on vibration cue, the reaction force should also be influenced by the mechanical properties of objects. Relationships between mechanical stiffness and indicators based on the reaction force were discussed in some studies [3,12]. However, the exact contribution of the damping factor is still unclear.

In this study, we investigated the relationship between the subjective hardness and reaction force produced when tapping various real objects. We focused on five parameters, including the peak force value, peak time, duration, maximum increase rate, and impulse as the parameters characterizing the reaction force. By focusing on the time characteristics of the reaction force, we attempted to discuss the contribution of the mechanical properties of objects, such as the stiffness and damping factor, to the selected five indicators. Through a correlation analysis, we investigated the effective physical indicators for subjective hardness. Furthermore, we computed a regression model for estimating subjective hardness by combining effects of multiple physical indicators. Describing subjective hardness based on physical indicators enabled us to connect sensual evaluation with quantitative design of materials and structures in the development of industrial products.

2 Hardness Specimens

Eighteen types of specimens listed in Table 1 were used in the experiments. Each specimen was a block made of a material commonly available in daily life. Blocks were rigid enough so as not to be deformed by pressing them with a fingertip.

The reaction force when tapping an object depends not only on its material but also its structure. In order to investigate the effect of an object's structure, for three materials, we prepared full and hollow specimens. The hollow specimens were blocks drilled from their bottom, leaving the top and side surfaces 5 mm thick.

3 Hammering Test for Measuring the Impulsive Reaction Force

We investigated the reaction force produced by hammering the surface of each specimen. It should be noted that we measured the reaction force per tapping speed following the indicator of hardness perception proposed in previous studies [1,2,12].

Table 1. Materials and dimensions of hardness specimens (partly used in [8])

Material	Size [mm]	Material	Size [mm]
ABS resin	60 × 60 × 30	Wood	60 × 60 × 30
ABS resin (hollow)	60 × 60 × 30	Wood (hollow)	60 × 60 × 30
Acrylic resin	60 × 60 × 30	Wax	60 × 60 × 30
Acrylic resin (hollow)	60 × 60 × 30	Stainless steel	60 × 60 × 30
Polycarbonate resin	60 × 60 × 30	Aluminum	60 × 60 × 30
Nylon resin	60 × 60 × 30	Granite	100 × 100 × 30
Nitrile rubber	60 × 60 × 30	Brick	100 × 100 × 60
Urethane rubber (soft)	60 × 60 × 30	Concrete	200 × 100 × 60
Urethane rubber (hard)	60 × 60 × 30	Cork	200 × 100 × 60

3.1 Apparatus

The reaction force was measured by tapping specimens with an impulse hammer because of the difficulty in directly measuring the force under a fingertip. In order to mimic fingertip action, we selected a commercially available hammer whose tip (half-sphere with the diameter of 6.4 mm) had physical characteristic closely matching those of a fingertip. Figure 1 shows the frequency characteristics of reaction force when tapping the same specimen with the fingertip and hammer; their responses were similar.

Figure 2 shows the measurement apparatus used in the hammering test. The apparatus was composed of an impulse hammer (GK-3100, Ono Sokki Co. Ltd., Japan, 140 g) and a rotator attached to the hammer. The reaction force was measured by the load cell embedded in the hammer. The tapping speed v was calculated as $v = l\omega$ where l and ω are the hammer length and the angular velocity measured by a rotary encoder (MR Type L 225787, Maxon, Switzerland), respectively. The force was sampled at 10 kHz using an oscilloscope.

3.2 Procedure

The hammer was lifted and released from a certain angle to collide with the specimen. The collision position was the central part of the upper surface of the specimen, and the collision angle was perpendicular to the surface. The contact speed ranged 0.9–1.1 m/s such that the mean was approximately 1.0 m/s. The specimen was fixed on a large metal plate (800 × 800 × 100 mm). Each specimen was tested multiple times to acquire 10 valid data sets.

3.3 Results: Reaction Force per Tapping Speed

The reaction force per tapping speed, which is the speed of the hammer at the moment of contact, was calculated from the force and velocity data. When

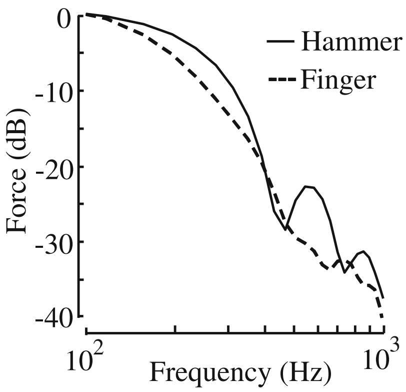

Fig. 1. Frequency characteristics of the reaction force. Those observed when the fingertip and hammer tapped the same object at similar speeds were similar.

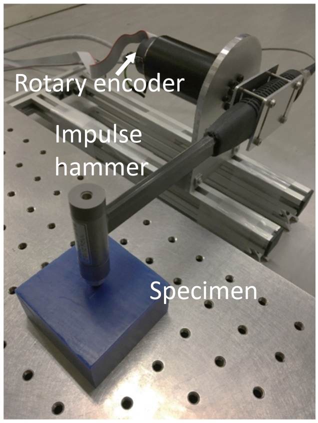

Fig. 2. Measurement apparatus for the hammering test

the relationship between the momentum of the input (hammer strike) and the reaction force as output is linear, this reaction force per tapping speed captures the property of the striking system. Figure 3 shows the reaction force per tapping speed computed for 18 types of specimens tested. For each specimen, the average of 10 trials is shown. The peak height and width of the waveform were different among the specimens. Notably, relatively soft specimens, made of cork or rubber, exhibited low and wide waveforms.

4 Subjective Hardness of Specimens

In this study, we used the subjective hardness scores obtained from psychophysical experiments; results of an experiment conducted in a previous study were used [8]. Herein, we introduce the outlines of the experimental protocol and the data summary.

4.1 Outline of the Experiment

The participants compared and ranked the hardness of 18 types of specimens by tapping their surfaces. The test was performed twice by each participant with a few-minutes break between tests. During the experiment, the visual and auditory cues were blocked by using foggy glasses and headphones playing pink noise. The participants were eight right-handed males in their 20s. All participants agreed to participate in the study and provided informed consent.

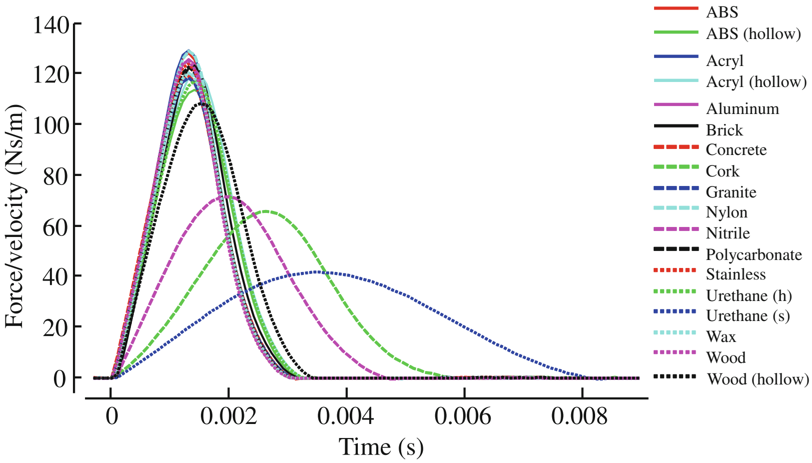

Fig. 3. Reaction force per tapping speed for the hardness specimens

4.2 Subjective Hardness Scores

The rank of each specimen was converted into a normalized rank [4]. Figure 4 shows the mean and standard error of the normalized ranking scores for each specimen. The highest scores were obtained for stone and metal specimens, followed by plastic, wood, and rubber specimens.

5 Analysis: Linear Regression Between Subjective Hardness and Reaction Force

5.1 Physical Indicators

In order to identify physical indicators affecting hardness perception, we focused on five types of parameters that varied among specimens. They included the peak force value $f_{\max}$, peak time $t_{\max}$, duration t_{d}, maximum increase rate $\Delta f_{\max}$ (corresponding to the rate-hardness [2,12]), and impulse f_{imp} as shown in Fig. 5.

5.2 Correlations Among Subjective Hardness and Physical Indicators

The middle column of Table 2 shows correlations between the subjective hardness and each physical indicator. Positive correlation coefficients were observed for $f_{\max}$ ($r = 0.69$) and $\Delta f_{\max}$ ($r = 0.67$). On the other hand, t_{d} ($r = -0.68$), $t_{\max}$ ($r = -0.67$), and f_{imp} ($r = -0.50$) exhibited negative correlation coefficients. These correlation coefficients are statistically greater or smaller than 0 at p value of 0.05 or smaller.

Fig. 4. Subjective hardness scores of the specimens, including the means and standard errors of the scores among the participants (modified from [8])

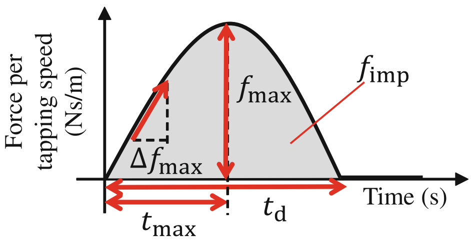

Fig. 5. Representative parameters characterizing the reaction force in the time domain

The right side of Table 2 shows correlations among the physical indicators. Except for impulse, there was a strong correlation between all other parameters ($|r| > 0.9$). Thus, only the impulse would be a parameter independent from the others.

5.3 Multiple Regression Analysis to Estimate Subjective Hardness

We computed a regression model with multiple physical indicators and the subjective hardness score as explanatory variables and objective variable, respectively. To avoid unstable analytical results due to collinearity among explanatory variables, independent variables were selected from the five types of physical indicators. As candidates for explanatory variables, we selected the peak force value $f_{\max}$, which displayed the strongest correlation to the subjective hardness, and the impulse f_{imp}, which was independent from the other parameters. We confirmed that the two explanatory variables significantly affect the hardness score by using a stepwise method. The regression model was acquired as

$$Subj.\ hard. = 2.7 + 0.017 f_{\max} - 26 f_{\text{imp}}. \tag{1}$$

Table 2. Correlation coefficients among subjective hardness and characteristic parameters of the reaction force

	Subj.Hard	I	II	III	IV	V
I. Peak force value	0.69	1.0	−0.95	−0.95	0.99	−0.43
II. Peak time	−0.67		1.0	0.99	−0.94	0.52
III. Duration	−0.68			1.0	−0.94	0.52
IV. Maximum increase rate	0.67				1.0	−0.43
V. Impulse	−0.50					1.0

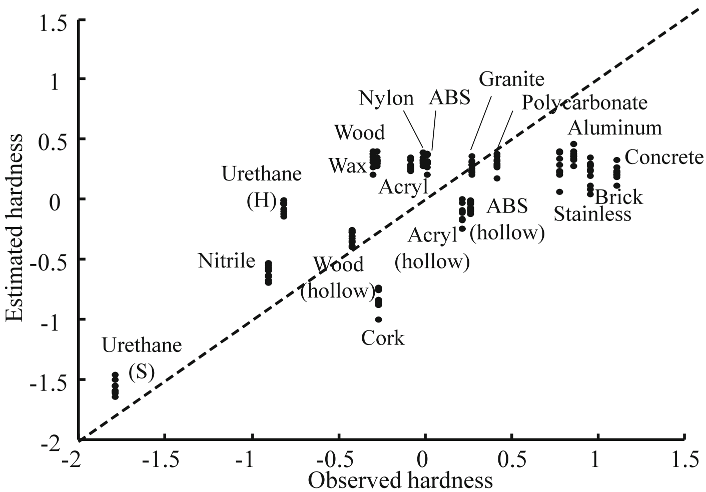

Fig. 6. Relationship between the observed and estimated hardness values. For each specimen, 10 hardness values were estimated from 10 times of reaction force measurements. The dotted line indicates equality of the observed and estimated values.

The p-values of the coefficients associated with $f_{\max}$ and f_{imp} were $p = 2.5 \times 10^{-19}$ and $p = 2.5 \times 10^{-5}$, respectively. Figure 6 shows the relationships between the observed and estimated subjective hardness. The correlation coefficient was $r = 0.72$.

6 Discussion

6.1 Maximum Reaction Force Linked to Object Stiffness

The maximum reaction force per tapping speed showed a positive correlation with subjective hardness. We speculated that humans judge the stiffness of objects from the maximum reaction force caused by tapping. Here, in order to focus on the relationship between the maximum reaction force and an object's stiffness, we considered the simplest object model with stiffness k, as shown in

Fig. 7. The fingertip of equivalent mass m collides with the object at an initial velocity v at $t = 0$. The displacement of the object's surface $x(t)$ is described as

$$x(t) = v\sqrt{\frac{m}{k}}\sin(\sqrt{\frac{k}{m}}t) \tag{2}$$

supposing that the mass vibrates at the tip of the stiffness element. The maximum reaction force per tapping speed $f_{\max}$ is

$$f_{\max} = \frac{\max(x(t))k}{v} \tag{3}$$

$$= \sqrt{mk}. \tag{4}$$

$f_{\max}$ is proportional to the square root of the object's stiffness. Thus, humans can estimate the stiffness of objects from $f_{\max}$. It is known that hardness perception by tapping increases with increasing stiffness of the object [6,7].

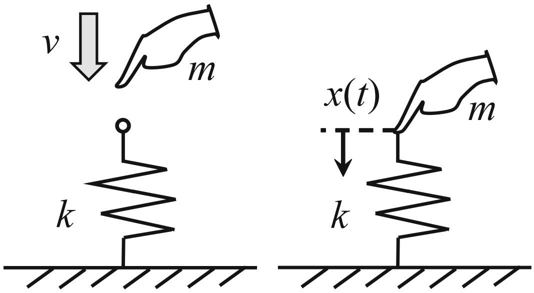

Fig. 7. Physical model of tapping an object

6.2 Impulse Reflects the Damping Factor

Since impulse exhibited a negative correlation to subjective hardness, we speculated that it is affected by the energy dissipation due to the damping factor of an object. Without the damping factor effect, based on the law of conservation of momentum, the impulse received from the object is equal to the momentum of the tapping finger before contact. On the other hand, considering the effect of the damping factor, the impulse decreases as the energy dissipation due to the damping factor becomes larger. Thus, humans can estimate the damping factor of objects from the impulse. It has been reported that the damping factor of objects affects hardness perception through tapping [7] the way greater damping factors lead to greater hardness perception.

6.3 To Improve the Prediction

By combining the effects of the maximum reaction force and impulse, the estimation accuracy for subjective hardness was improved. However, some specimens exhibited a large gap between the estimate and experimental result as shown in Fig. 6. For example, the estimates for the top-four specimens in Fig. 6 (concrete, brick, aluminum, and stainless-steel specimens) were almost the same and did not match the observations. In other words, subjective hardness was different even though the maximum reaction force and impulse were the same among these specimens. This suggests that factors other than maximum reaction force and impulse contribute to the discrimination of hardness through tapping. Since other physical indicators listed in Table 2 have a strong correlation to the maximum reaction force, it is necessary to investigate other independent parameters in order to improve the estimation model. Considering the frequency-dependent aspect of hardness perception [8], the analysis in the frequency domain will help us find other physical indicators for subjective hardness.

6.4 Consistency and Inconsistency in the Effects of Structural Properties

Comparing the full-block and hollow specimens, the experimental results varied depending on the structure of the specimen. As results of the hammering test show, the physical indicators consistently changed depending on the structure of specimens. The peak time, duration, and impulse when tapping hollow specimens were greater than those of full-block specimens. On the other hand, the peak force value and maximum increase rate of the hollow specimens were smaller than those for the full blocks. Considering the effects of physical indicators analyzed in Sect. 5.2, hollow specimens should be felt as softer than full-block specimens. However, the effect on subjective hardness was inconsistent among specimens. Wooden specimens with a hollow structure were felt as softer than full blocks; however, ABS and acrylic resins exhibited the opposite trend. Results suggest the existence of perceptual cues other than those investigated.

7 Conclusions

We investigated the relationship between the subjective hardness and the reaction force when tapping a variety of real objects. The peak force value and maximum increase rate of the reaction force exhibited positive correlation to subjective hardness; whereas, the peak time, duration, and impulse exhibited negative correlation. Results suggest that humans can judge the stiffness and damping factor of objects based on the reaction force caused by tapping. By combining the effects of the maximum reaction force and impulse, we computed an estimation model of hardness perception with a higher accuracy than a model based on any single indicator. Nonetheless, the peak time, duration, and maximum rate of the reaction force can be a substitute of the peak force, because they exhibited high correlation coefficients and are highly associated with each other. This research may contribute to the quantitative estimation of subjective hardness for designing industrial products and stimuli rendered on haptic displays.

Acknowledgment. This study was in part supported by ImPACT (Tough Robotics) and MEXT KAKENHI (15H05923).

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