Perceived Hardness by Tapping: The Role of a Secondary Mode of Vibration

Kosuke Higashi, Shogo Okamoto, Hikaru Nagano, Masashi Konyo and Yoji Yamada

Abstract Humans can discriminate among the hardness of objects by tapping their surfaces. The damped natural vibration caused by tapping and its frequency are known to be the cue for the perception of hardness. This study is an investigation of the characteristics of this perception of hardness, as induced by vibration stimuli including multiple frequency components. We performed a comparative experiment using several damped vibration stimuli, which included either one or two frequency components, and investigated the significance of the secondary vibration mode and the change in its frequency. We found that the presence of the secondary mode significantly enhanced the perceived hardness; however, its frequency had a lesser effect on hardness perception.

Keywords Hardness perception · Tapping · Vibration · Frequency

1 Introduction

Humans use the vibrotactile cue caused by tapping the surface of an object when judging the object hardness [6]. This fact is well known; however, it is astonishing that little is known about the perceptual mechanism responsible for this perception of hardness by tapping. The common understanding among researchers is that vibratory stimulation of higher frequency [3, 7] and larger attenuation [4] leads to greater perceived hardness. As a result, materials with greater rigidity [6] and viscosity loss [4] are felt to be harder.

K. Higashi (✉) · S. Okamoto · Y. Yamada
Graduate School of Engineering, Nagoya University, Nagoya, Japan
e-mail: higashi.kousuke@d.mbox.nagoya-u.ac.jp

H. Nagano · M. Konyo
Graduate School of Information Sciences, Tohoku University, Sendai, Japan

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There have been some attempts to simulate the dynamic characteristics of an impulsive contact between a fingertip and an object in terms of either a reaction force and acceleration [1, 2, 5]. Such stimulus mimicking the transient reaction of tapped object enhances the contact realism of objects [5]. Because one of the most significant features of such transient reaction is multiple frequency components of the waveform, it can be assumed that the vibration including higher-frequency component aside from the main component is felt harder than when the vibration merely comprises a single or primary component. However, the hardness perception when the natural vibration caused by tapping the object includes multiple frequency components has not been well studied.

In the present study, we investigated the perceptual roles of individual frequency components in the case of vibrations that include multiple components. Especially, we were interested in the role of the higher frequency component when the vibration consisted of two components, i.e., lower (primary) and higher (secondary) frequency components. We used a customized haptic interface based on a direct-driven DC motor and prepared several natural vibration stimuli. Invited participants compared these stimuli in terms of their perceived hardness, and we then investigated the significance of the frequency of the higher frequency component.

2 Experiment

2.1 Damped Vibration Stimuli

We used a damped vibration stimulus that includes either one or two frequency components. The displacement of the vibration stimulus was determined by

$$x(t) = \begin{cases} x_1(t) \\ x_1(t) + x_2(t) \end{cases} \tag{1}$$

$$x_i(t) = a_i v_t \exp(\frac{-t}{\tau_i}) \sin(2\pi f_i t) \tag{2}$$

where $x(t)$, v_t, a, τ, and f are the vibration displacement, tapping speed, amplitude per tapping speed, time constant, and frequency of the vibration, respectively. We compared five pairs of stimuli, which are listed in Table 1, by using a paired comparison method. Pair I included a vibration stimulus of 100 Hz and that of 100 and 200 Hz. By making this comparison, we aimed to demonstrate that the presence of the secondary vibration mode could result in the perception of greater hardness. In pairs II and III, we compared vibration stimuli including a single frequency component. Pair II included vibration stimuli of 80 and 100 Hz and pair III included that of 160 and 200 Hz. In each pair, the frequency change was set to 20% decrease from 100 and 200 Hz, respectively. These comparisons would enable us to verify that the higher frequency component is responsible for inducing the perception of greater

Table 1 Frequencies of the vibration stimuli for each stimulus pair

Stimulus pair	Stimulus 1		Stimulus 2	
	f_1 (Hz)	f_2 (Hz)	f_1 (Hz)	f_2 (Hz)
I	100	–	100	200
II	80	–	100	–
III	160	–	200	–
IV	80	200	100	200
V	100	160	100	200

hardness. We also compared the answer rates between pairs II and III and investigated the difference of the perceptual reaction against the frequency change in the vicinity of 100 and 200 Hz. In pairs IV and V, we compared vibration stimuli including two frequency components. Pairs IV and V included vibration stimulus made up of 80 and 200 Hz components and 100 and 160 Hz components respectively, and another made up of 100 and 200 Hz components. These comparisons would show whether the 20% frequency change was also effective for hardness perception in the first or secondary mode of multiple-frequency vibration. By comparing the answer rates between pairs IV and V, we investigated the difference of the perceptual reaction against the frequency change between the first and second vibration mode. The time constant of each vibration component was set to $\tau = 0.02$ s. The amplitude of an acceleration per tapping speed of each frequency component was set to $300\,\mathrm{s}^{-1}$ so that their max acceleration became equal. When expressed in displacement, the amplitude per tapping speed of the 100 Hz component was $a = 7.6 \times 10^{-4}$ s and that of the 200 Hz component was $a = 1.9 \times 10^{-4}$ s. The amplitude of the 160 Hz component was the same as that of the 200 Hz component to enable us to focus on the effect of the change in frequency.

2.2 Apparatus

We developed the haptic display shown in Fig. 1. The main components of this apparatus are a dial, DC motor (RE40, Maxon motor), current controller (ADS50/10, Maxon motor), and microcomputer (mbedLPC1768, ARM). The participant was able to experience a vibration stimulus by using their fingertip to rotate the dial to a certain angle, which was measured by a rotary encoder installed on the DC motor. The vibration of (1) was presented in the tangential direction of the dial. The tangential displacement of the dial can be described as $x(t) = r\theta(t)$ where r and θ are the radius of the dial and its rotational angle, respectively. The control system employed a feedforward control method operated at 5 kHz.

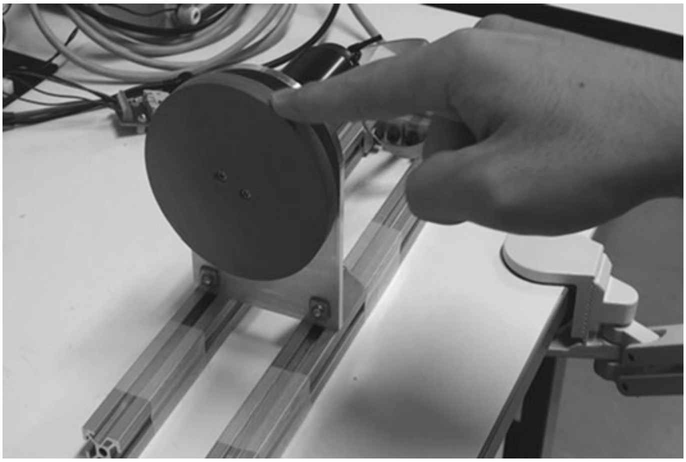

Fig. 1 One degree-of-freedom force display with direct DC motor drive

2.3 Tasks

The participants were five right-handed males in their twenties and thirties. They operated the haptic display and compared the two vibration stimuli presented in pairs. They were able to switch the presented stimulus by using a keyboard and judged which stimulus was felt harder. Each of the five stimulus pairs listed in Table 1 was tested 20 times. In total, 100 comparisons (5 pairs × 20 repetitions) were performed for each participant, and these 100 pairs were presented in randomized order.

2.4 Results

Table 2 and Fig. 2 show the answer rates at which the stimulus including a higher frequency component was judged to be harder.

Table 2 Probability at which higher frequency components induced greater hardness perception

Stimulus pair	Participants					
	A	B	C	D	E	Average
I	0.9	1.0	0.75	1.0	0.9	0.91
II	0.9	0.9	0.95	0.95	0.95	0.93
III	1.0	1.0	0.7	0.95	0.9	0.91
IV	0.8	0.9	0.85	0.95	0.85	0.87
V	0.7	0.85	0.65	0.8	0.3	0.66

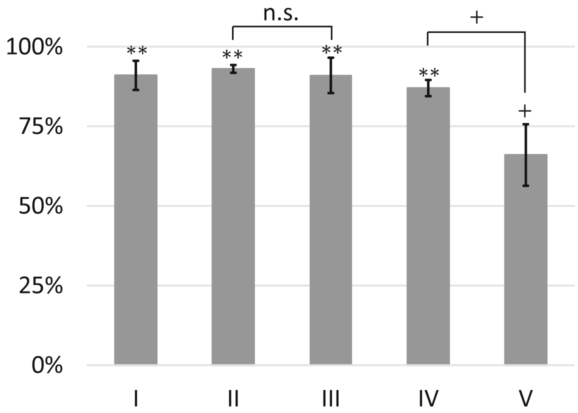

Fig. 2 Answer ratio at which vibration with greater frequency is felt harder. n.s.: not significant, +: $p < 0.1$, **: $p < 0.01$

The t-test between the average answer rate of each stimulus pair and a chance level of 0.5 showed that pairs I–IV indicated significant difference ($p < 0.01$) and pair V indicated significant tendency ($p < 0.1$). For pair I, all participants agreed that the stimulus including the secondary mode felt harder than that with only a primary mode. They answered that the stimulus with the higher frequency seemed to be harder for the single-frequency vibration of pairs II and III. By comparing the answer rates of pairs II and III, we could not confirm the significant difference of the perceptual reaction against the frequency change between the vicinity of 100 and 200 Hz. For the vibration including multiple frequency components of pairs IV and V, almost of all participants answered that the stimulus with the higher frequency component was felt harder just like pairs II and III. However, the comparison for pairs IV and V showed that the answer rate of pair V tended to be less than that of pair IV ($p < 0.1$).

3 Discussions

The results for pairs II and III indicate that the 20% frequency changes in the vicinity of 100 and 200 Hz clearly affected the hardness perception. However, comparing the results of pairs IV and V, the frequency change of the secondary mode was less effective than that of the primary mode for all of the participants, even though the frequency of each component was changed just like in pairs II and III. Nonetheless, the presence of the secondary mode is apparently effective as indicated by the answers for pair I. Our experiment indicated that the presence of the secondary mode significantly enhanced our perception of hardness; however, changing its frequency had a lesser effect on the hardness perception than for the vibration with a single-frequency component. This aspect of human hardness perception may lead to a reasonable rendering of object hardness, even if it is difficult to present high-frequency vibrations because of limitations in the hardware or software of haptic interfaces.

4 Conclusions

This study addressed the characteristics of hardness perception by vibration stimuli including multiple frequency components. By comparing five types of stimulus pairs, we investigated the effects of a secondary vibration mode as well as the effect of changing its frequency. The experimental results suggested that the presence of the secondary mode significantly enhanced perceived hardness; however, changing the frequency of this mode was less effective in terms of hardness perception unlike the single-component vibration stimuli.

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