Perceived Distance from Hitting with a Stick Is Altered by Overlapping Vibration to Holding Hand

Ryuta Okazaki
The University of Electro-communications
1-5-1 Choufugaoka
Choufu, Tokyo, Japan
JSPS Research Fellow
okazaki@kaji-lab.jp

Hiroyuki Kajimoto
The University of Electro-communications
1-5-1 Choufugaoka
Choufu, Tokyo, Japan
Japan Science and Technology Agency
kajimoto@kaji-lab.jp

CHI 2014, April 26–May 1, 2014, Toronto, Ontario, Canada.
ACM 978-1-4503-2474-8/14/04.
http://dx.doi.org/10.1145/2559206.2581244

Abstract
Distance perception by hitting with a holding stick is quite important for the people with visual impairments who daily use white cane. If the mechanism of this perception is well understood, it can be applied for the development of more intuitive and simple electric white cane consisting of a range sensor and a haptic display. A hypothetical mechanical model of a stick and a holding palm told us that hitting at a closer point should induce a stronger vibration at thumb side of the palm, and percussing a farther point should induce equally distributed vibrations in the palm. To verify if this vibration distribution plays role in the distance perception, we conducted an experiment that superimpose vibration to the real vibration while percussing, to change the center of gravity of vibration. The experimental results showed that adding vibration to the thumb side shortened the perceived collision distance than adding vibration to the little-finger side, which partly agrees with our hypothetical model.

Author Keywords
Distance perception; hitting; stick; vibrotactile

ACM Classification Keywords
H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O

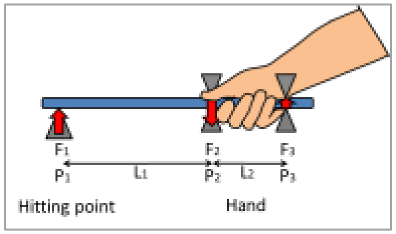

Figure 1. Hypothetical model for distance perception of percussion with handheld rod.

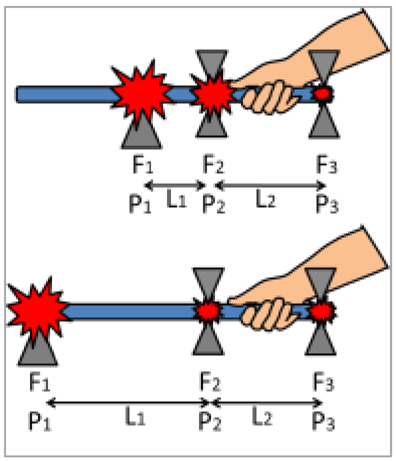

Figure 2. Hypothesis of distance perception with cutaneous cue. Hitting a closer point induces a stronger vibration at the thumb side (top). Hitting farther induces equally distributed vibrations (bottom).

Introduction

Most of us have an experience of perceiving distance by hitting objects with a stick. This perception is quite important in some situations, especially for the visually impaired who use white canes in daily life. Understanding the perception mechanism underlying this phenomenon might help developing supporting devices, such as an electric white cane that consists of a range sensor and a haptic display[1].

The mechanical characteristics of held objects can be perceived by haptic cues even if the objects are visually occluded [2]. This exploratory behavior is known as dynamic touch and has mainly been studied as part of ecological psychology [3]. In recent years, researchers have succeeded in producing the illusion of length, weight, or center of gravity of a virtual object by using haptic devices [4]. The length of a handheld rod can be estimated from cues such as its density, diameter, center of gravity, the user's swing, and grasping posture [5][6][7]. The "sweet spot" of a handheld tennis racket can be estimated before the actual hit [8].

However, most studies dealt with estimating the mechanical characteristics of the handheld object itself and did not directly consider distance perception from percussing objects with a handheld stick. Yao and Hayward [9] found that "rolling" small object inside the rod can be expressed by simple vibration, but they did not directly deal with distance perception from hitting an object. The contribution of the rotational moment was considered but not fully explored [10]. Sreng et al. proposed that transient of frequency component after hitting with a stick may play role for the perception [11]. However, the vibration frequency should be easily affected by the material or the length of the stick, which leads the frequency cue to be not robust. We presume that simpler yet robust cutaneous cue should play role in this perception.

In this study, we setup a hypothesis that the distance information when hitting with a stick can be retrieved by the "center of gravity" of vibration in the palm. We tried to verify this hypothesis by superimposing vibration to the real vibration while percussing.

Hypothetical Model of Distance Perception by Cutaneous Cues

First, we needed to determine the mechanism that may underlie the cutaneous perception of distance between an object and the hand.

Figure 1 shows a simplified mechanical model for percussing an object with a handheld rod. P_1, $P_{2,}$ and P_3 indicate the positions of the object, thumb, and little finger, respectively. We assumed that the hand only contacts the rod with the thumb and little finger to simply the model, although in actual cases the rod is held with the whole palm. F_1, F_2, and F_3 represent the generated forces by percussion, and L_1 and L_2 indicate the distances between P_1 and P_2 and P_2 and P_3, respectively.

As the handheld rod stops after the contact, the total rotational moment and translational force must be zero, which leads to the following equations.

$$F_1 + F_2 + F_3 = 0 \quad (1)$$

$$F_1 \cdot L_1 = F_3 \cdot L_2. \quad (2)$$

Figure 4. Stick-type experimental device.

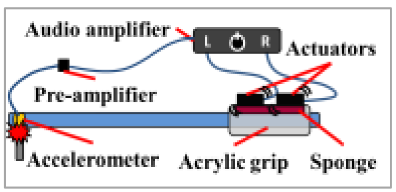

Figure 3. System configuration.

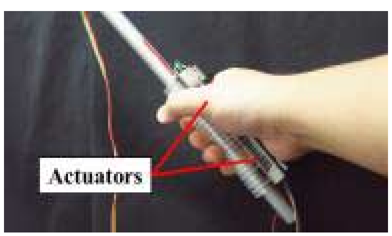

Figure 5. Enlarged view of the acrylic grip.

From these equations of balance, distance L_1 is obtained as follows;

$$L_1 = \frac{F_3 \cdot L_2}{F_1} = \frac{-F_3 \cdot L_2}{F_2 + F_3}. \tag{3}$$

As L_2 (distance between the thumb and little finger) is constant, this equation means that the distance of percussed object L_1 is directly related to the ratio of F_2 and F_3, which are perceived as cutaneous sensations at the thumb side and little-finger side.

For instance, when the object is quite close, L_1 is nearly equal to zero, which gives $F_3 = 0$ in the equation. This means that the transmitted vibration at the thumb (P_2) is greater than that of the little finger (P_3) (Figure 2, top). In contrast, when the position of percussed object P_1 is far away, L_1 is infinite, which gives the solution $F_2 = -F_3$. Therefore, the intensities of the transmitted vibrations to the thumb and little finger become equal (Figure 2, bottom).

This simple model shows that the position of percussed object P_1 can be estimated from the ratio of transmitted vibrations to the thumb (F_2) and little finger (F_3). This model is not accurate because we usually grasp the rod with the whole palm, but it shows that we may estimate the position of percussed object by perceiving the position of the "center of gravity" of vibration in the palm. Presenting vibration at multiple sites is known to elicit the perception of a center of gravity, which is called a funneling or phantom sensation [12].

Based on this hypothesis, we fabricated an experimental device embedded with two actuators located at the bases of the thumb and little finger. We conducted an experiment to determine whether the position of the percussed object perception is modified by changing the vibration center of gravity that is transmitted to the palm.

Experimental Device

To verify our hypothesis, we produced a stick-type experimental device that can superimpose vibrations generated by actuators to the real vibration induced by percussion.

The device is shown in Figure 4 and comprises an aluminum pipe (diameter: 15 mm, length: 1000 mm, weight: 110 g), an acrylic grip, a single-axis accelerometer (±250 g, ADXL193, Analog Devices), two vibrotactile actuators (Haptuator Mark II, TactileLabs) on the grip, a pre-amplifier circuit, and an audio amplifier (RSDA202, Rasteme Systems Inc.). The accelerometer was placed at the tip of the aluminum pipe to record the real contact, and its analog output was connected to the two actuators through the pre-amplifier circuit and audio amplifier (Figure 3). The two actuators were mounted on the grip beneath the bases of the thumb and little finger. They directly touched the skin surface when the device was grasped (Figure 5). A sponge was installed between the acrylic grip and actuators to avoid possible howling caused by the actuators and accelerometer. The total weight of the device was about 250 g.

Thanks to the simple implementation, the time delay from actual contact to the replayed vibration became imperceptible. Each actuator was connected to the right and left channels of the audio amplifier; the amplitude ratio of the two actuators could be controlled by the balance control knob of the audio amplifier.

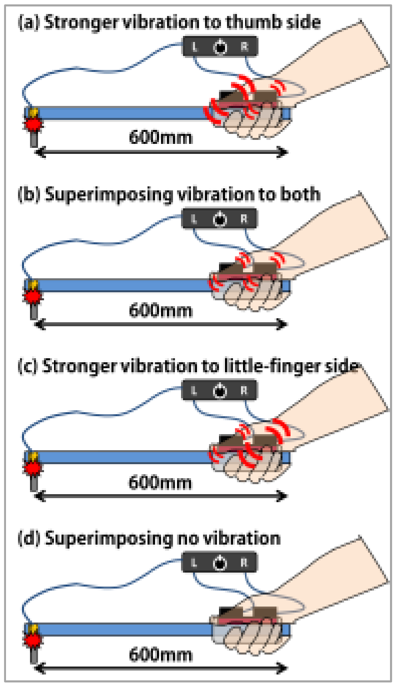

Figure 6. Experimental conditions

We prepared an object made of acrylic plate (height: 100 mm, width: 200 mm, thickness: 5 mm). It was attached vertically to the linear servomotor (F14-20-200-5L, Yamaha Motor Co., Ltd.) with a vice. To avoid the possible destruction of the stick and object, a rubber sheet (thickness: 5 mm) was attached on top of the object. This rubber sheet also helped mute the percussive sound, which can act as a cue for distance estimation.

Experiment

We carried out an experiment to verify the hypothesis of percussion distance perception. We assumed that participants would misjudge the position of the percussed object when vibration was superimposed since this would alter the vibration center of gravity in the palm.

Experimental Conditions

Four experimental conditions were prepared: (a) superimposing vibration from the thumb-side actuator to the real collision, (b) superimposing vibration from both actuators, (c) superimposing vibration from the little-finger side actuator, (d) without superimposing vibration. Under condition (b), the vibration amplitude of each actuator was set to half (Figure 6).

Experiment Procedure

The experiment had 11 participants (9 males and 2 females, 21–27 years old, no reported tactile impairments). The participants sat on a chair and grasped the stick-type device with their right hand. To avoid visual and aural estimation of the collision distance [13], a black wall was installed on the right side of the participant, and the participants wore an active noise-canceling headphone (QuietComfort, BOSE) and listened to white noise at a pleasant volume. A 1000 mm scale ruler was placed in front of the participants to determine the visually and aurally occluded collision position (Figure 7).

Under each vibration condition, participants percussed the object using the stick-device. Each trial had no set time limit nor number of percussive strikes, however, participants were instructed to keep their right hand at the same height so that they could not estimate the distance from the stick angle at the moment of percussion (Figure 8). Similarly, they were instructed to keep the end tail of the stick-device at the same position so that the position of collision was always 600 mm away from the end tail of the stick-device. The object was mounted on a servomotor to suggest to participants that it could move between trials, but the object was not actually moved throughout the experiment. After percussion, participants answered the perceived distance by using the scale of the ruler. Each vibration condition was presented ten times but at random; each participant performed 40 trials. To prevent fatigue, participants rested at least once every five trials.

Results and Discussion

Results among Participants

Figure **9** shows the experimental results. The vertical axis represents the perceived collision distance. The horizontal axis represents the participants and conditions. The error bars indicate the standard deviation.

Based on the results, all participants tended to perceive the collision distance as shorter than the actual

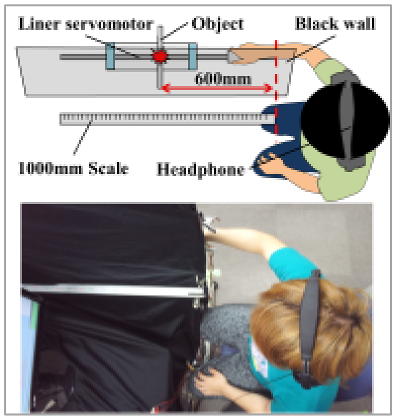

Figure 7. Top view of experiment appearance.

Figure 8. Side view of experiment appearance.

distance (600 mm), including condition (d) (the natural condition).

Results for Different Conditions
To verify the difference among conditions, one-way repeated measures ANOVA and multiple comparison were performed. The results are shown in Figure **10**. The vertical axis represents the average results of the perceived collision distance among all participants. The horizontal axis represents the conditions. The error bars indicate the standard deviation. There was a significant difference between conditions (a) and (b), (a) and (c), and (a) and (d) ($p < 0.05$).

We compared these statistical results with our proposed hypothetical model. As there was a significant difference between conditions (a) (vibration added to thumb side) and (d) (the natural condition), superimposing vibration to the thumb side shortened the perceived collision distance compared to the natural condition. Furthermore, there was also a significant difference between conditions (a) and (c) (vibration added to little-finger side), that means presenting the vibration to the thumb side shortened the perceived collision distance more than vibration to the little-finger side. These results agreed with our proposed hypothesis.

On the other hand, there was no significant difference between condition (c) and (d). If we only perceive the distance by the vibration center of gravity in the palm, condition (c) should be perceived as longer than condition (d). Therefore, the results of condition (c) do not fully support our hypothesis. Our hypothesis may need to be reconsidered to include the contribution of kinetic sensation.

Nevertheless, these two findings—the perceived collision distance can be altered by providing additional vibration, and increasing the vibration ratio on the thumb side significantly shortens the perceived collision distance compared to doing so on the little-finger side (which we consider counterintuitive)—will contribute to the development of a compact electric white cane.

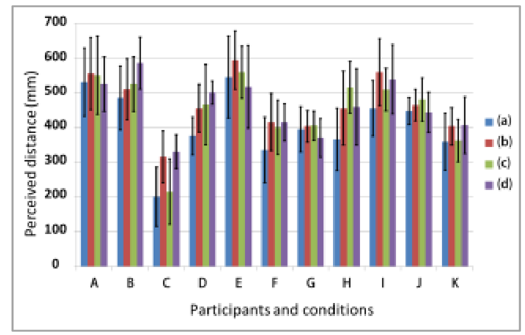

Figure 9. Results of participants.

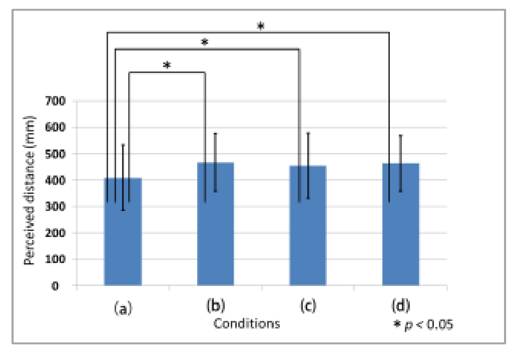

Figure 10. Results for different conditions.

Conclusion
We aimed to clarify the mechanism for perceiving distance from percussion with a handheld rod. We

proposed a hypothetical model of possible cutaneous perception and verified it experimentally.

If we consider the cutaneous sensation and vibration center of gravity position, percussing at a closer point should induce a stronger vibration at thumb side, and percussing a farther point should induce equally distributed vibrations in the palm. Based on this idea, we hypothesized that the perceived position of the percussed object can be modified by changing the vibration center of gravity transmitted to the palm. We fabricated an experimental device embedded with two actuators positioned at the bases of the thumb and little finger. We conducted an experiment to determine whether the perceived distance of the percussed object is altered by changing the vibration center of gravity transmitted to palm. The experimental results were partly positive and partly negative: vibration to the thumb side shortened the perceived collision distance than vibration to the little-finger side, which agreed with our hypothesis, but vibration to the little-finger side did not change the perceived distance relative to the natural condition, which did not agree with our hypothesis.

In the present study, we superimposed vibration to the real vibration from percussion. In future work, we will investigate whether using artificial vibration that is synchronized with the movement of the arm can induce percussion perception and determine how to intuitively present positional information of the collision.

REFERENCES

[1] P. Vera et al., A smartphone-based virtual white cane. *Pattern Analysis and Applications*, 2013.

[2] H. Y. Solomon and M. T. Turvey, Haptically perceiving the distances reachable with handheld objects. *Journal of Experimental Psychology: Human Perception and Performance,* 14(3):404–427, 1988.

[3] J. J. Gibson, The Senses Considered as Perceptual Systems. Houghton Mifflin, Oxford, UK, 1966.

[4] K. Minamizawa et al., Gravity grabber: wearable haptic display to present virtual mass sensation. In *Proc. SIGGRAPH 2007*.

[5] T.-C. Chan. The effect of density and diameter on haptic perception of rod length. *Perception & Psychophysics*, 57(6):778–786, 1995.

[6] C. Carello et al., Inertial eigenvalues, rod density, and rod diameter in length perception by dynamic touch. *Perception & Psychophysics*, 60(1):89–100, 1998.

[7] K. Idsart et al., Which mechanical invariants are associated with the perception of length and heaviness of a nonvisible handheld rod? Testing the inertia tensor hypothesis. *Journal of Experimental Psychology: Human Perception and Performance*, 30(2):346-354, 2004.

[8] C. Carello et al., Perceiving the sweet spot. *Perception*, 28(3):307–320, 1999.

[9] H.-Y. Yao and V. Hayward. An experiment on length perception with a virtual rolling stone. In *Proc. Eurohaptics 2006*, 325–330.

[10] W. Felicia and J. S. Zelek. Tactile & inertial patterns from a long white cane. In *Proc. Biomedical Robotics and Biomechatronics 2006*, 519–524.

[11] J. Sreng et al., Spatialized haptic rendering: Providing impact position information in 6DOF haptic simulations using vibrations. In *Proc. Virtual Reality Conference 2009,* 3-9.

[12] G. Bekesy. Neural funneling along the skin and between the inner and outer hair cells of the cochlea. *Journal of the Acoustical Society of America*, 31(9):1236–1249, 1959.

[13] C. Carello et al., Perception of object length by sound. *Psychological Science,* 9(3):211–214, 1998.