Modulation of Curvature of Soft Ball by Facing Motion

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***Abstract*— Two fingers coming into contact with each other at the same speed sometimes produces the sensation of contact with a flat rigid surface. This illusory sensation is considered to be caused by skin deformation and kinesthesia similar to those that would be produced by contact with a hard surface. We speculated that it would be possible to produce the same tactile sensation as that of contact with a flat rigid plate by placing a soft sphere with the same curvature and hardness as a finger against a finger and moving it at a speed equal to that of the finger. We conducted an experiment to verify the modulation effect of perceived curvature by comparison with various curvature samples. In addition, we developed a prototype of an encountered-type haptic display using this illusion and verified the applicability of the illusion.**

I. Introduction

When the fingertips of both hands are pressed together and the pressing force is varied with a period of several Hertz, the resulting sensation is sometimes perceived as if there is a thin hard plate between the fingers (Fig. 1, left). The purpose of this paper is to show the possibility of curvature modulation achieved utilizing this illusion by replacing one of the fingers with an artificial soft sphere.

The mechanism of this phenomenon can be speculated to be as follows. Tactile perceptions can be classified as active touch or passive touch. In the case of active touch, skin deformation and kinesthesia are considered to contribute to tactile perception [1]–[3]. According to Hertz's contact theory, the contact of two spheres of the same size with the same elasticity produces symmetric deformations of their spheres, and their boundary surface becomes a plane. Therefore, their contact can be regarded as equivalent to contact with a rigid plane without friction [4]. In addition, if both hands are moving at the same speed, the left and right forces are balanced, and the absolute position of the plane caused by the skin deformation always remains the same, as shown in Fig. 1. In this way, the skin deformation, contact area, and kinetic sensation, which are thought to affect the perception of softness and curvature, are all thought to produce the same sensation as when a finger is pressed against a fixed hard plate, and the aforementioned illusion is thought to have occurred.

We have previously reported subjective quantitative measurements of the softness perceived when a finger and a hemispherical soft sphere are brought into contact by opposing motions with various velocity ratios [5]. We confirmed that the closer the velocities of the finger and the soft hemisphere are to each other, the harder the soft hemisphere is perceived to be. However, curvature modulation was not within the scope of the previous research cited.

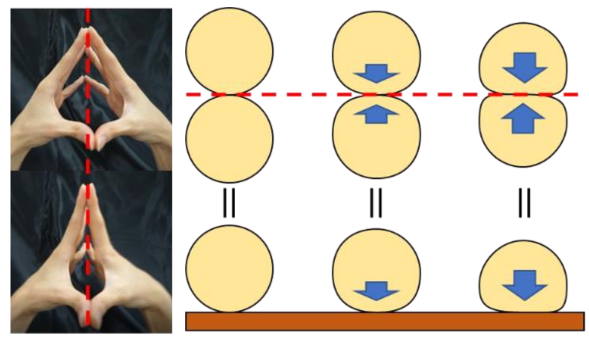

Figure 1. The boundary surface perceived when the fingers touch each other at the same velocity is the same as that perceived when the fingers touch a hard plate.

In this study, we examined whether the subjective sensation of curvature of a soft hemisphere changes when it is touched at various velocity ratios, as in the previous paper, and whether it can be perceived as the flattest as the hemisphere and finger collide with the same velocity. Furthermore, to investigate the applicability of this illusion, we created a prototype of an encountered-type haptic display in which the softness and curvature of the soft sphere change when the sphere is opposed by the user's finger movement.

II. Related Work

A. Soft and Hard Sensation and Display

Compressibility is an important factor in softness perception, and it is known that both skin deformation and kinesthesia cues influence this perception [6]. Friedman et al. [7] and Tiest et al. [8] investigated the contribution of kinesthesia and cutaneous sensation by comparing individual softness in active and passive touch situations.

Humans may perceive softness from sources other than physical deformation. Cavdan et al. showed that there may be dimensions of softness perception other than compliance, which is a common measure of softness [9]. Thus, it is still not completely clear which sense is dominant nor whether other factors are also involved.

Typical haptic displays use displacement-related force to represent softness, but there have also been attempts to represent softness by pure cutaneous sensation. Bicchi et al. [10] and Fujita et al. [11] proposed displays that dynamically control the contact area of a finger. Wearable jamming mitten [12] and jamming user interfaces [13] have been proposed to

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physically change the stiffness of an object using the jamming phenomenon.

B. *Encountered-type Haptic Display*

One type of haptic display for virtual reality (VR) space is encountered-type haptic display (ETHD). ETHD directly represents haptic sensation using physical proxies (end effectors) [14][15]. As realistic tactile sensations can be generated easily by changing the end effector, numerous applications have been proposed in the human–computer interaction (HCI) literature in recent years [16][17][18][19] .

A typical ETHD requires a plane of contact to face the user's finger and requires at least 5 degrees of freedom (DOF) of control to determine the position and orientation of the plane. In contrast, if the illusion phenomenon on which we are focusing can be stably represented, it would be possible to construct the ETHD using a sphere with the same softness and curvature as the fingertip as a proxy. In this case, in principle, because the end effector is a sphere, we only need to control the position of the sphere with 3 DOF.

III. Experiments in Curvature Perception

The purposes of this experiment were to confirm that (a) when a finger and an object with the same elasticity and curvature as the finger come into contact at various velocity ratios, the curvature of the object is perceived to be smaller, i.e., flatter and (b) that effect is the greatest when the two velocities are the same. In this experiment, a soft hemisphere was placed opposite to the subject's finger, and rigid samples with different curvatures were used as comparison stimuli. The evaluation was conducted by measuring the subjective equivalent points using the double staircase method with the Parameter Estimation by Sequential Testing (PEST) [20].

A. *Experimental Conditions*

3D printed samples were used as comparison stimuli for the experiment. The curvatures of the samples were set as shown in Table 1 and were based on the Weber ratio of perceived curvature [2] and the just noticeable difference (JND) [3]. The height of each sample was controlled so that the maximum height was 15 mm (Fig. 2).

Figure 2. Samples used in the experiment

TABLE I. Curvature of the Sample. The Blue Cell is the Same as the Size of the Soft Hemisphere Used in the Experiment

Curvature radius (mm)	Curvature (/m)	Curvature radius	Curvature	Curvature radius	Curvature	Curvature radius	Curvature
Flat surface	0.00	385.77	2.59	83.95	11.91	18.27	54.73
1611.46	0.62	350.70	2.85	76.32	13.10	16.61	60.20
1464.96	0.68	318.82	3.14	69.38	14.41	15.10	66.23
1331.78	0.75	289.83	3.45	63.08	15.85	13.73	72.85
1210.71	0.83	263.49	3.80	57.34	17.44	12.48	80.13
1100.65	0.91	239.53	4.17	52.13	19.18	11.34	88.15
1000.59	1.00	217.76	4.59	47.39	21.10	10.31	96.96
909.63	1.10	197.96	5.05	43.08	23.21	9.38	106.66
826.93	1.21	179.96	5.56	39.17	25.53	8.52	117.32
751.76	1.33	163.60	6.11	35.61	28.09	7.75	129.05
683.41	1.46	148.73	6.72	32.37	30.89	7.04	141.96
621.29	1.61	135.21	7.40	29.43	33.98	6.40	156.16
564.81	1.77	122.92	8.14	26.75	37.38	5.82	171.77
513.46	1.95	111.74	8.95	24.32	41.12	5.29	188.95
466.78	2.14	101.59	9.84	22.11	45.23	4.81	207.84
424.35	2.36	92.35	10.83	20.10	49.76	4.37	228.63

An elastic rubber (human skin, EXSEAL) was used for the soft hemisphere. The hemisphere had a radius of 15.1 mm, as shown in Fig. 3, and its hardness was set to 29.5 (Asker type E2), which is equivalent to the hardness of the fingertip. The radius of the hemisphere was calculated by approximating the first joint of one of the authors' index finger as part of a sphere, taking the surface distance from the tip to the first joint as the arc length and the straight-line distance as the chord length.

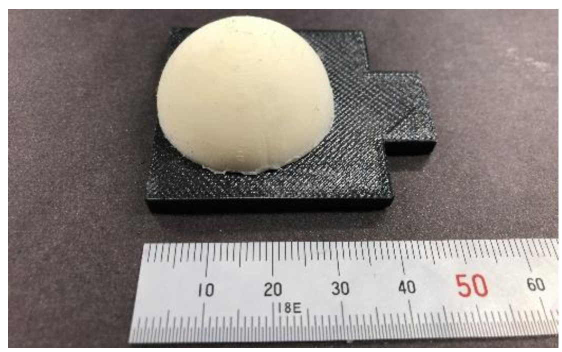

Figure 3. Soft hemisphere used in the experiment

B. *Experimental Procedure*

An overview of the experiment is shown in Fig. 4. We created an experimental setup using two self-propelled slide volumes (Alps Alpine Co., Ltd., RSA0N11M9A0K) that move left and right, as shown in Fig. 5. This slide volume is self-propelled with a built-in DC motor and can generate enough force to move the finger and the soft hemisphere. The positions of the finger and the soft hemisphere were controlled by proportional–derivative (PD) control using a microcontroller (Espressif Systems, ESP32 DevkitC). During the experiment, the subjects were instructed to close their eyes, and white noise was played through headphones to block out external environmental noise, such as the driving sound of the motor. The entire system was covered with a black curtain to prevent visibility of the shape and motion of the soft hemisphere. In each experiment, after three consecutive rounds of contact between the finger and the hemisphere, the subject touched the sample to be compared and was asked to choose whether the sample was flatter or more curved (a forced choice between two alternatives). Once an ascending or descending series was randomly selected, the number of steps in the sample to be compared was determined by PEST. For both the ascending and descending series, the initial step was set to 8, and the set was continued until the number of steps was less than 1.

We considered five ratios of the speed of the finger to that of the hemisphere: (a) 10:0, (b) 7:3, (c) 5:5, (d) 3:7, and (e) 0:10, where 10 corresponds to 30 mm/s. Condition (a) corresponded to the case of the hemisphere not moving, condition (e) corresponded to the case of the finger not moving, and condition (c) corresponded to the case of the two colliding at the same speed. The order of the experimental conditions was pseudo-randomized to eliminate any order effect. The average of the endpoints of the ascending and descending series was treated as the equivalent value. The experimental time per person was approximately 60 min.

The experiment was conducted with seven naïve subjects (all males) aged 22–26 years (mean age: 24.1 years). Six of them were right-handed; one was left-handed.

Figure 4. Scene of the experiment

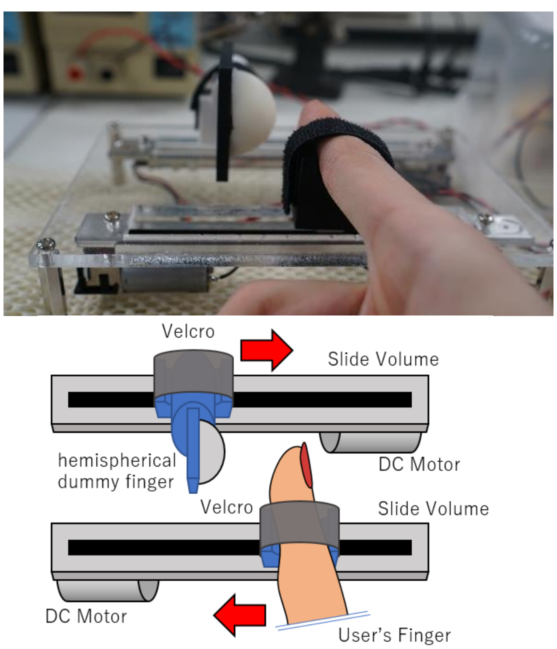

Figure 5. Equipment used in the experiment (top), schematic illustration of the system (bottom)

C. Result of the Experiment

Fig. 6 shows a box plot of the results for all subjects for each condition. The dotted blue line indicates the actual curvature of the soft sphere, the orange line indicates the median, the green circle indicates the mean, and the crosses indicate outliers.

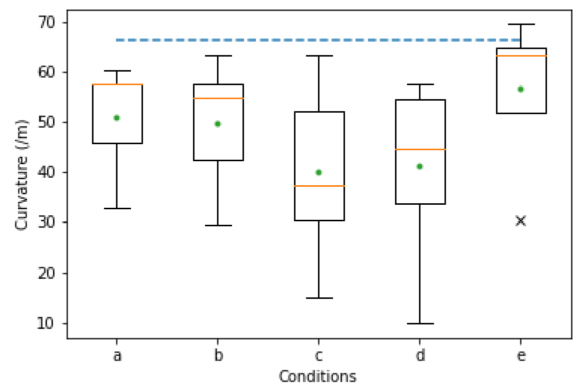

Figure 6. Experimental results for each condition
(The dotted blue line indicates the actual curvature of the soft sphere, the orange line indicates the median, the green circle indicates the mean, and the crosses indicate outliers.)

The mean values (and in parentheses, standard deviations) for conditions (a) to (e) were, in order, 50.98 (10.67), 49.71 (13.83), 40.11 (16.87), 41.26 (17.90), and 56.64 (13.43). The average values for the contact between the finger and the soft hemisphere show that the curvature of the soft hemisphere was perceived to be the smallest when the finger and the hemisphere were moving at the same velocity (condition (c)), i.e., it was perceived to be the flattest. To confirm the difference between the perceived curvature in each condition and the actual curvature of the soft sphere (66.23), a t-test was conducted with a significance level of 0.05. The results showed a significant difference from the actual curvature in conditions (a) to (d) and no statistically significant difference in condition (e).

It was also observed that the perceived curvature decreased as the two velocities became closer. One-way ANOVA conducted with a significance level set at 0.05 detected no significant differences among the conditions ($F(4,30) = 1.555$, $p = .212$).

For a more detailed analysis, fig7 shows the results for each subject. In addition, the relationship between the ratio of the largest to the smallest perceived curvature in all conditions for each subject and the measured width at the base of the fingernail is plotted in fig. 8.

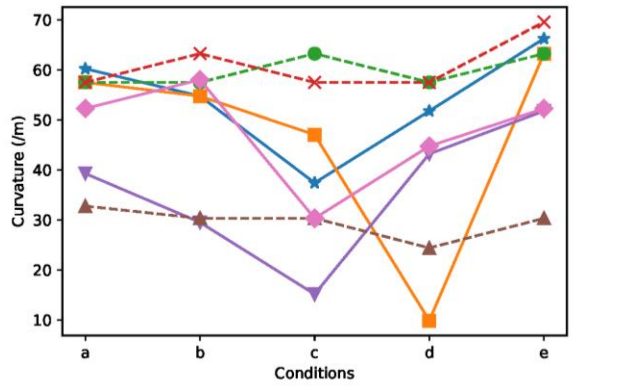

Figure 7. Experimental results for each subject. The solid lines correspond to subjects whose curvatures changed dramatically. The dotted lines correspond to subjects whose curvature did not change much.

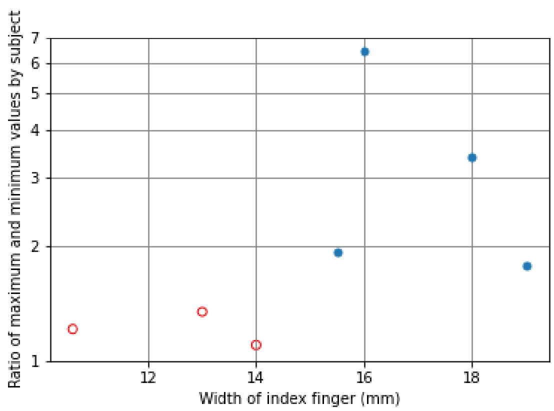

Figure 8. Subjects' finger widths and ratio of the maximum to minimum values of their answers.

IV. Preliminary Application to ETHD

We created the device shown in Fig. 9 to assess whether the observed illusion can be applied to the case in which a user's hands can freely explore a space. The 4-DOF robot arm used was equipped with DC motors (Dynamixel XM430-W350) at each joint, along with a microcontroller (ROBOTIS, OpenCR1.0) for position control and a motion capture device (OptiTrack, V120:Duo). In this preliminary study, we tried to represent a horizontal plane. The robot arm was mainly responsible for horizontal 2-DOF motion. In order to achieve an accurate facing velocity in the vertical direction at the end effector, a DC motor (Dynamixel XC430-W150) was attached to the end effector to raise and lower the soft hemisphere. The hemisphere was the same as the one used in the previous experiment.

The users were able to move their hands freely while wearing optical markers for the motion tracker. The robot arm constantly tracked the horizontal coordinates of the user's finger and slightly raised the hemisphere just before the user touched the object. The opposing motion of the finger and the soft sphere created the aforementioned illusion, and the user was expected to perceive the object as being harder and flatter than usual.

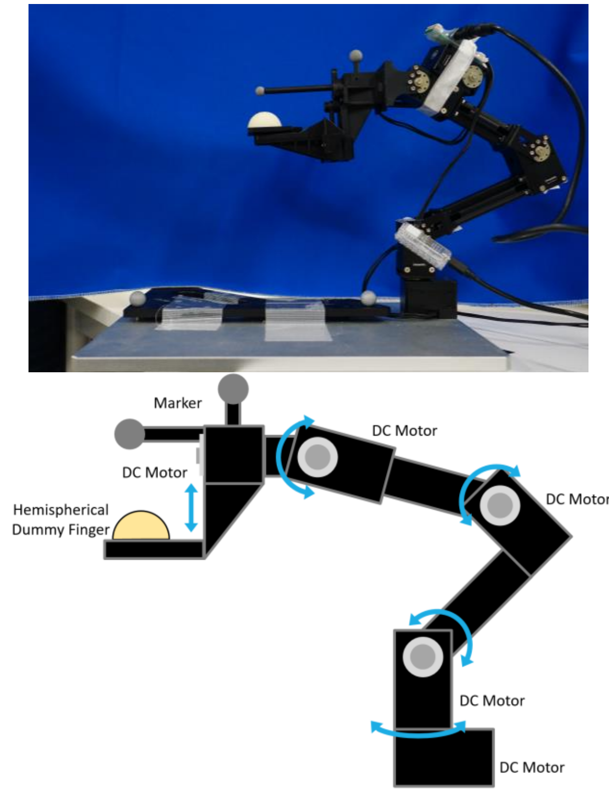

Figure 9. Created device (top), system overview (bottom)

A. *Evaluation of Opposing Speed*

We examined whether the hemisphere could be raised at the same speed as that of the finger. The optical markers were attached to the index fingernail and to the base of the hemisphere, and the vertical positions were acquired by the motion tracker while the pushing motion of the finger was performed multiple times, with the pushing speed slowed down for each trial.

a. Results

Fig. 10 shows the change in the z-coordinate of the finger and the base of the hemisphere, and Fig. 11 shows the velocity derived by temporal differentiation. When the speed of the finger was high, the base could not follow that speed, and its speed was saturated at 154.8 mm/s, which is consistent with the hardware limitations of the motor (140.5 mm/s). In contrast, when the finger movements were slower (in the range of approximately 11 to 18 s), the base moved at the same speed as the finger. Fig. 10 also shows that there was a time delay of up to 0.23 s at the time of contact.

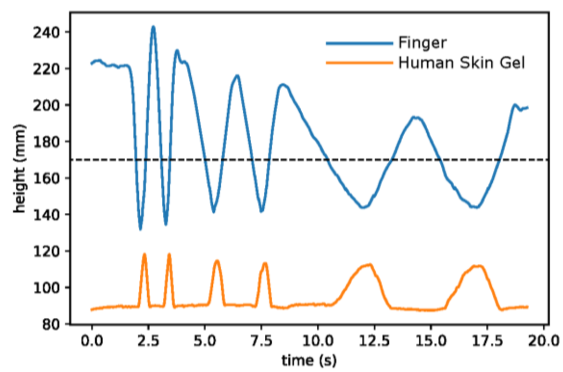

Figure 10. Height of the finger and gel pedestal (the black dotted line is the height at which the gel starts to rise)

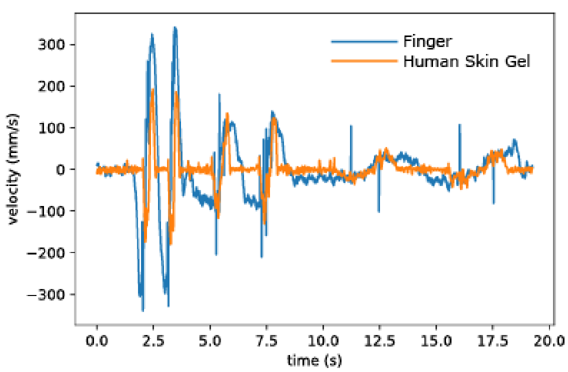

Figure 11. Velocities of the finger and gel pedestal (the finger and gel are opposite each other, so the results for the gel show reversed positive and negative values)

B. *User Study*

Seven subjects were asked to experience the device with their eyes closed and while listening to white noise. We prepared two conditions. In one condition, the vertical motion was deactivated, and the tip only followed the finger horizontally. In the other condition, the vertical motion was turned on, and facing motion tried to generate the illusion. Five out of seven subjects answered that the hardness was changed, and six subjects answered that the curvature was changed. Furthermore, with respect to the time delay, there were no reports of discomfort, such as fingers being actively pushed back, and many commented that they felt as though they were touching a stationary board.

V. DISCUSSION

A. *Verification of Curvature Perception*

Fig. 6 suggests that the soft hemisphere might be perceived as flatter when the velocities of the hemisphere and finger are more similar. The ratio of perceived curvature for conditions (c) and (e) was 4.12 times the Weber ratio of perceived curvature (0.1) [2].

In contrast, the results of the statistical tests did not reveal significant difference between the conditions. To explore the reason for this, the results for each subject were examined. As Fig. 10 shows, the subjects were divided into two groups, one with varying curvature values for each condition (shown by solid lines) and the other with almost constant curvature values (shown by dotted lines). To determine whether this difference was caused by individual differences in the size of fingers, we measured the width of the finger of each study participant at the base of the nail, and we also calculated the ratio of the maximum and minimum curvature responses for all conditions for each subject. The results plotted in Fig. 11 show a clear dependence on the finger size. The ratios of the maximum to minimum curvatures were the highest at a width of approximately 16 mm, but when the finger was small (less than 15 mm), the ratio was close to 1, which indicates that the illusion did not occur.

After the experiment, some subjects commented that the shape of the soft hemisphere was not perceived as a hemisphere but rather seemed to have different curvatures in the direction of the finger's short and long axes. Others commented that only the center of the contact surface was flat, and that the periphery was spherical. This suggests that the illusion might have occurred at least in part.

In the present experiment, the relative velocity between the finger and the soft hemisphere was always constant (30 mm/s). Thus, the skin deformation should not have varied for any of the conditions. Therefore, based on the aforementioned contact theory, if we only consider skin deformation, it is plausible that all conditions should be equally felt as flatter than contact with a rigid body of the same curvature. In particular, for conditions (a) to (d), the curvature was significantly smaller than the actual curvature of the soft sphere (indicated by the dotted line in Fig.6). However, for condition (e), there was no statistical difference from the actual curvature. This may be owing to a passive search being superior to active search in terms of curvature discrimination ability [21]. It is possible that condition (e), in which the finger is not moved completely, resulted in a smaller difference from the actual curvature than the other conditions in which the finger is moved. In addition, as the opposing velocities become closer to equal, the boundary surface of the finger and the hemisphere are expected to become more static to the world coordinate. This is assumed to lead to the perception of stiffness in terms of kinesthesia; however, in the present experiment, it seemed to contribute to a decrease in curvature, i.e., a perception of a flatter surface. This suggests that curvature perception and elasticity perception may not be independent of each other; this seems reasonable because perceiving the curvature of a deforming elastic body requires a judgment that includes elasticity.

However, the number of subjects was only seven, and the fact that the average value for all conditions was smaller than the actual curvature of the soft sphere might have been due to some other cause of offset. In addition, we must note that condition (a) cannot be regarded as a strictly active touch condition, because the fingers were moved by the device. It is necessary to conduct experiments with hemispheres with different elasticities and curvatures, and true active touch conditions must also be investigated.

B. Applicability to ETHDs

We found that many people sensed changes in hardness and curvature when they experienced the robotic device. This suggests that this illusion can be applied to situations in which the user can freely explore. In this study, we limited the expression of the plane to a horizontal plane and attached a motor to the end effector for vertical motion. Most conventional ETHDs, especially those that represent a flat surface, require at least 5-DOF control to drive an actual flat plate. The proposed method, however, does not require control of the orientation because it uses a sphere and can be used with only 3-DOF control of the position, which is expected to be easier to create. However, we must also note that this method would require constant measurement and control of the fingertip. In contrast, a time delay of up to 0.23 seconds was not noticed by any subjects. We must determine the largest allowable time delay that does not affect the illusion.

As in the previous experiments, there was a great deal of individual variability in the results, ranging from subjects who "felt as if a hard plane like a desk was spreading" to those who "definitely changed the perception, but not dramatically," but only one out of seven subjects experienced no change in perception at all. This suggests that, unlike the experiment described above, the active touch situation allowed them to move their own fingers, and it might have made it easier for the illusion to occur.

VI. Conclusion

In this study, we conducted experiments to confirm the phenomenon that an object with the same curvature and elasticity as a finger is perceived to be flatter when it comes into contact with an opposing finger moving at the same velocity. The results of the experiments show that a soft hemisphere tends to be perceived as flatter than it actually is under most conditions and that it is perceived to be the flattest when it comes into contact with an opposing finger moving at the same velocity.

A prototype was fabricated to confirm the applicability of this illusion as an encountered-type haptic display. Most of the study participants perceived the change in hardness and curvature, although there were hardware limitations, such as a limited speed and a time delay. This suggests that this illusion can be applied to ETHD.

Our future work will include larger-scale experiments and investigation of the contributions of cutaneous sensation and kinesthesia to curvature perception, as well as the interaction between elasticity perception and curvature perception. In addition, we will develop an encountered-type haptic display that is an extension of the prototype device developed in this study, and we will analyze the effect of time delay and on the robustness of the illusion studied.

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