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Pseudo-haptic feedback on softness induced by squeezing action

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***Abstract*— The pseudo-haptic feedback is a method to represent illusion of haptic sensation, induced by non-haptic stimuli, such as vision and acoustics. This is a prospective method that enables us to develop haptic display without using any actuators. That considered to be a benefit for composing a small, light weighted haptic display. However quantitative control of haptic representation is often difficult because the method uses illusion. In this research, we propose a novel method to induce illusion of haptic sensation on softness, by using a pressure sensor integrated smartphone and squeezing action. In this paper, a prototype system to induce the pseudo-haptic phenomenon is described. Then, two experiments were conducted. The first experiment was conducted to confirm that the device has enough capability to induce the pseudo-haptic phenomenon. The second experiment was for qualitative analyzation of the relationship between the visual stimulus and the induced pseudo-haptic feeling on softness.**

I. Introduction

In daily life, human perceive haptic related information such as shape, weight and hardness/softness by grasping objects. And so far, many haptic display devices have been developed to reproduce and present this information. In many haptic displays, force generated by actuators such as DC motors and pneumatic actuators is transmitted to fingertip and/or hands to represent haptic related information. While such an expression method has excellent characteristics with respect to accurate reproduction of force, it requires users to put on or hold actuators and links or wire mechanisms. That considered to result in loss of convenience.

On the other hand, pseudo-haptic phenomenon is pulling attention these years. The pseudo-haptic is not a method that directly presenting force to users, but presenting non-haptic stimulation, such as visual and acoustic stimulus, to induce illusion of haptic feeling. Various pseudo-haptic such as friction feeling, weight feeling, hardness feeling etc. have been reported [1]. In those research works, most system are composed of a device for measuring hand movement such as a mouse, and a display for presenting visual stimulus. They do not require any actuators. This characteristics contributes to simplify the system structure comparing to that of traditional haptic display devices. However, it is often hard for pseudo-haptic display method to express undoubtful, strong effects. More important problem is that the generated sensation relies on human illusion. That means, the method has difficulty in quantitative control of expression.

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In this paper, we first describe the basic method for generating pseudo-haptic on softness induced by squeezing action which we found[2][3]. Then, we also describe detail of experiments that we conducted to clarify the relationship between actual feeling on softness and illusionary generated feeling on softness.

II. Related works

A. Mechanical haptic display systems

The most straightforward method for presenting a hard and soft feeling is that applying a certain force to user's finger. such as PHANToM [4] and SPIDAR[5]. With the evolution of technology, it has become possible to present a sense of hardness with high reality, but there is a problem that it is necessary to attach or bring the actuator to the body. That property makes such system relatively big, hard to use. On the other hand, several methods are proposed that to change softness of a certain object to be touched by users. Matoba et al. Proposed a Claytric Surface that can dynamically change the hardness of the display surface [6]. This uses fine particle material such as expanded polystyrene beads sealed in a material with high airtightness and flexibility as a display, and by changing the air pressure inside the display, the softness is changed.

B. (Visually) induced pseudo-haptic sensation

Visually induced pseudo-haptic sensation is a method to induce illusion of haptic feeling by providing visual stimulus. Many research has been done in this field [1]. Lecuyer et. al. proposed a new device that to induce pseudo-haptic on softness[7]. In their system, the user pushes a piston to push a soft physical object. At the same time, the user sees a virtual piston and soft object displayed on a display. The system is designed to control the illusion of haptic feeling on softness by changing the amount of deformation of the virtual soft object on the display when pushed. Kokubun et al. proposed a system that can deform the CG displayed on the mobile terminal, according to the applied force onto the back of the terminal. It is also capable of provide an illusion of haptic feeling on softness [8]. Unfortunately, those research were not intended to induce pseudo-haptic sensation on softness related to squeezing action, which is one of the common action when testing various objects' softness in daily life.

III. Prototype system

In this chapter, we will describe our proposed method to induce illusion of haptic on softness. The basic procedures of the method are as follows:

- Preparing an image display device that can be grasped with one hand
- The user grasps the device while observing the image on it
- An image that deforms according to squeezing action and its force is shown on the device

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In the procedures shown above are intended to induce illusion of softness. Actually, the user holds a solid hard object, but the user feels as if he/she holds a soft object, because of the induced illusion. The detail of the hardware setup and the stimulation design.

A. *Configuration of the hardware setup*

Figure 1. shows the hardware setup of the prototype system to induce desired illusion. The system consists of a smartphone (Samsung Nexus S, Size:123.9 x 63 x 10.9 mm, Weight:129 g, Display: Super AMOLED, 480 x 800 pixel)[9], Arduino RT-ADK (RT Accessory Demo Kit) [10] and pressure force sensors (FSR-400, Interlink Electronics Inc.)[11]. To measure the squeezing force, two pressure sensors are attached to each side of the smartphone. i.e., a total of four sensors are used. The value from the pressure sensors are transmitted to the smartphone via the RT-ADK and used for controlling the visual stimulus displayed on the screen.

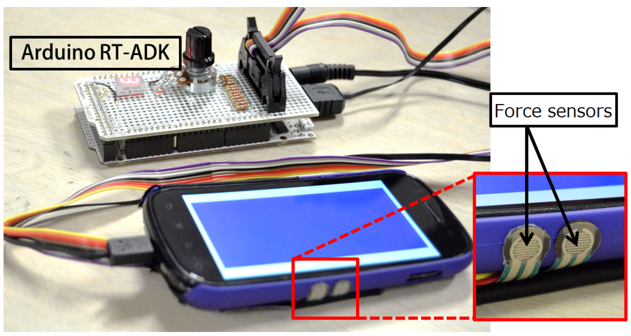

Figure 1. The prototype system based on a smart phone.

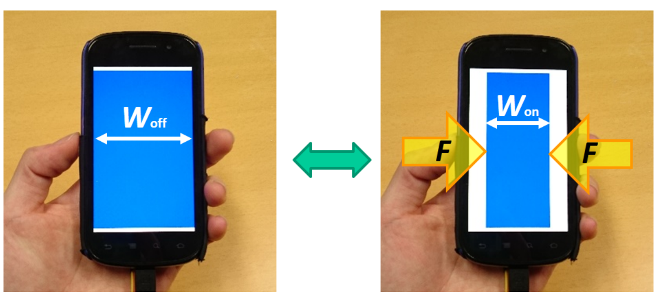

Figure 2. The basic principle of the visual stimulus.

B. *Design principle of the visual stimulus*

The visual stimulus shown on the display deforms according to the user's squeezing force, based on the Hooke's law. As shown in the Figure 2. , assuming that the image width of the visual stimulus in the state where no force is applied to the device is $W_{off}\mathrm{W_{off}}$ (mm). The width when the force F (N) is applied to the device is W_{on} (mm). Then, W_{on} can be described by using the Hooke's law as follows:

$$W_{on} = W_{off} - \frac{F}{k} \qquad \text{Eq 1}$$

In the equation, k denotes the spring constant in N/mm, which can be used to control the effect of the visually induced pseudo-haptics on softness. For example, here we assume spring constants A, B, C as shown in Figure 3. A is the largest, followed by B and C. In this situation, when the same force F is applied to the smart phone, the W_{on} changes as shown in Figure 3. The larger the spring constant become, the harder feeling can be generated.

Then, a preliminary study was conducted to confirm that the proposed method is capable of generating pseudo-haptic sensation on softness. The detail of the experiment and its result is described on the next chapter.

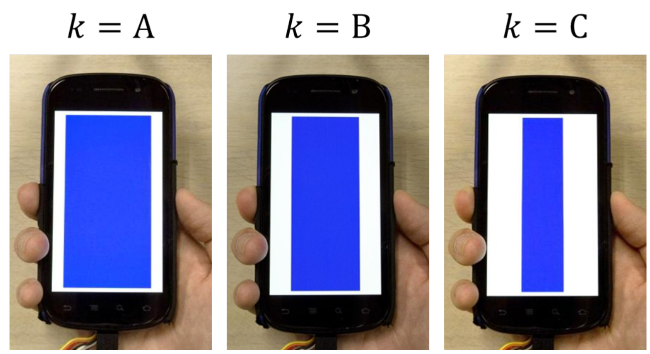

Figure 3. Examples of visual stimulus at different spring constant.

IV. Preliminary Experiment

In this chapter, we describe the preliminary experiment to confirm the visual stimulus capable of generating the pseudo-haptic sensation on softness.

A. *Preparation*

First, three types of visual stimulus (VS) with different spring constant were developed. Each VS is labeled as "VS(H)", "VS(M)" and "VS(S)", which means "Visual Stimulus Hard/Medium/Soft" accordingly. At the same time, physical spring based comparison objects were developed to provide physical stimulus (PS) as shown in Figure 4. . The size of the objects (width: 65 mm, height: 120 mm) are identical to that of the smartphone which is used to provide VSs. Following four types of PSs (Dummy, Soft, Medium and Hard) were prepared to provide actual different feeling on softness. Each of them is denoted as PS(D), PS(S), PS(M) and PS(H). The spring constants of them are as follows: PS(D)=0.471, PS(S)=0.853, PS(M)=1.197, PS(H)=1.521 (N/mm)(Figure 5.).

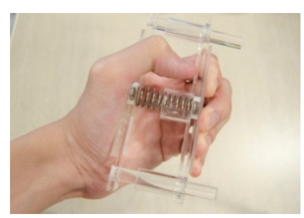

Figure 4. Physical Stimulus(PS) composed of a physical spring.

Figure 5. PSs installed with different springs (k=0.471, 0.853,1.197, 1.521 in order from left to right).

As shown in TABLE I. , the spring constants of each VS corresponds to that of PS that we prepared. The softest physical spring (k = 0.471 N/mm, denoted as PS(D)) is used as a dummy object, which does not have any corresponding visual stimulus.

TABLE I. LIST OF THE SPRING CONSTANTS FOR PRELIMINARY STUDY

	Spring constants in N/mm	
	PS	**VS**
Hard	PS(H) (k = 1.521)	VS(H) (k = 1.521)
Medium	PS(M) (k = 1.197)	VS(M) (k = 1.197)
Soft	PS(S) (k = 0.853)	VS(S) (k = 0.853)
Dummy	PS(D) (k = 0.471)	

B. Procedure

In this experiment, the number of participants was three. They were in their early twenties, male and right-handed. The experiment was conducted as follows:

(1) One visual stimulus was selected randomly from among three VS patterns. Participants are required to squeeze the smartphone based prototype device. Then they also required to remember the feeling related to haptic sensation they felt when squeezing.

(2) Then, participants put on an eyemask. They are asked to squeeze four PSs in random order.

(3) Finally, participants are asked to choose one PS that has most similar feeling on softness to that of they felt when squeezing the smartphone based prototype device.

The procedures from (1) to (3) is repeted five times per each visual stimulus. In this experiment, the softness of the object they grasp is always the same in (1). Therefore, if no pseudo-haptic effect is occurring, it is considered that the same result should always be selected, i.e., PS(H) shouls be selected in (3). On the other hand, if a certain pseudo-haptic effect is occurring, it is expected that a PS corresponding to the VS should be selected.

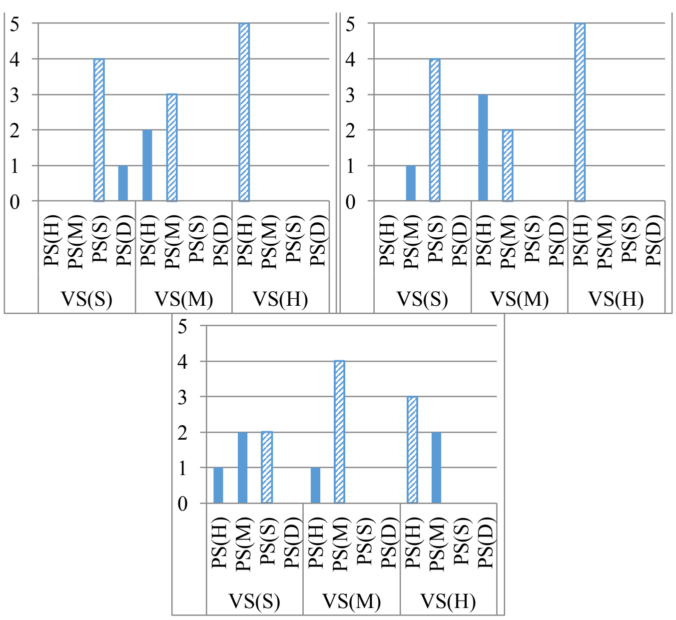

Figure 6. Results of each patricipants of the preliminary experiment.

C. Result

The results of the experiment are shown in Figure 6. The each of the graph shows result of each participants. The vertical axis denotes the number of counts to show which PS is selected in (3). Each graph is seperated into three parts, VS(S), VS (M), VS (H). They are the visual stimulus that are chosen in (1). PS(D), PS(S), PS(M), PS(H) denotes the physical spring that are chosen in (3). From these result, when showing VS(H), participants tend to choose PS(H). However, when showing VS(M) and VS(S), participants tend to choose softer PSs. This result is considered to support the following claim, that the visual sitmulus have some sort of effect to modify the haptic feeling on softness.

In the next chapter, we will conduct further experiment to clarify the quantitative relationship between physical feeling on softness and induced pseudo-haptic feeling on softness.

V. EXPERIMENT

From the result of the preliminary experiment, it can be said that the visual stimulus has potential to affect the feeling on softness. In this chapter, we describe a detail of further experiment to investigate the quantitative relationship between the physical feelings on softness and induced pseudo-haptic feeling on softness by using constant the constant method.

A. Preparation

Before conducting the experiment, a set of stimuli must be designed. In this case, a series of VSs and PSs with appropriate spring constants must be designed. In this section, abstract of the procedure to design those stimuli will be described. The number of participants of this experiment was four, all male and all of them were in their twenties.

Firstly, a range of constant spring for VS was investigated. The participant required to squeeze the smartphone based device with his/her minimum force. Then a spring constant k_1 is determined to perform maximum deformation of the visual stimulus. This method is used to investigate the minimum spring constant for VS. In the same way, the participant required to squeeze it with his/her maximum force. Then a spring constant k_2 is also determined to perform minimum deformation of the visual stimulus. Then, intermediate spring constant k_{sm} is defined by the following equation:

$$\log(k_{sm}) = \frac{1}{2}(\log(k_2) - \log(k_1)) + \log(k_1) \qquad \text{Eq 2}$$

Secondly, a physical spring which of the spring constant value corresponds or similar to k_{sm} was investigated. To achieve this goal, PSE corresponds to k_{sm} was investigated by using the constant method. In this experiment, VS based on k_{sm} was used as a standard stimulus and six physical springs (0.647, 1.01, 1.196, 2.03, 2.785, 4.737 N/mm) were used as comparison stimulus. Then, a physical spring which of the spring constant is 1.196 N/mm was chosen, which will be denoted as k_{bm}.

Thirdly, a VS which of the spring constant value corresponds to k_{bm} was investigated. To achieve this goal, PSE corresponds to k_{bm} was investigated by using the constant method. At the same time, JND was also investigated.

Fourthly, with the PSE and JND investigated at the third phase mentioned above, a new series of visual stimulus is designed based on rules as follows:

- Logarithmically equally spaced VSs
- At least 2 VS in between PSE and PSE+JND
- Eight VSs in maximum to reduce the number of the case of the experiment.

The defined series of VS is shown in TABLE II. In the next section, the detail of the experimental setup is described.

TABLE II. LIST OF THE SPRING CONSTANTS

Spring constant in (N/mm)			
PS as Standard Stimulus(SS)			**VS as Comparison Stimulus(CS)**
1.010	1.196	2.030	0.300
			0.416
			0.577
			0.800
			1.109
			1.538
			2.133
			2.958

B. *Experimental setup*

To improve the accuracy of the experiment, experimental condition was carefully designed. The proposed method is a kind of visually induced pseudo-haptic phenomenon. Thus, participants' arms and head was fixed to the frame to keep the appearance of the visual stimulus during experiments. Furthermore, it is known that the feeling of softness changes according to its temperature. Thus, in the experiment, all equipment and participants' hands were heated so as to be almost the same temperature as their body. Participants were also required to practice using the experimental system before participating in the experiment.

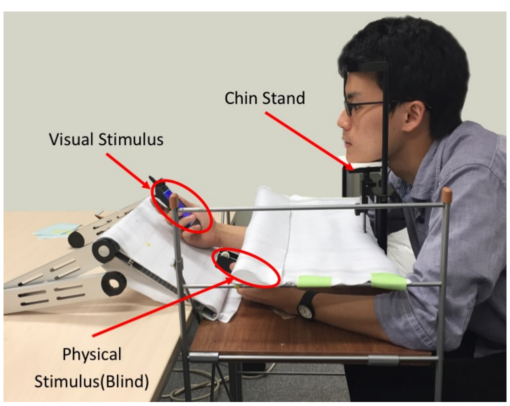

Figure 7. An overview of the experimental setup.

C. *Procedure*

The number of participants were seven, all of them were right-handed and were in their twenties. The experimental procedure of this experiment is shown below. The participants were seated in front of the PS on the desk. The VS were provided through our developed smartphone based. Stickers were placed on the middle finger and the thumb as shown in Figure 8. Those stickers were affixed to each device side so that the participants could always grip and squeeze the same place. The detail of the experimental procedures is as follows:

(1) Choose one physical spring for PS from TABLE II. as a standard stimulus. Then, the spring constant of VS is randomly selected.

(2) Participants are asked to hold the PS on the left hand and VS on the right hand.

(3) Participants secure both wrists and fix the jaw on the chin rest. The hand holding the PS is covered so as not to be visible to the experiment participants.

(4) While looking at the visual stimulus, participants are asked to squeeze and release motion several times until he/she learn softness. After the learning phase, the participant is required to do the same squeeze and release motion of his/her both hands, i.e., squeeze PS and VS at the same time. Then, he/she asked to answer which is harder between PS and VS (2 Alternative Forced Choice).

(5) A short break

(6) A dummy VS that does not deform is produced. The participants are required to squeeze it several times to reset the sensation.

(7) A short break

(8) Change {PS to the right hand, VS to the left hand} to grasp and perform Steps 4 to 7.

(1) - (8) are carried out for eight times in all combinations while changing spring constants of PS and VS. Stop securing arms between each set and take a break.

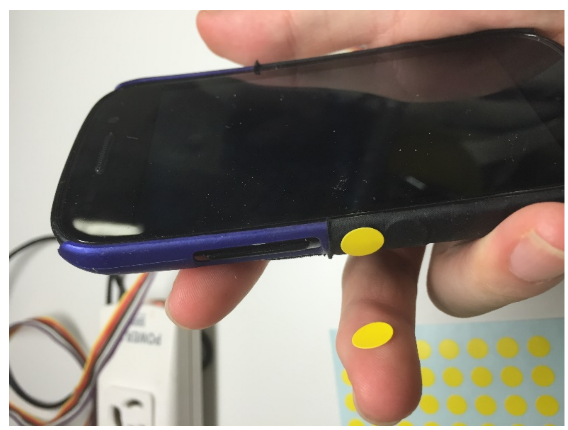

Figure 8. Markers attached on participant's fingertip.

D. *Results*

The psychometric measurement function created based on data obtained from all experiment participants is shown in Figure 9. TABLE III. shows PSE, JND obtained from these psychometric measurement functions. As a result of one-way ANOVA analysis on PSE with three types of standard stimulus, F value was 6.35 > finv(0.05, 2, 18), p value was 0.0082<0.05. In addition, the result of Tukey-Kramer's multiple comparison test is shown in TABLE IV. Also, logarithmic approximation of the data plotted in Figure 9. is represented by the following equation.

$$k_{V-both} = 0.609 \ln(k_{R-either}) + 1.357 \qquad \text{Eq 3}$$

$k_{R-either}$ (N/mm) is the spring constant of the PS (standard stimulus), and k_{V-both} (N/mm) is the spring constant of the VS felt equivalent.

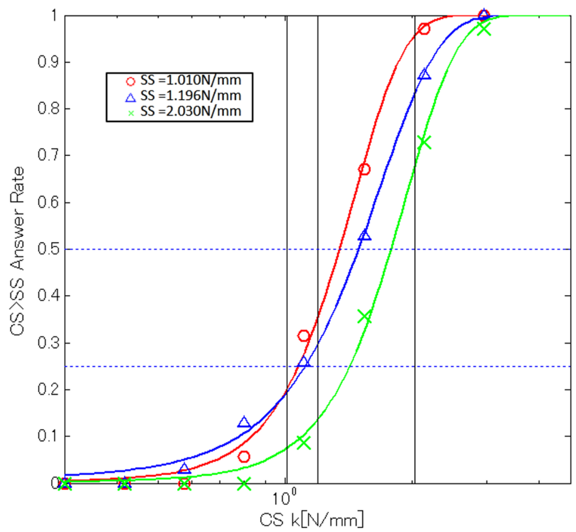

Figure 9. Result(SS:Standard Stimulus, Physical Stimulus in this experiment, CS: Comparison Stimulus, Visual Stimulus in this experiment).

TABLE III. PSE AND JND OBTAINED FROM THE EXPERIMENT

Standard Stimulus (N/mm	Average of PSE (N/mm)	Average of 25%JND (%(N/mm))	Standard deviation (N/mm)
1.010	1.344	20% (0.269)	0.201
1.196	1.491	25% (0.375)	0.303
2.030	1.782	20% (0.361)	0.288

TABLE IV. TUKEY-KRAMER'S MULTIPLE COMPARISON TEST

Group 1 (N/mm)	Group 2 (N/mm)	P-value
1.010	1.196	0.758
1.010	2.030	0.009
1.196	2.030	0.040

E. Discussions

When focusing on the PSE in this experiment as shown in TABLE III. , it can be said that all participants felt the hardest at the case of PS (Standard Stimulus) of 2.030 (N/mm), comparing to the cases of 1.010 (N/mm) and 1.196 (N/mm). This is also confirmed from the result of Tukey-Kramer's multiple comparison test as shown in TABLE IV. There is no significant difference between 1.010 (N/mm) and 1.196 (N/mm), but there is a significant difference from 2.030 (N/mm). Considering the fact that the hardness of the smartphone itself has an extremely large spring constant that cannot perceive the displacement even if it is grasped full force, it can be said that the pseudo-haptic on softness can be generated by this proposed method.

Unfortunately, measuring the amount of illusion is a challenging task. It is hard to affirm that the participants never have a certain strategy to answer the questions. We carefully designed the experimental procedure to reduce such risk. However, we still recognize the necessity of further investigation to confirm the effect of pseudo-haptic on softness.

The prototype device shown in Figure 1. is still complex and large to be used. To shrink the size, and reduce the weight and complexity, we have developed a new prototype system as shown in Figure 10. By changing the control board from Arduino ADK to Physicaloid[12], it is succeeded to reduce the size from 101x53x17(mm) to 33x31x5(mm). The weight of the control board (NOT including the smartphone) was also reduced from 88(g) to 8(g).This second prototype could show a potential to compose a small and light weighted haptic display.

Figure 10. Second prototype.

VI. CONCLUSION

In this paper, we proposed a new method to generate pseudo-haptic on softness by using smartphone and force sensors. In addition, we conducted experiments to verify the effect of the proposed method. From the result, it is succeeded to obtain an equation to present the relationship between physical softness property and visually induced pseudo-haptic sensation on softness.

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