Effect of haptic feedback on pseudo-haptic feedback for arm display

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Abstract: We propose a haptic feedback system for an arm in order to obtain the sensation of stiffness and the boundary of virtual objects. Powerful haptic displays are large and heavy, interfering with movement in the virtual environment. Here, we focus on an illusion called pseudo-haptic feedback, which provides the results of haptic feedback using only visual impressions. Since pseudo-haptic feedback is known to be inappropriate for applications requiring strong force, a combination of pseudo-haptic feedback and real haptic feedback is proposed for a compact haptic display. This study examines the effectiveness of this combination by comparing the stiffness of two walls. Pseudo-haptic and real haptic feedbacks are applied to one wall, and only real haptic feedback is applied to the other wall. The results verify that the magnitude of the force perceived with the application of a combination of pseudo-haptic and real haptic feedbacks is greater than that of the force perceived by the application of only real haptic feedback.

Keywords: pseudo-haptic, haptic feedback, virtual reality.

1. INTRODUCTION

Virtual reality technology provides us with the sensation of walking into a computer graphic environment and actually operating an object in it. Haptic feedback assists us in manipulating a virtual object. If there is no haptic feedback, we have to determine whether we have touched an object or not by sight alone. If our hand is visualized along with the object, the reality is spoiled. Therefore, haptic feedback is important for virtual reality technology.

Various haptic displays have been previously proposed. In this study, a haptic display for an arm with the sensation of softness and boundary, which is thought to be essential for interaction with virtual objects, is considered. Since the fingers and palms of a hand are most often used when an object is touched, most of the existing haptic displays focus on them. However, in everyday life, other parts of the body are also used to touch objects. For example, the hand and arm are used to touch a large object such as a soft toy. Therefore, in this case, a haptic display using the arm would be functional (as in Fig. 1). It is desirable to move freely in the virtual environment; therefore, a haptic display should not restrict the workspace or interfere with bodily movements.

There are many methods for providing haptic feedback to arms. For example, methods that involve the direct application of force to an arm, production of symbolic tactile feedback, direct stimulation of a muscle or a nerve, and use of visual feedback have been proposed. Litier et al. [1] presented a 7-DOF (Degree of Freedom) portable exoskeleton with DC motors and sensors, and Furisoli et al. [2] proposed a 5-DOF ground exoskeleton with DC torque motors and carbon fiber structural parts. These displays are placed on the arm, and force is directly applied when a virtual object is touched. These displays can produce a large force. However, the larger the force these displays apply, the larger and heavier the devices become. A large and heavy device restricts workspace and interferes with bodily movements. Bloomfield et al. [3] proposed a display with vibratory tactors. This display provides only a symbolic tactile feedback, not a force feedback. An example of a method that directly stimulates a muscle or a nerve is FES (functional electrical stimulation). Fujita et al. [4] proposed a method for controlling the motion of a paralyzed upper limb using FES and a neural network. However, FES does not seem to be good for haptic feedback, because an invasive display is difficult to use casually, and stick-on electrodes cannot produce a constant sensation. An example of a method that involves the use of visual feedback is a pseudo-haptic approach. Pseudo-haptic feedback does not need a force display. However, it is known that pseudo-haptic feedback varies with each individual, and it may be difficult to produce a large force using it. The abovementioned haptic methods seem ineffective for obtaining desired results.

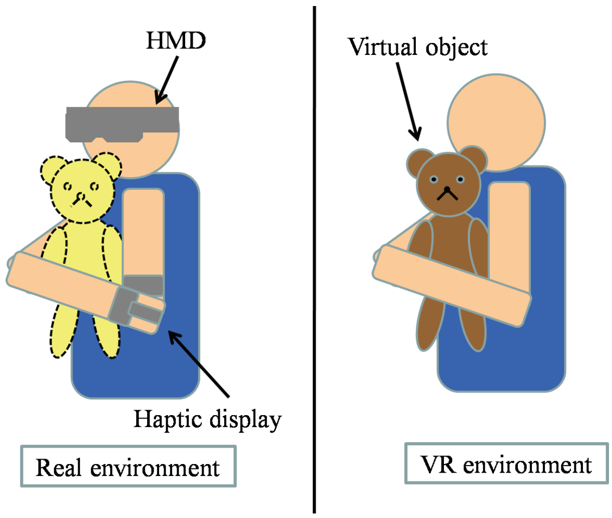


Fig. 1 Illustration of an interaction with a virtual object.

A compact haptic display using both pseudo-haptic and real haptic feedback is proposed in this study. (A force that is directly applied to the arms is referred to as "real haptic" in this paper). It is expected that the proposed haptic display will produce a larger force than the display using only real haptic feedback, and the target value of the real haptic feedback will become small along with the display. The effectiveness of a real haptic and pseudo-haptic combination is examined to show its benefits.

2. METHOD OF COMBINATION

The proposed combination of pseudo-haptic and haptic feedback for a compact haptic display is shown in Fig. 2.

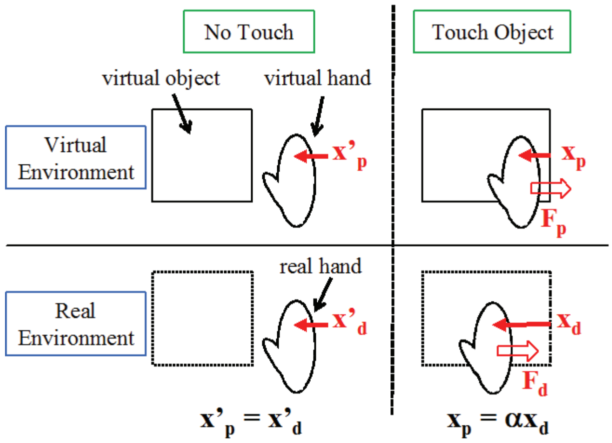


Fig. 2 Image of the proposed method.

2.1 Real haptic feedback

A display using real haptic feedback provides stiffness based on the positions of the user's hand and the object. In accordance with Hooke's law (Eq. (1)), the force (F_d) that the device applies to a user is related to the stiffness (k_d) of the device and the displacement of the user's arm from the boundary of the object (x_d).

$$F_d = k_d x_d \tag{1}$$

Displays using real haptic feedback are mainly categorized into the following two types: portable and ground-based displays. These displays can produce large forces. However, motors that are needed to produce these large forces tend to be cumbersome. Therefore, displays that are capable of producing a large force become heavy and awkward, interfering with the movement of the body. It becomes difficult to move the arm upward or rapidly and to walk around and move the arm carrying the weight of the device. On the other hand, the ground-based display is lighter than the portable display, because the ground-based display is hung from a roof, wall, or supporting post. However, the ground-based display still restricts workspace and interferes with movement.

2.2 Pseudo-haptic feedback

Pseudo-haptic feedback is a well-known illusion, where haptic feedback is obtained by using only visual feedback. For example, when we constantly manipulate a mouse but the cursor moves slowly, we feel a bumpy surface [5]. There have been studies on the perception of stiffness and friction using this phenomenon.

The force (F_p) that the pseudo-haptic feedback applies to a user can be assumed to be related to the stiffness (k_p) of a virtual object and the displacement (x_p) of the virtual arm from the boundary of a virtual object (Eq. (2)) [4]. x_p is related to the proportionality coefficient (α) and x_d (Eq. (3)). The value of k_p seems to depend on the user, in other words, in pseudo-haptics, k_p is a value of individual difference. It appears that the magnitude of F_p can be changed by changing the value of α.

$$F_p = k_p x_p \tag{2}$$

$$x_p = \alpha x_d \tag{3}$$

In contrast, when a virtual object is not touched, the displacement (x'_p) of the virtual arm is equal to the displacement (x'_d) of the user's arm.

Pseudo-haptic feedback does not need a mechanical haptic display. Therefore, the body can be moved freely. However, considering the force the pseudo-haptic feedback can apply, there are questions whether pseudo-haptics can produce an adequate force. Lecuyer et al. [6] showed that we feel something is wrong according to the ratio between the user's displacement of the input interface and the visual displacement of the object in the virtual environment. When the difference between the visual information and the sensation of proprioception becomes large, pseudo-haptics will not work normally. However, this ratio becomes large when we attempt to apply a large force using pseudo-haptic feedback. Therefore, it appears to be difficult to apply a large force using pseudo-haptic feedback. A small force, which can be applied using pseudo-haptic feedback, is inadequate for our purpose. Another known defect of pseudo-haptic feedback is that some people only slightly perceive the feedback.

2.3 Combination of real haptic and pseudo-haptic feedback

As previously mentioned, both real haptic feedback and pseudo-haptic feedback have advantages and disadvantages. To compensate for the disadvantages of each type of feedback, a combination of pseudo-haptic and real haptic feedback is proposed for a compact haptic display.

It appears to be difficult to apply a large force using pseudo-haptic feedback. However, helpful experimental facts can be extracted from previous work. Paljic et al. [7] observed that pseudo-haptic feedback is enhanced by using an elastic interface as opposed to using isotonic interfaces, such as a mouse. It is considered that the resistance of the device produces real force feedback and enhances the pseudo-haptic sensation. Therefore, it is considered that pseudo-haptic feedback appears to be enhanced when used in combination with real haptic feedback. If pseudo-haptic feedback can be enhanced, it may apply a larger force so that our sensation of touch allows us to more strongly perceive stiffer objects as well as the boundaries of objects.

In the combination of real haptic and pseudo-haptic feedbacks, the force (F_u) that the user perceives appears to be expressed as a function of F_d and F_p (Eq. (4)). Large F_u can be achieved by increasing F_d. However, since our objective to develop is a compact haptic display, a small F_d and a large F_p are desired.

$$F_u = f\left(F_d, F_p\right) \tag{4}$$

When both real haptic and pseudo-haptic feedbacks are used, the target value of F_d is probably smaller than that when only real haptic feedback is used. Therefore, it would be possible to develop a compact haptic display using both pseudo-haptic and real haptic feedbacks.

There are some questions about the function of F_u. Firstly, is pseudo-haptic feedback produced when pseudo-haptic feedback is combined with real haptic feedback? Pseudo-haptic feedback is an illusion of haptics caused by visual information. It is thought that we cannot perceive pseudo-haptic feedback when we apply pseudo-haptic feedback with real haptic feedback. In the worst case, it is considered that the pseudo-haptic feedback decreases the magnitude of the perceived force applied using the real haptic feedback. Secondly, how large is the pseudo-haptic feedback? If the magnitude of the pseudo-haptic feedback is very small, it cannot be expected that the magnitude of the perceived force will be enhanced by the combination of pseudo-haptic and real haptic feedbacks. Thirdly, does the magnitude of the pseudo-haptic feedback change depending on the magnitude of the real haptic feedback? If the value of the real haptic feedback that efficiently enhances the magnitude of the pseudo-haptic feedback is known, it will be valuable in deciding the target value of the real haptic feedback that should be applied to the haptic display. Therefore, an experiment was performed to provide the answers to these questions.

3. EXPERIMENTS

In this experiment, the effect of the perception of force was examined when pseudo-haptic feedback was applied with real haptic feedback. The F_p and F_d conditions were compared with the F_d only condition.

3.1 Experimental procedure

Fig. 3 and Fig. 4 show the experimental setup and visual information that was applied to the experimental subjects. PHANToM (SensAble Technologies Inc.) was used as a haptic display for applying real haptic feedback and determining the user's hand movements. To eliminate the effect of the sound that PHANToM makes when the subjects manipulate it, the subjects listened to white noise with headphones during the experiment. The subjects moved a red ball (pointer) right and left on the screen by manipulating PHANToM and touching the virtual wall (the white area on the computer screen).

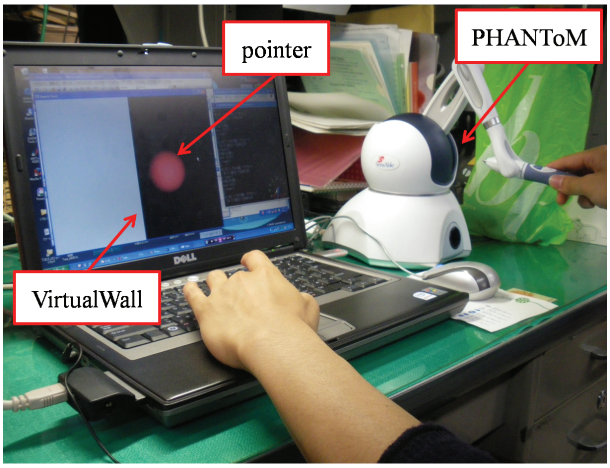


Fig. 3 Experimental set-up.

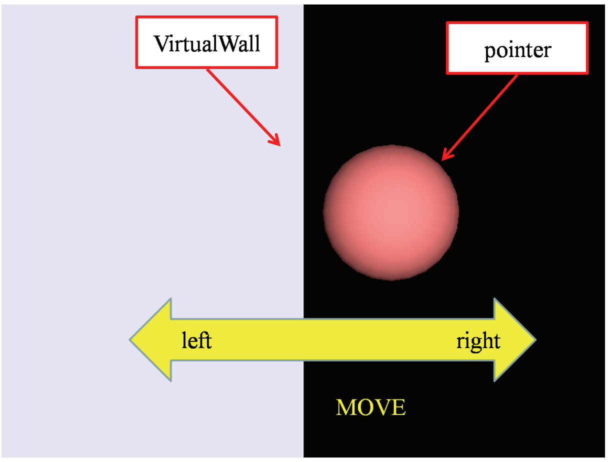


Fig. 4 Visual information in the experiment.

The magnitudes of F_u and F_p were quantified by comparing them to the magnitude of the force that PHANToM applied to the subjects. The psychophysical experiment performed was an up-and-down method (it is sometimes called a stair-case method). In this method, there are two series—an ascending series and a descending series. The subjects were instructed to move PHANToM to the left and touch the virtual wall A while pseudo-haptic feedback with real haptic feedback or only real haptic feedback was applied. In this experiment, the magnitude of real haptic feedback was not affected by the distance that a pointer presses into the wall. The magnitude of the pseudo-haptic feedback was constant in order to determine the magnitude of the pseudo-haptic feedback than the stiffness. First, the value of the real haptic feedback was 0. Then, the subjects were instructed to touch the virtual wall B while only real haptic feedback was applied for reference. First, the value of the real haptic feedback was 0 for reference. The subjects were supplied with visual information with no pseudo-haptic feedback when they touched wall B.

The subjects were instructed to choose the stiffer wall between the two virtual walls displayed on the screen and indicate their answer by typing "A" or "B" on the keyboard. If the subject chose "A," the magnitude of the real haptic feedback was increased by 0.1 [N] for reference. The comparing and increasing was repeated until the subject chose "B." This process was an ascending series. If the subject chose "B," the value of the real haptic feedback was changed to 3.3 [N] for reference, and the stiffness of the two walls was compared. If the subject chose "B," the magnitude of the real haptic feedback was decreased by 0.1 [N] for reference. The comparing and decreasing was repeated until the subject chose "A." This process was a descending series. The value of real haptic feedback was increased by 0.5 [N] when the descending series ended, and the subject started an ascending series with a new real haptic feedback value.

In this experiment, the magnitude of the pseudo-haptic feedback was constant, and the value of α was 0.2. Each subject performed these two series for the following five values of real haptic feedback for wall A: 0, 0.5, 1.0, 1.5, and 2.0 [N]. The subjects repeated this trial two more times. The subjects who took part in this experiment included 5 men, aged 22–28. All the subjects were right handed, and they used their dominant hand to determine the stiffer wall. During each trial, the subjects were allowed to test each wall as many times as they wanted.

To eliminate the effect of habituation, the subjects conducted training trials, which included an ascending series and a descending series, for two values of real haptic feedback.

3.2 Result and discussion

Fig. 5 shows the effect of combining real haptic feedback with pseudo-haptic feedback. The graph in this figure shows the values for each subject (a–e) as well as an average of the 5 subjects (f). The horizontal axis denotes the magnitude of the real haptic feedback for wall A, and the vertical axis denotes the magnitude of the real haptic feedback for wall B. Therefore, the vertical axis shows the magnitude of the force the subjects perceived (F_u). The vertical bar indicates the standard deviation in graph (f). The green line shows the simulation magnitude of F_u when the subjects were provided with real haptic feedback. The blue line shows the experimental results of the magnitude of F_u when the subjects were provided with only real haptic feedback. The red line shows the experimental results of the magnitude of F_u when the subjects were provided with a combination of real haptic feedback and pseudo-haptic feedback.

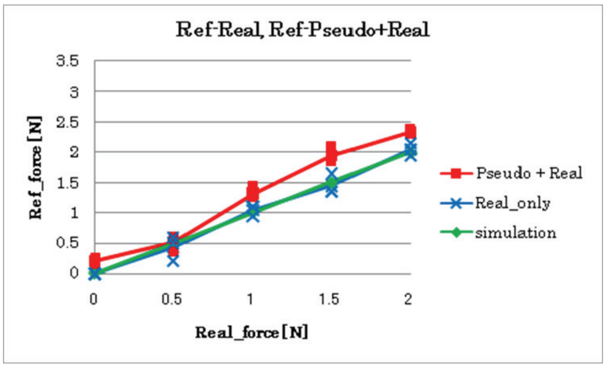
The red line is above the blue line for each value of real haptic feedback for wall A for subjects A, B, and C. This shows that pseudo-haptic feedback is certainly perceived even under the condition of a combination of pseudo-haptic feedback and real haptic feedback. This implies that the combination of pseudo-haptic feedback and real haptic feedback extends the maximum output value of the haptic display. It may be possible to develop a haptic display that is small and light by combining pseudo-haptic feedback and real haptic feedback. It is interesting to note that pseudo-haptic feedback can be perceived without being reversed with real haptic feedback, even when a large real haptic feedback is applied.

There is a possibility that the magnitude of the pseudo-haptic feedback changes depending on the magnitude of the real haptic feedback. As shown in Fig. 5 (f), the magnitude of the pseudo-haptic feedback is approximately 0.15 [N] under the experimental condition. Furthermore, the magnitude of the pseudo-haptic feedback is approximately 0.25 [N] when the magnitude of the real haptic feedback is 1.5 [N], and 0.4 [N] when the magnitude of the real haptic feedback is 2.0 [N]. This result indicates a possible connection between the magnitude of the real haptic feedback and that of the pseudo-haptic feedback. This trend is clearly shown in Fig. 5 (b).

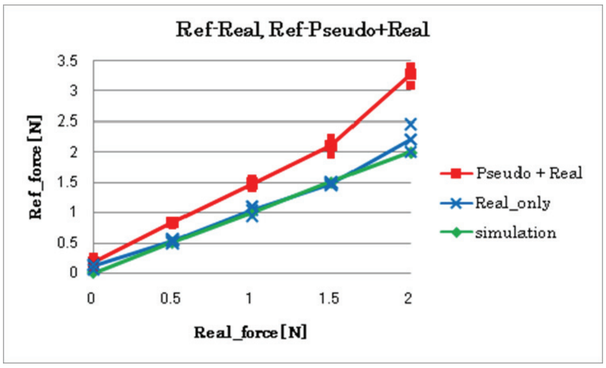
The magnitude of the pseudo-haptic feedback without the real haptic feedback is small. This result confirms the findings of Lecuyer et al., because the ratio between the user's displacement of the input interface (PHANToM's displacement) and the visual displacement of the object in the virtual environment (the red ball's displacement) become large when only pseudo-haptic feedback is applied. However, the findings are not confirmed when the magnitude of real haptic feedback becomes large. This is because only five values of real haptic feedback were used for wall A up to 2.0 [N] in this experiment, and the ratio of the two displacements may not become so large. We are interested in examining how the effect of the value of real haptic feedback on the value of pseudo-haptic feedback changes with larger values of real haptic feedback.

Pseudo-haptic perceptions differ from person to person. In this experiment, subject B perceived pseudo-haptic feedback only slightly without real haptic feedback. However, he perceived pseudo-haptic feedback more strongly along with real haptic feedback. If the ratio of people who can perceive pseudo-haptic feedback increases with the use of real haptic feedback, it implies that a display with a combination of pseudo-haptic feedback and real haptic feedback may be beneficial for more people than those with only pseudo-haptic feedback. Therefore, the occurrence probability of pseudo-haptic feedback depending on the addition of real haptic feedback is significant.

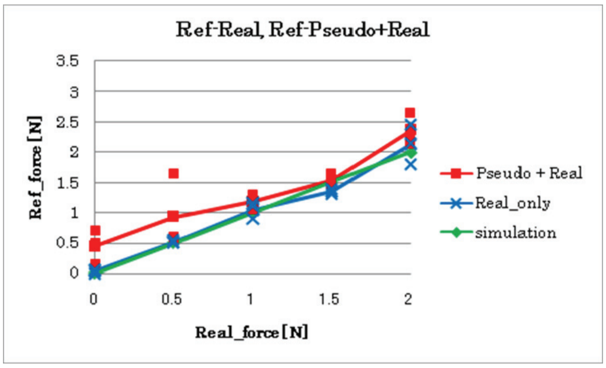
In this experiment, the parameter of pseudo-haptic feedback was constant ($\alpha = 0.2$). Therefore, examination of the variance of pseudo-haptic feedback is also needed. If we can adjust magnitude of pseudo-haptic feedback in high resolution, a haptic display with a large range of output force and high resolution may be realized, by



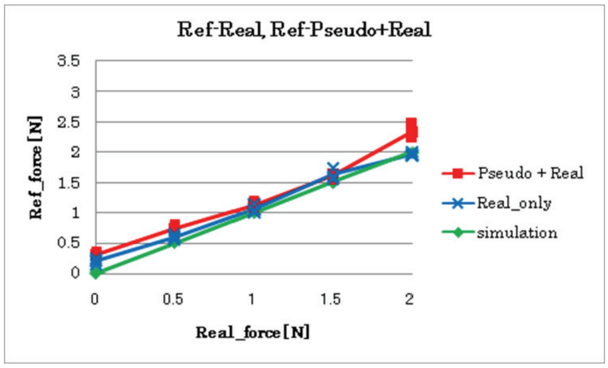
(a) subject A



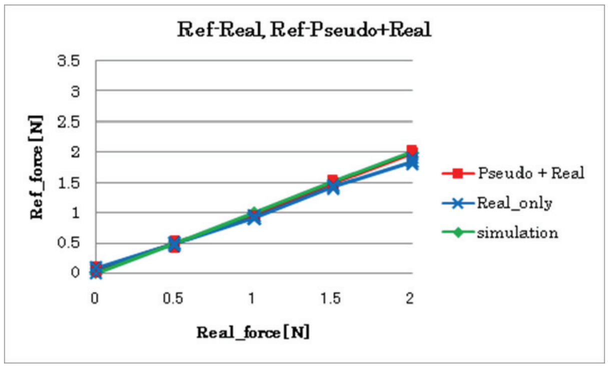
(b) subject B



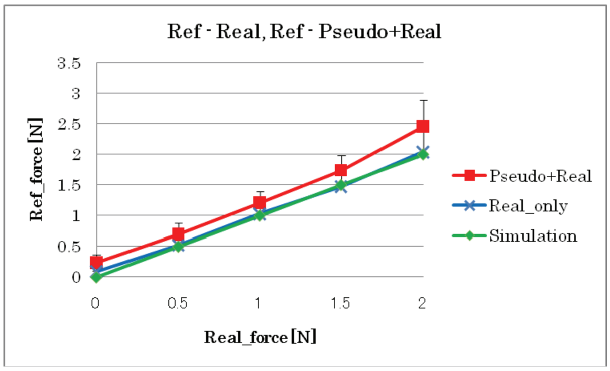
(c) subject C



(d) subject D



(e) subject E



(f) average of all subjects

Fig. 5 Effects of the real haptic feedback on pseudo-haptic feedback.

combining a haptic feedback that has a large range of output force and low resolution and a pseudo-haptic feedback that has a narrow range of output force and high resolution. Furthermore, it is interesting to determine whether pseudo-haptic feedback applies to forces in a negative direction. By changing the parameters of the pseudo-haptic feedback, we may perceive a smaller force than that perceived with real haptic.

This experiment shows that pseudo-haptic feedback is perceived even when pseudo-haptic feedback and real haptic feedback are applied. When $\alpha = 0.2$, the magnitude of pseudo-haptic feedback is approximately 0.15 [N] when only pseudo-haptic feedback is applied, and it is approximately in the range of 0.2–0.4 [N] when pseudo-haptic and real haptic feedbacks are applied. The magnitude of pseudo-haptic feedback is nearly 10 percent of the magnitude of real haptic feedback, which is smaller than we expected. This method appears to fall short of our needs for realizing a compact haptic display, although it may be modestly beneficial. However, the magnitude of the force we perceive certainly becomes larger by combining pseudo-haptic feedback and real haptic feedback, and it would appear that this method can be used as an enhancement to real haptic feedback. When we applied a very large real haptic feedback, it was considered that the proportion of the pseudo-haptic feedback to the real haptic feedback would become small. However, this method may be effective in cases where the touched object has a particular stiffness. That case would occur when the magnitude is such that the proportion of the pseudo-haptic feedback to the real haptic feedback is very large. The experiments in this study were performed in a determinate condition in which the parameter of the pseudo-haptic feedback was constant (α = 0.2), and the values of the real haptic feedback were 0–2.0 [N]. Future studies will include experiments in which the value of α changes and the value of the real haptic feedback is greater than 2.0 [N].

4. CONCLUSIONS

This study focused on a haptic display for arms. A strong force is required to perceive the sensation of stiffness and the boundary of virtual objects. Therefore, the haptic display becomes large and heavy. On the other hand, the application of a strong force using only pseudo-haptic feedback appears to be difficult. Therefore, we examined the effectiveness of a compact haptic display using a combination of pseudo-haptic feedback and real haptic feedback. In the results, subjects perceived pseudo-haptic feedback when it was applied along with real haptic feedback. Therefore, a force of approximately 0.2–0.4 [N] more was perceived by combining pseudo-haptic feedback and real haptic feedback than when only real haptic feedback was applied. The magnitude of the difference is nearly 10 percent of the magnitude of real haptic feedback. Similar experiments will be performed under the condition where the value of α changes and the value of real haptic feedback is greater than 2.0 [N].

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