Simplified Design of Haptic Display by Extending One-point Kinesthetic Feedback to Multipoint Tactile Feedback

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ABSTRACT

For designing a simple and more realistic haptic feedback system, we propose integrating an underactuated mechanism with one-point kinesthetic feedback from the arm with multipoint tactile feedback. By focusing on the division of roles between the cutaneous sensation in fingers and the proprioception in the arm. We have implemented a prototype system that provides kinesthetic feedback to the arm and tactile feedback to the fingers, examined the difference of weight recognition according to the applied point of kinesthetic feedback, and confirmed the effectiveness of the proposed method.

Keywords: Haptic display, underactuation

Index Terms: H.5.2 [INFORMATION INTERFACES AND PRESENTATION]: User Interfaces—Haptic I/O; H.1.2 [MODELS AND PRINCIPLES] User/Machine Systems—Human information processing

1 INTRODUCTION

In recent times, there has been an increasing demand for realistic haptic feedback for the intuitive operation of computer graphic systems or entertainment systems and for highly immersive virtual reality environments such as CAVE [1] and TWISTER [2]. A number of user interface devices with haptic feedback functions, such as CyberTouch (CyberGlove Systems LLC) and the DualShock controller (Sony Computer Entertainment, Inc., 1997) have been developed. However, their haptic feedback is limited only to vibrations because a suitable method for providing haptic feedback through a small and portable/wearable device has not been established thus far. Glove-type haptic displays such as Rutgers Master II [3] can provide force sensations to all five fingers of the hand simultaneously. These devices can present a grasping force with the aid of a wearable device; however, these devices are complex and heavy, and the sensation of weight of a virtual object cannot be represented. To realize highly realistic haptic feedback, the tactile sensations and kinesthetic sensations in each finger and arm have to be reproduced; however, it is difficult for a device to reproduce all these sensations. A number of researches have been conducted to simplify haptic devices by sorting the sensations to be represented. PHANToM [4] and Spidar [5] are types of grounded haptic displays that apply proprioception on the arm via a stick or a ball driven by motors. In these systems, although the kinesthetic sensation in the arm is well represented, the posture of the hand is fixed, and the tactile sensations in the fingers are summed up; therefore, the user cannot grasp a virtual object with his/her hand. These grounded haptic displays have been applied to multifingers in several researches [6]. However, these methods are highly complex and difficult to apply in a wearable or portable device because the mechanical linkages have to be fixed to a desk or the ground. Therefore, a simplified design method for a highly realistic wearable multifinger haptic display is required.

Realistic haptic feedback systems that can be applied to multifingers have been realized using ungrounded haptic displays [7][8][9]. In our previous research [10], we focused on the vertical and tangential forces generated on each fingerpad because of the interaction between a human finger and an object, and developed a finger-worn haptic display shown in figure 1. The vertical force and tangential force on the user's fingerpad are reproduced by pulling up the belt on the fingerpad using dual motors on the dorsal side of the finger.

Figure 1. The finger-worn haptic display using dual motors

It has been confirmed that estimating the grasping force and the object weight can reasonably reproduce tactile sensations on fingers. However, these ungrounded haptic displays cannot be used for objects heavier than a few hundred grams because of the absence of kinesthetic sensations in the fingers and the arm. It is known that the cutaneous sensation in the fingers and the proprioception in the arm play different roles in estimating the weight of the grasped object. In order to design an optimal mechanism for multifinger haptic displays that strike a balance between the simplicity of the device and the quality of the represented sensation, we examine the division of roles between tactile sensation and kinesthetic sensation and their synergetic effects.

2 PROPOSED METHOD

In the proposed method, the user wears a small tactile display on each finger and a single kinesthetic display somewhere on the arm. Each tactile display delivers the contact information between the virtual object and a finger, and the kinesthetic display delivers the total force due to the weight and the inertia of the object. Figure 2

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shows conceptual illustration of the tactile display worn on the index finger and thumb and the kinesthetic display worn on the forearm. In this configuration, although the proprioceptions on the elbow and shoulder are the same as those when grasping a real object, there is a lack of proprioception on the fingers and the wrist. This missing haptic information can result in difficulties during object manipulation. However, as compared to cumbersome kinesthetic displays worn on each finger, this configuration has considerable benefits: the kinesthetic mechanism can be underactuated and the total system can be simplified.

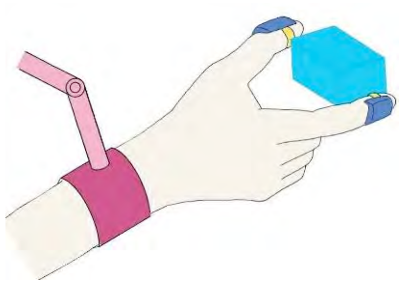

Figure 2. Conceptual illustration of proposed system

3 Experiments for Applied Points of One-point Kinesthetic Extension

In this section, we compare the just notified difference (JND) when reproducing the weight of a virtual object under four conditions: applying kinesthetic feedback on the palm, wrist, and forearm, and applying no kinesthetic feedback.

In the experimental setup, we used a finger-worn haptic display [10] for tactile feedback, and the OMEGA.3 haptic device (Force Dimension Inc.) for kinesthetic feedback. The finger-worn haptic display was attached on the index finger of the subject, and the kinesthetic display was worn on the palm, wrist, or forearm. We placed urethane forms between the arm and OMEGA.3 to minimize the cutaneous stimuli on the arm and fixed the arm and OMEGA.3 using a Velcro strap as shown in figure 3. The subjects were asked to wear headphones with white noise and a blindfold; they were also asked to extend their index fingers with the pad side up. Constant stimuli were provided to three male subjects in this experiment. As a standard stimulus, a virtual weight of 50, 100, 200, or 400 g was represented by both the tactile display and the kinesthetic display for 1 s. After an interval of 1 s, another virtual weight that was 70%, 80%, 90%, 100%, 110%, 120%, or 130% of the standard stimulus was represented randomly as a test stimulus for 1 s. The subjects then stated whether the weight of the virtual object that acted as the test stimulus was “heavier” or “not heavier” than that that provided as the standard stimulus according to the two-alternative forced-choice procedure. Thirty-five trials were performed for each standard stimulus, with each test stimulus appearing five times. It took approximately 5 min to conduct a set of 35 trials. We performed 16 sets of trials for four types of standard stimuli under the four-abovementioned conditions on each subject.

Figure 4 shows the JNDs of the virtual weight on each applied point of kinesthetic extension. In this figure, “tactile only” denotes the threshold when kinesthetic feedback was not applied and only tactile feedback was applied, “tactile + palm” denotes the threshold when the kinesthetic feedback was applied on the palm in addition to the tactile feedback on the index finger, “tactile + wrist” denotes the threshold when the kinesthetic feedback was applied on the palm in addition to the tactile feedback on the index finger, and “tactile + forearm” denotes the threshold when the kinesthetic feedback was applied on the forearm in addition to the tactile feedback on the index finger. This result shows that the one-point kinesthetic extension was effective, especially when the virtual object was heavier than 200 g, where the JND became worse when the kinesthetic extension was not applied. A considerable difference was not observed according to the applied point. By comparing the required working area and the degrees of freedom for the kinesthetic display, it appeared reasonable to apply the one-point kinesthetic extension on the forearm because it requires only four degrees of freedom, whereas seven degrees of freedom are required to apply the kinesthetic extension on the palm.

Figure 3. Experimental setup under “tactile + palm” condition

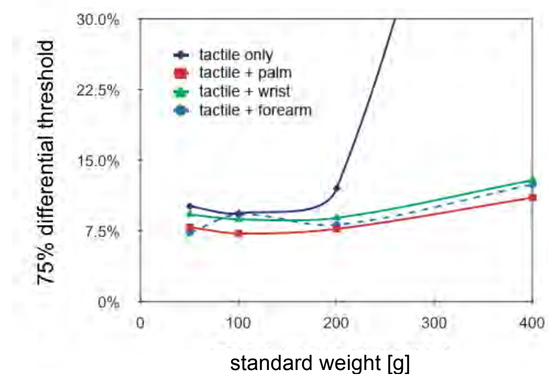

Figure 4. JNDs on each applied point of kinesthetic extension. The vertical axis of the graph shows the 75% differential limens with a ratio to each standard stimulus.

4 Experiments for Effectiveness of One-point Kinesthetic Extension

We constructed a prototype of a haptic interaction system with one-point kinesthetic extension on the forearm and then examined the effectiveness of this system by comparing JNDs between the four conditions shown in figure 5. Similar to the previous experimental setup, we used a finger-worn haptic display [10] for tactile feedback and the OMEGA.3 haptic device for kinesthetic feedback.

- Condition 1, “real object”: A lightweight cube (side: 5 cm) was fixed on the kinesthetic display. Double-sided tapes were placed on the sides of the cube to increase friction. The subject held the cube between the index finger and thumb, and then, the virtual weight was applied.
- Condition 2, “kinesthesia on forearm”: The kinesthetic display was fixed on the forearm of the subject. The subject was asked to hold the lightweight cube with bare fingers to fix the posture of the hand. Urethane forms were placed between the arm and the device, and the subject felt little cutaneous sensation on the forearm.

- Condition 3, "tactile on fingertips": The subject was asked to wear the tactile displays on the index finger and thumb and hold the lightweight box.
- Condition 4, "integration": According to the proposed method, the subject was asked to wear the tactile displays on the index fingers and thumb and the kinesthetic display on the forearm. Then, the subject held the lightweight cube in the same manner as under the other conditions.

The subjects were asked to wear headphones with white noise and a blindfold. Constant stimuli were provided to three male subjects in this experiment. As a standard stimulus, a virtual weight of 100, 200, 300, or 400 g was represented by both the tactile display and kinesthetic display for 1 s. After an interval of 1 s, another virtual weight (85%, 90%, 95%, 100%, 105%, 110%, or 115% of the standard stimulus under condition 1; 70%, 80%, 90%, 100%, 110%, 120%, or 130% of the standard stimulus under the other conditions) was represented randomly as a test stimulus for 1 s. The subjects then stated whether the weight of the virtual object that acted as the test stimulus was "heavier" or "not heavier" than that the standard stimulus according to the two-alternative forced-choice procedure. For each standard stimulus, five trials were performed in the order of standard stimulus -> test stimulus, and five more trials were performed in the reverse order. It took about 10 min to conduct a set of 70 trials for one standard stimulus. We performed 16 sets of trials for four types of standard stimuli under the four conditions. Therefore, the total number of trials was 1120 for each subject. The subjects took a break for a few minutes between each set of trials.


(1) real object (2) kinesthesia on forearm (3) tactile on fingertips (4) integration

Figure 5. Experimental setup in each condition

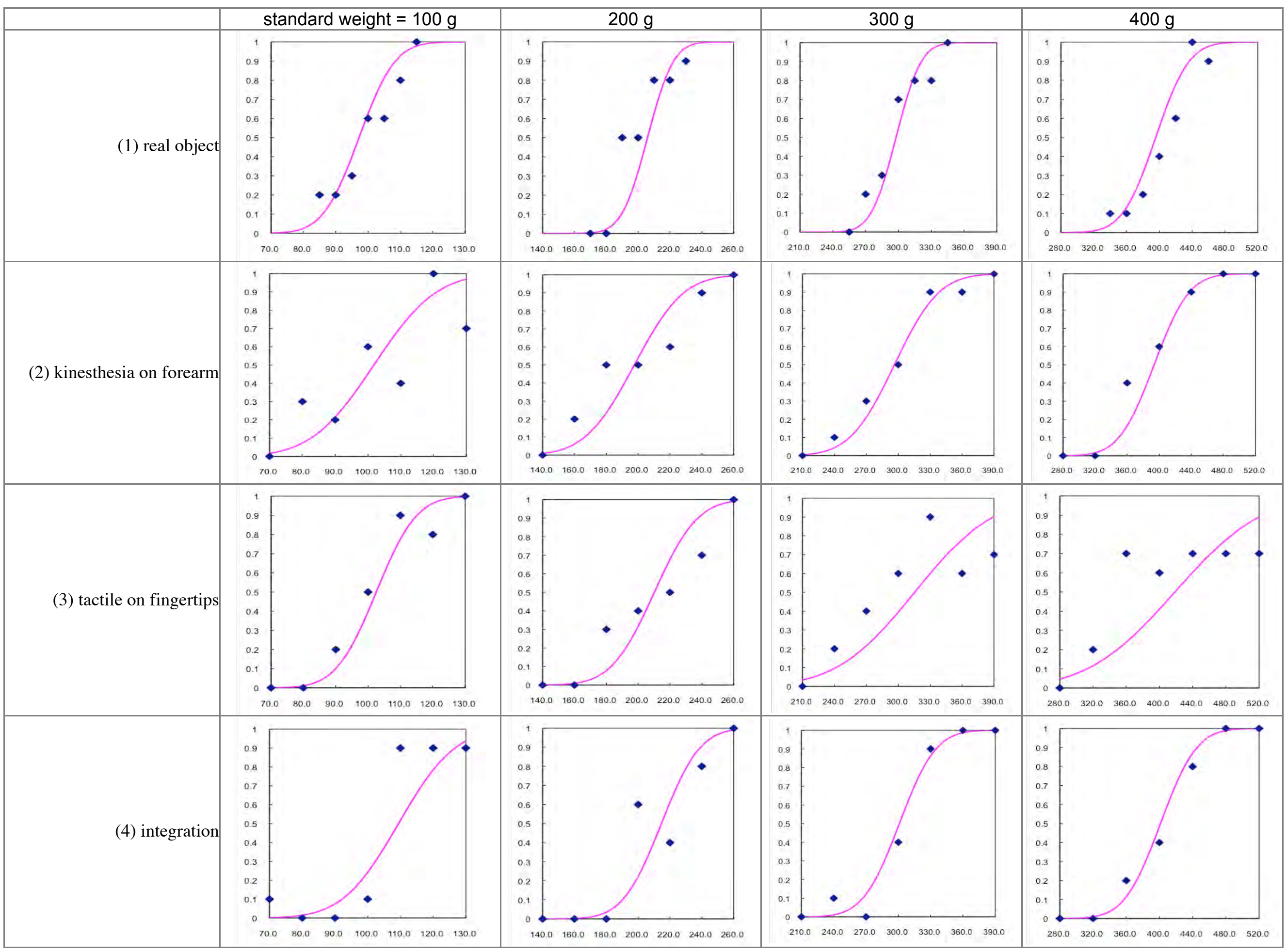

Figure 6. Experimental result of typical subject.
In each graph, the vertical axis represents the ratio of "heavier" responses, and the horizontal axis represents the weight of test stimuli.

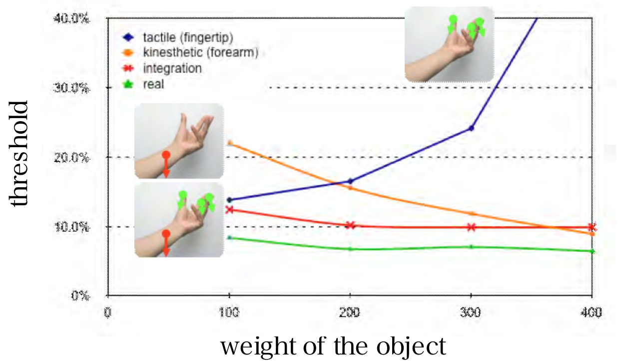

Figure 7. Recognition thresholds for all subjects under each experimental condition

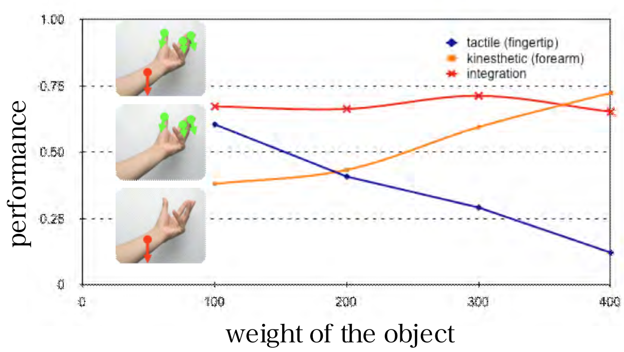

Figure 8. Recognition performances under each condition normalized with "real object"

Figure 6 shows the ratio of "heavier" responses in each set of trials for a typical subject. Figure 7 shows the integrated result of five subjects, and figure 8 shows the performances of haptic feedback under each condition calculated by dividing the 75% differential limens under each condition by that under the "real object" condition. These results show that when we used only kinesthetic feedback on the arm and the standard weight was small, the performance of weight representation was poor. Further, when we used only tactile feedback on the fingers and the standard weight was large, the performance was poor. However, the proposed system that integrates kinesthetic feedback on the arm and tactile feedback on the fingers could represent the virtual weight with a highly stable performance around 0.7 for every weight. Although the debasement in performance of the integrated condition relating to the real object condition is attributed to the lack of kinesthetic feedback on the wrist and the fingers, the most important thing of the proposed method is to design the balance between the performance of haptic feedback and the complexity of the system for various purposes. It was also suggested that the tactile sensation on the finger has high accuracy in small range, on the other hand, the proprioception on the arm has low accuracy in wide range. This results show that the complementary relationship between the fingers and the arm.

5 Conclusion

In this paper, we propose a design principle for a simplified haptic display that integrates the tactile feedback on the fingers and the kinesthetic feedback on the arm. By focusing on the division of roles between the cutaneous sensation on the fingers and proprioception on the arm while grasping an object, we apply underactuated kinesthetic feedback on the forearm and small tactile displays on the fingers. We construct a prototype system and examine that the proposed system can represent haptic sensations with a high resolution for a wide range of weights. As a future work, we will implement a wearable haptic interaction system for multifingers that can represent a more realistic sensation than the conventional systems.

As a future work, we are designing a wearable kinesthetic display on the basis of the underactuation of kinesthetic feedback. Although the kinesthetic display used in the experimental setup was a grounded device, our proposed method shows a possibility of designing a wearable multi-fingered haptic display that reproduces both kinesthetic sensation on the arm and tactie sensation on the fingers with a small number of actuators.

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