On Utilizing Pseudo-Haptics for Cutaneous Fingertip Haptic Device

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Abstract

In this paper, we explore possible utility of pseudo-haptics for the cutaneous fingertip haptic device, whose performance is inherently limited due to the lack of kinesthetic feedback. We experimentally demonstrate that: 1) pseudo-haptics can render virtual stiffness to be more rigid or softer only by modulating visual cue; 2) pseudo-haptics can be used to expand the range of the perceived virtual stiffness; and 3) pseudo-haptics can be confusing, if the haptic and visual cues are contradictory and that contradiction is too large to be overridden by the visual perception dominance.

Index Terms: Cutaneous Haptic Feedback, Human Evaluation, Multimodal, Pseudo-Haptics, Stiffness Perception

1 Introduction

Humans use fingers attached to their hands to haptically interact with objects and environments. This human haptic perception via the fingered-hand, in its most generality, consists of the two part: kinesthetic haptic feedback and cutaneous haptic feedback. Majority of the commercial haptic devices are targeting to provide the kinesthetic haptic feedback, with some well-known examples including Geomagic's Phantom® and Force Dimension's Omega®. These kinesthetic haptic devices, yet, are typically bulky, expensive and also require mechanical ground. Thus, they are not well-suited to construct portable and affordable haptic devices, which are widely deemed as necessary to enable haptic technology to penetrate mass market, and thereby to impart significant impact on our everyday life.

As an alternative to the current haptic feedback devices mentioned above, for the fingered-hand haptics, the possibility of using cutaneous fingertip haptic devices has been actively researched (e.g., [1–6]) with the limitation of using the cutaneous feedback *alone* also noticed. In [2], a dual-motor based fingertip cutaneous haptic feedback device was proposed and its usage together with a real object (e.g., glass) was suggested to present the kinesthetic constraint via the real object. On the other hand, the results in [3–5] showed a better performance of the cutaneous fingertip haptic device (i.e., dual-motor device of [2]) when combined with the kinesthetic device (i.e., Force Dimension Omega®) than the case of solely relying on the cutaneous feedback device. We also experienced a similar limitation of the cutaneous fingertip device only to produce believable haptic sensation due to its lacking of the kinesthetic feedback.

In this paper, as a way to deal with this limitation (or enhance the performance) of the cutaneous fingertip haptic device, we explore a possibility of integrating pseudo-haptics into the cutaneous haptic device. Pseudo-haptics utilizes

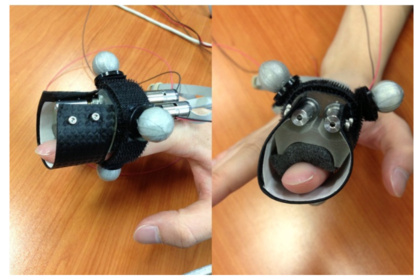

Figure 1: Cutaneous fingertip haptic feedback device using dual motors [14].

visual feedback and its dominance over haptic feedback to present haptic sensation even without using physical haptic devices [7]. This pseudo-haptics has been used to simulate various haptic properties such as mass [8], friction [9], stiffness [9,10], and texture [11]. In the majority of these pseudo-haptics works, the so-called C/D ratio (control/display ratio), which is the ratio of the user's real displacement to the virtual displacement of the user's avatar in the computer screen, has been frequently used. By adjusting this C/D ratio, it then becomes possible to produce illusionary visual cues. Due to the dominance of the visual perception over the haptic perception, human can be "confused" to feel as if s/he haptically perceives some sensation, that is consistent with the visual cues as scaled by the C/D ratio.

In this paper, we show that, at least for some scenarios and to some extent, this pseudo-haptics can be used to enhance the performance of the cutaneous fingertip haptic feedback devices and might even possibly supplement the absence of kinesthetic feedback in some circumstances. More precisely, through three human perception experiments, we experimentally demonstrate that: 1) pseudo-haptics can be used to render the stiffness of the virtual plane to be more rigid or more compliant only by modulating the visual cue; 2) pseudo-haptics can be used to expand the perceived level of the virtual plane's stiffness (in this work, at least twice stiffer) as compared to the case of cutaneous device only; and 3) pseudo-haptics, when produced with contradicting visual and haptic cues, can be confusing, if that contradiction is too large to be overridden by the visual perception dominance.

Despite its possible supplementary and synergistic role, integration of pseudo-haptics into haptic applications has been rather rare and limited only to the case of vibro-tactile feedback [12,13]. In particular, the utility of pseudo-haptics to enhance the performance of cutaneous haptic devices, to our knowledge, is evidenced for the first time in this paper.

The rest of the paper is organized as follows. Our cutaneous fingertip haptic device, whose design is adopted from [2], and its calibration result presented in [14], are briefed in Sec. 2. The three experiments to exhibit utility of pseudo-haptics for our cutaneous device are presented in Sec. 3. Some concluding remarks are given in Sec. 4.

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IEEE Haptics Symposium 2014
23-26 February, Houston, Tx, USA
978-1-4799-3131-6/14/$31.00 ©2014 IEEE

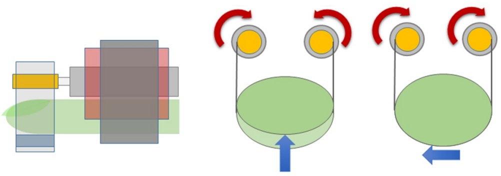

Figure 2: Dual-motor cutaneous haptic feedback device generating the normal force and shear force [2], [14].

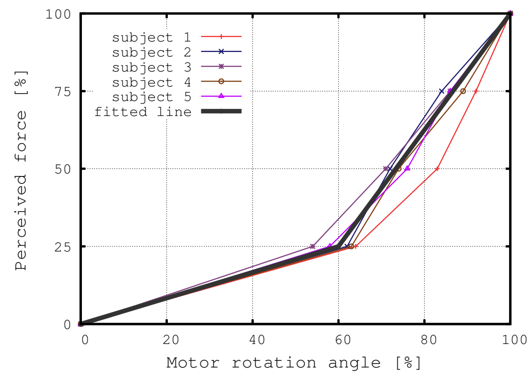

Figure 3: Angle-force calibration result for cutaneous haptic device with humans as surrogate force sensor [14].

2 Cutaneous Fingertip Haptic Device

2.1 Principle and Specification

Following [2], we constructed a cutaneous fingertip haptic device [14] as shown in Fig. 1 and Fig. 2. The device is equipped with two motors (Maxon DCX motor, $\phi = 10$mm, 3W, 16:1 gear ratio), each of which has encoder with the resolution of 1024 cnt/rev attached to their motor shaft. Using Quanser® q8-usb DAQ board and Arduino® microcontroller board, current angle of motor is measured and controlled in about 1kHz. The rubber block is attached between the band and human finger in order to transmit the motor torque right onto the fingertip.

The normal force to the user's fingertip is then produced by rotating the two motors in the opposite direction, while the shear force in the same direction. In this paper, we only consider the case with the normal force, and spare that with the shear force for future research.

2.2 Angle-Force Calibration

We can then control the fingertip force of the device by regulating the rotation of the motors. For this, we need to calibrate the motors' rotation angle to the fingertip force. Since it is difficult to robustly measure (or model) the fingertip force against various shapes, compositions, and compliances of human subjects' fingertip, in [14], we instead used human as a surrogate force sensor. In other words, we utilized the calibration result based on the responses of human subjects.

More precisely, we first set a certain maximum torque for the motor. We then applied it to the subject and measured the motor rotation angle. This was defined as the maximum rotation angle for 100% maximum force. We then asked the subject, while adjusting the motor angle from zero to maximum, when they perceived the half of the maximum, to set 50% of the maximum force. By repeating this process with the range of 0-50% and 50-100%, we obtained the angles for 25% and 75% of the maximum force. Therefore, desired rotation angles for perceived 25%, 50%, 75% of the maximum torque were identified in each trial.

The calibration result from [14] is shown in Fig. 3, which exhibits a consistent trend among 5 different subjects. Each subject practiced 5 trials and average data were used after normalizing maximum angles to be 100. The graph suggests that we can calibrate the angle-force relation by a combination of two linear lines, with the breakaway point approximately at 60% of the maximum motor angle with 25% of the maximum motor torque. We use this calibration result between motor angle and human-perceived force to produce a desired force for our cutaneous haptic device.

To summarize, 1) measure the maximum motor angle for human subject in the beginning of experiment, 2) use the fitted curve in Fig. 3 to compute the desired motor angle for certain desired force, and 3) apply a PID control to drive the motor to that desired angle.

2.3 Calculation of Desired Force

While using our cutaneous haptic device, human fingertip is represented as a 3D sphere on the computer screen as shown in Fig. 4. Then, the desired fingertip force is computed by

$$F_{\mathrm{des}} = K_o \cdot \Delta x \quad \text{where} \quad K_o := \frac{\text{maximum device force}}{\text{diameter of sphere}} \tag{1}$$

where K_o is the stiffness of the virtual plane and Δx is the largest difference between the plane surface and fingertip sphere surface. Therefore, when the sphere's penetration depth is the same as its diameter, the maximum fingertip force (i.e., produced by maximum motor torque) is attained. The desired motor angle is then obtained by referring to the calibration curve in Fig. 3. To measure the fingertip position, we also use the VICON® motion capture system with markers attached on the cutaneous device as shown in Fig. 1.

From our experiences as reported in [14] (i.e., virtual object boundary detection with cutaneous feedback) and other previous researches, we found that the realism of the cutaneous haptic device quickly deteriorates after the contact due to the lack of kinesthetic feedback, which is supposed to maintain the user's fingertip at the virtual object's boundary. This is the motivation of this paper to explore a possible utility of pseudo-haptics for the cutaneous haptic device as proceeded in the next Sec. 3.

3 Experimental Study of Integrating Pseudo-Haptics and Cutaneous Haptic Feedback

3.1 Common Settings

3.1.1 Pseudo-haptic feedback

To produce the pseudo-haptics effect, we adopt the idea of C/D ratio [9, 10]. When user's fingertip contacts with the virtual object, we scale the fingertip's virtual displacement on the computer screen by

$$\Delta x_{\mathrm{virtual}} = \alpha \cdot \Delta x_{\mathrm{real}} \tag{2}$$

where $\alpha \in \Re$ defines the ratio of the virtual displacement $\Delta x_{\mathrm{virtual}}$ seen on the screen to the user's real displacement Δx_{real}, which is measured by our VICON® motion capture system. Note that α is in fact the reciprocal of C/D ratio [9, 10]. Note also that, if $\alpha \leq 1$, a pseudo-haptics illusion of stiffer virtual object would arise as $\Delta x_{\mathrm{virtual}}$ is scaled-down as compared to Δx_{real}, whereas if $\alpha \geq 1$, softer virtual object as $\Delta x_{\mathrm{virtual}}$ scaled-up than Δx_{real} [7].

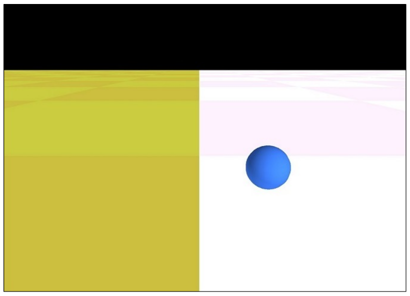

Figure 4: Virtual 3D environment with fingertip sphere, reference (RF) plane without pseudo-haptics effect (left), and pseudo-haptics (PH) plane with pseudo-haptics effect (right).

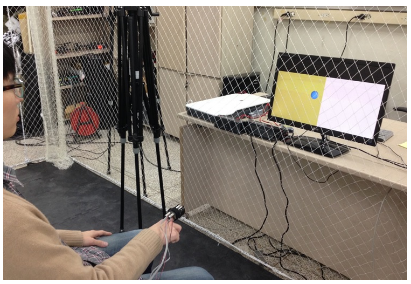

Figure 5: Environmental scene

3.1.2 Environmental Settings

As shown in Fig. 5, in the following experiments, the subjects practiced every trial in front of computer screen while equipped with cutaneous fingertip haptic device on index finger. Four VICON® motion capture cameras surrounded the subject in the distance of about 1m. The distance between the subject and the monitor screen was set to 1m. Subjects were able to see their fingers, yet, encouraged to focus on the fingertip sphere of the screen. There was no motor noise masking, also.

We constructed the virtual 3D environment on the computer screen, consisting of a sphere, which represents the user's fingertip position, and two virtual planes divided by colors as shown in Fig. 4. Colors of the planes were switched for each trial of the experiment to reduce the sensory difference induced by different colors.

Cutaneous haptic feedback to the user is produced by the relation as given in (1) with $\Delta x = \Delta x_{\text{real}}$ (for Experiments #1 and #2: see below) or $\Delta x = \Delta x_{\text{virtual}}$ (for Experiment #3: see below), only when the fingertip sphere makes a contact with the planes. No haptic feedback is produced when the sphere loses the contact with the planes. The pseudo-haptics effect is simultaneously implemented by using α according to (2), also only when the fingertip sphere contacts with the planes. This pseudo-haptics effect is implemented only for the right plane in Fig. 4, which we call *PH-plane* (pseudo-haptics plane), with randomly varying α depending on the experiment trial. The left plane, which we call *RF-plane* (reference plane), has no pseudo-haptics effect with $\alpha \equiv 1$ throughout the experiment.

Human subject can freely move the fingertip sphere in the real world. However, when its displacement Δx exceeds certain threshold value during the contact, the cutaneous device force can be saturated. This force saturation can deteriorate the stiffness perception, e.g., making users misperceive the object less stiff when the device force is saturated. To prevent this saturation, at the moment of force saturation (detected by displacement measurement), we turned the color of the plane, where the force saturation occurred, to red to notify the subject of this saturation. We also guided them before the experiment to avoid such saturation as much as possible.

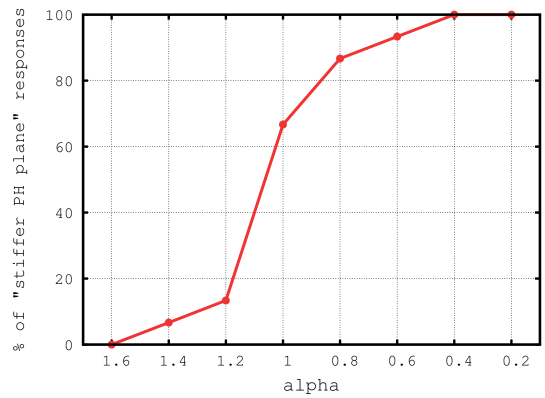

Figure 6: Result of Experiment #1: modulation of perceived virtual stiffness via pseudo-haptics effect α.

3.1.3 Participants

Three Experiments, #1, #2 and #3, were performed separately with five human subjects, all male, from the age of 23 to 31, with no known perception disorder. All the subjects were right-handed and used their index finger of dominant hand for all the experiments. The experiments were conducted in accordance with the requirements of the Helsinki Declaration.

3.2 Experiment #1

3.2.1 Objective and Procedure

The purpose of Experiment #1 is to see if the pseudo-haptics effect, when combined with the cutaneous feedback, can provide an illusionary perception of stiffer or softer virtual planes, as compared to the case of the sole usage of the cutaneous feedback. For this, we set $\alpha = 1$ for the RF-plane through the Experiment #1, whereas randomly varying α from 0.2 to 1.6 with 0.2 interval was applied to PH-plane. We also set K_o to be the same between the planes throughout the Experiment #1. During the experiment, each subject was allowed to spend enough time to get familiar with the device first. After that, they were asked to report which was stiffer between RF-plane and PH-plane, with randomly chosen α applied to the PH-plane. Three trials were given for each α, making 24 trials for each subject, and 120 trials totally. During each trial, the subjects were also allowed to spend as much time as they wanted before making the decision on the stiffness difference between RF-plane and PH-plane.

3.2.2 Result

From Fig. 6, it can be noticed that pseudo-haptic feedback is indeed helpful in rendering the virtual stiffness by sole manipulation of visual cue α. The y-axis value in Fig. 6 is the percentage of responses choosing PH-plane as the stiffer plane. Fifty percent of y-axis value means that the subjects reported that both planes rendered similar stiffness on average. When $\alpha < 1$, subjects tended to choose the PH-plane

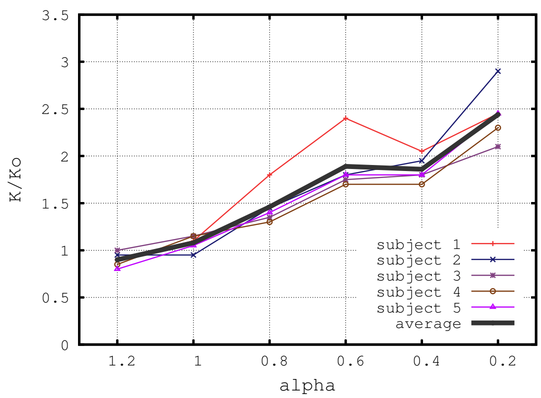

Figure 7: Result of Experiment #2: expansion of the renderable range of the perceived virtual stiffness via pseudo-haptics effect α.

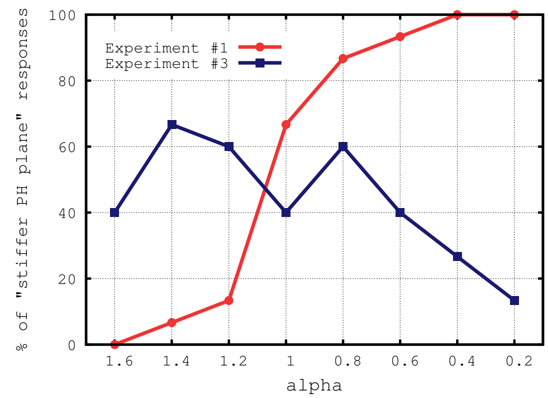

Figure 8: Result of Experiment #3: confusion induced by contradictory haptic and visual cues.

as the stiffer one, when $\alpha > 1$, exactly opposite situation occurred, i.e., RF-plane felt softer. This clearly manifests the efficacy of pseudo-haptic feedback for our cutaneous haptic device, as it made subjects perceive as if the virtual plane became stiffer (with $\alpha < 1$) or softer (with $\alpha > 1$).

3.3 Experiment #2

3.3.1 Objective and Procedure

A quantitative analysis on the effectiveness of the pseudo-haptics when integrated with the cutaneous feedback was examined in Experiment #2. For this, we adjusted the stiffness K of the RF-plane with no pseudo-haptics effect (i.e., $\alpha = 1$) and compared it with the PH-plane with the fixed baseline stiffness K_o and arbitrary α.

More precisely, we randomly chose a certain α from 0.2 to 1.2 with 0.2 increment and applied it to the PH-plane, which was rendered via (1) with the baseline stiffness K_o. On the other hand, for the RF-plane with $\alpha = 1$ fixed, we gradually adjusted its stiffness K and applied it instead of the baseline K_o for (1). For each trial of Experiment #2, we increased and decreased K to change the ratio K/K_o within the range of 0.2 to 5.0 with the interval of 0.2, while K_o fixed.

At each trial, the subjects were asked to practice the same operation as stated in Experiment #1 to tell which plane was perceived stiffer. For each set of (α, varying K), each subject had 4 trials, 2 with the increasing K and 2 with the decreasing K. We measured the value K when the subject's answer on which plane was stiffer changed, divided them by K_o, and averaged them from the 4 trials. We then used this average value of four K/K_o as the "representative" perceived stiffness value of the PH-plane with the pseudo-haptics effect.

3.3.2 Result

The result of Experiment #2 is summarized in Fig. 7, where the y-axis represents the averaged value of K/K_o as defined above, which we used to denote "representative" stiffness of the PH-plane with the pseudo-haptics effect. Note that this Fig. 7 is consistent with the results in Fig. 6, in that, with $\alpha < 1$, the subjects perceived the PH-plane as if stiffer, although we used the same baseline K_o to generate the haptic feedback via (1). Note also that this result in Fig. 7 quantitatively characterizes the efficacy of the pseudo-haptics effect for our cutaneous haptic device in interacting with the virtual plane.

In other words, as can be seen from Fig. 7, pseudo-haptics effect for our cutaneous haptic device can render virtual plane at least twice stiffer than the case of utilizing cutaneous feedback only. It means that cutaneous haptic device of the motors with a half of current motor torque can achieve similar haptic perception when combined with pseudo-haptics effect. Since one of our motivation is to challenge with the limited stiffness level of cutaneous device due to the lack of kinesthetic feedback, utilizing a wider range of stiffness by means of pseudo-haptics seems possible to improve the device performance.

3.4 Experiment #3

3.4.1 Objective and Procedure

In Experiment #3, we intentionally provided human subjects with contradictory haptic and visual cues, to emphasize the importance/effectiveness of handling the pseudo-haptics effect for the cutaneous feedback device. For this, when computing cutaneous feedback, Δx in (1) was replaced by $\Delta x_{\text{virtual}}$ from (2), instead of Δx_{real} which was used in Experiment #1 and #2. By this modification, for instance, with $\alpha > 1$ (or $\alpha < 1$, resp.), the visual cue will suggest the virtual plane be softer (or stiffer, resp.) as the movement perceived visually is exaggerated (or mitigated, resp.) via (2). Yet, the haptic cue will suggest the same virtual plane be stiffer (or softer, resp.) as the force is generated by the scaled-up (or scaled-down, resp.) displacement $\Delta x_{\text{virtual}} = \alpha \Delta x_{\text{real}}$. Other than this, way of choosing Δx, the subjects were asked to practice the same operation as Experiment #1 with all the other conditions to be the same.

3.4.2 Result

In the Experiment #3, confusing effect from the contradictory vision and haptic cues was investigated. The results are shown in Fig. 8, from which we can see that the subjects' responses are very different from that from Fig. 6. This inconsistency happened in almost every range of α. Both stiff and compliant sensation intended by pseudo-haptics effect are missing. This, we believe, is the result of contrary visual and haptic cues. If $\alpha > 1$ (or $\alpha < 1$, resp.), the visual cue suggests softer plane (or stiffer, resp.), while the haptics cue suggests otherwise. For instance, 0.2 in α means that the subjects needed to move the actual fingertip position 5 times in PH-plane as much as in RF-plane to perceive same physical force in both planes. In other words, same magnitude of subjects' real displacement Δx_{real} induced less force feedback in PH-plane compared to that in RF-plane. On the contrary, the fingertip sphere visualized on the screen will hardly move (stiffer motion) in PH-plane. In spite of the general belief that visual feedback is dominant over haptic feedback, subjects showed the opposite result; only 13 percent of the subjects answered that PH-plane was perceived stiffer.

3.5 Discussion

According to the results of the experiments above, pseudo-haptic feedback assisted human subjects to perceive a wider range of stiffness with our cutaneous feedback device in the situation of touching a virtual plane. As pseudo-haptic feedback modulated the virtual stiffness of the plane, subjects responded correspondingly. When $\alpha < 1$ (or $\alpha > 1$, resp.), the visual displacement on the screen became scaled-down (or, scaled-up, resp.) in comparison with users' actual displacement, which deceived subjects into recognizing the virtual plane be stiffer (or be softer, resp.).

The effectiveness of pseudo-haptics with cutaneous haptic device was evaluated in Experiment #1, with the quantitative analysis performed in Experiment #2. From the results, the implementation of pseudo-haptic feedback is deemed to be able to extend the renderable range of stiffness to be twice larger than the case without it. Accordingly, a wider range of the stiffness perception would be possible by modulating pseudo-haptics effect with stiffness K_o fixed.

Some interesting results were also observed when contradictory information of visual and haptic feedback was presented. In Experiment #3, $\Delta x_{\text{virtual}}$ was used as Δx to compute the desired force in (1), instead of previously used Δx_{real}. Unlike the results of Experiment #1 and #2, subjects generally responded that PH-plane felt softer even if $\alpha < 1$, i.e., pseudo-haptic feedback suggests the contrary. At the same time, cutaneous haptic feedback in PH-plane delivered more compliant sensation in contrast with the pseudo-haptics. This indicates that although pseudo-haptic feedback uses its visual-perception dominance over haptic feedback, that phenomenon is valid only for certain range of mismatch between the visual cue and cutaneous haptic cue. Therefore, it would be more practical to utilize the pseudo-haptic feedback as a complement for cutaneous haptic feedback, than totally rely on it.

4 Conclusion and Future Work

The main objective of this paper is to examine the integration of cutaneous feedback device and pseudo-haptic feedback. We performed experiments to show the efficacy of the pseudo-haptics when used for cutaneous fingertip haptic device. The results of Experiments #1 and #2 presented that the pseudo-haptics can indeed expand the range of renderable stiffness by complementing a sole usage of cutaneous feedback, suggesting a possibility of complementing the lack of kinesthetic feedback. The confusion caused by contradictory pseudo-haptics effect (i.e., contradictory haptics and visual cues) was demonstrated in Experiment #3, suggesting that the pseudo-haptic feedback be combined with the cutaneous haptic feedback, rather than being used excessively alone.

Some topics for future research include: 1) extension of the result to two-finger and multi-finger cutaneous haptic devices; 2) development of such multi-finger cutaneous haptic devices with portable localization devices (e.g., Microsoft Kinect®); and 3) more thorough and comprehensive human subject test including an experiment that compares the effect of the integrated feedback of pseudo-haptics and cutaneous haptic device to that of the kinesthetic feedback.

Acknowledgements

Research supported by the Global Frontier R&D Program on 'Human-centered Interaction for Coexistence' (NRF-M1AXA003-2011-0028355) and the Basic Science Research Program (2012-R1A2A2A0-1015797) of the National Research Foundation (NRF) of Korea funded by the Ministry of Education, Science & Technology (MEST).

References

[1] M. A. Salada, J. E. Colgate, M. V. Lee, P. M. Vishton, "Fingertip haptics: A novel direction in haptic display," *Proc. Int. Conf. Mechatronics Forum*, pp.1211-1220, 2002.

[2] K. Minamizawa, S. Fukamachi, H. Kajimoto, N. Kawakami, S. Tachi, "Gravity grabber: Wearable haptic display to present virtual mass sensation," *ACM SIGGRAPH*, pp.8, 2007.

[3] K. Minamizawa, D. Prattichizzo, S. Tachi, "Simplified design of haptic display by extending one-point kinesthetic feedback to multipoint tactile feedback," *Proc. IEEE Haptics Symposium*, pp.257-260, 2010.

[4] C. Pacchierotti, F. Chinello, M. Malvezzi, L. Meli, D. Prattichizzo, "Two finger grasping simulation with cutaneous and kinesthetic force feedback," *Proc. EuroHaptics*, pp.373-382, 2012.

[5] D. Prattichizzo, C. Pacchierotti, G. Rosati, "Cutaneous force feedback as a sensory subtraction technique in haptics," *IEEE Transactions on Haptics*, 5(4): pp.289-300, 2012.

[6] K. Minamizawa, K. Tojo, H. Kajimoto, N. Kawakami, S. Tachi, "Haptic interface for middle phalanx using dual motors," *Proc. EuroHaptics*, pp.235-240, 2006.

[7] A. Lecuyer, "Simulating haptic feedback using vision: A survey of research and applications of pseudo-haptic feedback," *Presence: Teleoperators and Virtual Environments*, 18(1): pp.39-53, 2009.

[8] L. Dominjon, A. Lecuyer, J. M. Burkhardt, P. Richard, S. Richir, "Influence of control/display ratio on perception of mass of manipulated objects in virtual environments," *Proc. IEEE Int'l Conf. Virtual Reality*, pp.19-25, 2005.

[9] A. Lecuyer, S. Coquillart, A. Kheddar, P. Richard, P, P. Coiffet, "Pseudo-haptic feedback: Can isometric input devices simulate force feedback?" *Proc. IEEE Int'l Conf. Virtual Reality*, pp.83-90, 2000.

[10] M. A. Srinivasan, G. L. Beauregard, D. L. Brock, "The impact of visual information of the haptic perception of stiffness in virtual environments," *ASME Winter Annual Meeting*, pp.555-559, November 1996.

[11] A. Lecuyer, J. M. Burkhardt, L. Etienne, "Feeling bumps and holes without a haptic interface: the perception of pseudo-haptic textures," *Proc. ACM CHI Int'l Conf. Human Factors in Computing Systems*, pp.239-246, 2004.

[12] T. Hachisu, G. Cirio, M. Marchal, A. Lecuyer, H. Kajimoto, "Pseudo-haptic feedback augmented with visual and tactile vibrations," *IEEE International Symposium on Virtual Reality Innovation*, pp.327-328, 2011.

[13] T. Hachisu, G. Cirio, M. Marchal, A. Lecuyer, H. Kajimoto, "Virtual chromatic percussions simulated by pseudo-haptic and vibrotactile feedback," *Proc. ACM ICAC*, pp.20, 2011.

[14] I. Jang, D. J. Lee, "Experiments with cutaneous haptic feedback - A preliminary study (2-Page Work-in-Progress Extended Abstract Paper)," *Int'l Conf. Ubiquitous Robots & Ambient Intelligence*, pp.232-233, 2013.