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Enlarging Just Noticeable Differences of Visual-Proprioceptive Conflict in VR using Haptic Feedback

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***Abstract*— Wearable finger-based haptics with cutaneous feedback is promising, as it allows us to duplicate many real-world rich/important tasks that are relying on the dexterity of fingers and hands in the virtual-world. For this system, one of the key challenges is the finger-tracking, which can of course never be perfect, yet, if used in VR (e.g., with HMD), would still be adequate as long as its tracking error is under a certain detection threshold. In this paper, for such wearable finger-based haptics in VR with HMD, via some suitably-designed human subject studies, we aim to quantitatively answer the following questions: 1) what is the detection threshold (i.e., just noticeable difference (JND)) of visual-proprioceptive conflict (i.e., error tolerance of the finger-tracking system in VR); and 2) is it possible to further reduce this visual-proprioceptive conflict by utilizing cutaneous haptic feedback. We believe these results would be useful to determine the design specification of finger-tracking systems for haptic and general VR applications alike.**

I. INTRODUCTION

Finger-based haptic interaction, where we manipulate and interact with virtual objects by our fingers in virtual-reality(VR), would be arguably the ultimate goal of haptics, as it allows us to transfer our main source of dexterity - the usage of fingers and hands - to the VR, thereby, realize many rich and important tasks of our everyday life in the VR. Another recent technical trend, which would allow for broader consumer market penetration, is to make this finger-based haptic system be wearable and portable.

For this wearable finger-based haptics, the idea of using cutaneous haptic feedback was proposed, first in [1], and later adopted in [2], [3], [4]. This cutaneous haptic system is more promising for consumer market as compared to, for example, finger-based exo-skeleton haptic system (e.g., [5], [6], [7], [8]), which are often technically very difficult to instrument and, consequently, very expensive to construct. It has also been reported that, even with the absence of kinesthetic feedback, the cutaneous haptic feedback alone can often provide adequate haptic sensation for virtual manipulation, particularly when the magnitude of the required force feedback is not so large (e.g., [4]).

One of the key challenges of this wearable haptic system is how to track the pose of the fingers, which is also relevant to any finger-based user interfaces for general human-computer

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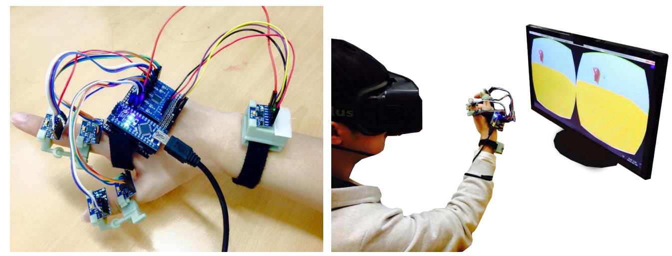

Fig. 1: IMU-based finger-tracking system for wearable cutaneous haptics.

interaction, for which several attempts have been made to utilize RGB-D camera (e.g., [9], [10]). Recently, we also developed an IMU-based wearable finger-tracking system as shown in Fig. 1. But regardless of which finger-tracking techniques are used, it is impossible to perfectly eliminate the tracking error (e.g., slow update-rate/occlusions of RGB-D camera, acceleration/magnetic perturbation of IMU-based systems).

However, at the same time, humans' proprioceptive perception is not perfect [11]. This implies that, particularly for VR applications where users can only see the virtual-world with the real-world visual information completely blocked (e.g., wearing head-mounted display (HMD)), the functioning of a finger-tracking system would still be proper if its tracking error can be made below a certain detection threshold of visual-proprioceptive conflict of users [12].

The goal of this paper is to answer the following two questions related to this visual-proprioceptive conflict for wearable finger-based cutaneous haptics: 1) what is the detection threshold (i.e., just noticeable difference (JND)) of visual-proprioceptive conflict when performing finger-based operation in the VR world (i.e., tolerance of tracking error between visual cue in VR scene and proprioception of real fingers); and 2) is it possible to further reduce this visual-proprioceptive conflict by suitably utilizing cutaneous haptic feedback (i.e., can fool users to tolerate more tracking error with cutaneous feedback). We believe these questions would be useful to define the design specification of finger-tracking systems for haptics and general VR applications alike.

Several results have been proposed on the visual-proprioceptive conflict: static orientation error [13], effect of latency and noise [14], and drift angle of the arm [15] in virtual or mixed reality. It was shown in [16] that the position perception of the human is determined by a weighted sum of visual, proprioceptive and other senses, implying that the haptic feedback would be able to affect the perception of finger-tracking error as also aimed for in this paper. This interplay between haptic and other senses were also studied: the role of haptic and visual senses in curvature

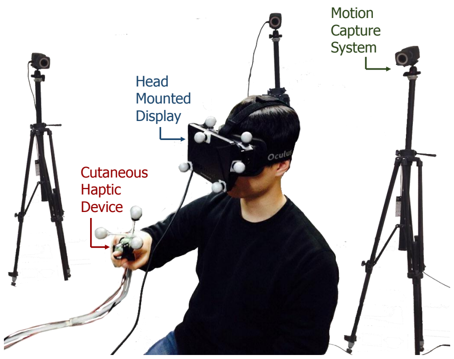

Fig. 2: Experimental setup to study visual-proprioceptive conflict and effect of cutaneous haptic feedback on that: The subjects wore the cutaneous haptic device on their index finger and the HMD on their head and sat on a chair surrounded by the MOCAP system.

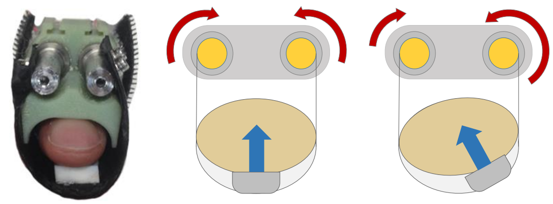

Fig. 3: Cutaneous haptic device [4]: The normal force can be produced by rotating the two motors in the opposite directions and same angle, while the shear force can be produced by differing the angles of the two motors.

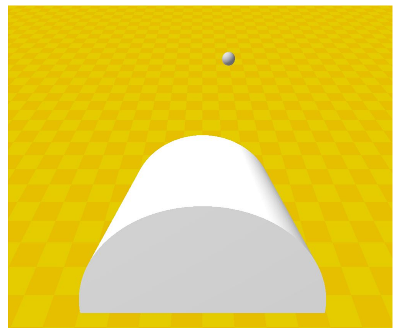

Fig. 4: Virtual environment as seen from the HMD, with the sphere, which represents the user's index finger-tip position, and the cylinder to produce contact force.

perception [17]; pseudo-haptic effects by modifying visual cues [4] and the effect of matching visual cues with haptic cues on modifying felt position of subjects [18]. Yet, to our knowledge, quantitative (e.g., JND) analysis of the visual-proprioceptive conflict for complex 3D spatial motion and, further, quantitative analysis of the effect of haptic feedback on the visual-proprioceptive conflict threshold have not been explored before.

The rest of the paper is organized as follows. The testbed of Fig. 2, used for our investigation, is detailed in Sec. II, by which we can then suitably generate visual-proprioceptive conflict and haptic sensation. Two human subject studies, i.e., JND analysis of visual-proprioceptive conflict for finger-based VR operation and of the effect of haptic feedback on that, are performed in Sec. III and discussed in Sec. IV. Concluding remarks are given in V.

II. Experimental Setup

A. Hardware Components

To study the visual-proprioceptive conflict and the effect of cutaneous haptic feedback on that, we utilize the experimental setup as shown in Fig. 2, which consists of motion capture system (MOCAP), HMD, and wearable cutaneous haptic feedback device on the index finger, each of them now detailed below.

1) MOCAP System: In order to measure human's head and finger motion, we used VICON® MOCAP system, which provides the position and orientation of a set of reflective markers by using multiple IR cameras with 200Hz sampling rate and millimeter-range spatial resolution. We attached set of markers on the HMD and on the cutaneous haptic device to measure the pose (i.e., position and orientation) of the HMD and that of the cutaneous haptic device worn on the user's index finger-tip.

2) HMD: All the experiments in this paper were executed in the VR setting, i.e., all the visual information of the real-world was completed blocked from the subjects. This is particularly crucial, because real visible hands will directly inform the subjects where their finger-tip is. To show only the virtual environment while also providing 3D immersive virtual visual information generated for experimental purposes, we adopted Oculus Rift® HMD, which provides 3-D vision with 1200×800 $(640 \times 800\text{per eye})$ resolution and 90 degree field of view, which is one the widest among the commercial HMDs.

3) Cutaneous Haptic Device: For generating haptic feedback on the user's finger-tip, we utilized a cutaneous haptic device as shown in Fig. 3, which was first proposed in [2] and adopted also in [4]. The device has two motors (Maxon DCX motor, ϕ = 10mm, 3W, 16:1 gear ratio) and each motor has the encoder in the motor shaft which provides the resolution of 1024 cnt/rev. It is connected to desktop with US Digital® USB4 DAQ board and Arduino® board and we can measure and control the angle of motors in about 1kHz. The rubber block attached between the finger-tip and the band was manipulated by the motors. We can then transmit normal or shear force by controlling the two motors to their respective designated angles.

4) Virtual Environment: The virtual environment for the experiments was constructed using the above equipments and OpenGL®. In the virtual environment, the virtual sphere, which represents the position of the index finger-tip was shown to the subjects by measuring the relative position of the HMD and the finger-tip by using the MOCAP system. Human subjects could freely move their hands and head. Also for generating the contact force, we used a virtual cylinder fixed in the virtual environment, because that shape can easily give the intuition of position sense to the subjects by delivering directional contact force as used in [17]. Penetration of finger sphere into the cylinder was prevented in graphics rendering. By projecting the virtual environment on the HMD, the subjects were able to see their finger-tip motion as the motion of the virtual sphere. See Fig. 4.

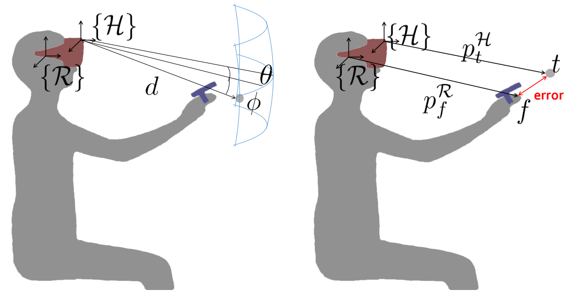

Fig. 5: The HMD frame $\{\mathcal{H}\}$, which is measured by MOCAP system and serves as the reference for the virtual-world graphics rendering, and the visual perception reference frame $\{\mathcal{R}\}$ for the real-world perception. In this paper, we also use spherical coordinate system attached at the HMD frame $\{\mathcal{H}\}$.

B. Visual Perception Reference Calibration

If we directly measure the pose of the real finger-tip w.r.t. the pose of the HMD by using the MOCAP system, and render its image to the user via the HMD, we found the rendered image appears often too close to the human eyes than how it appears in the real world. This is because the user's eyes are not sitting on the HMD frame (as measured by MOCAP system), but somewhere inside user's head. In order to reduce this pose-difference between the HMD frame (reference for VR scene generation) and the visual perception reference frame (for the real-world visual perception), we performed the calibration as follows.

For this, we defined two coordinate frames: the HMD frame $\{\mathcal{H}\}$ and the visual perception reference frame $\{\mathcal{R}\}$. The goal was then to identify the rigid body transformation between these two frames, that is, the translation offset $p^{\mathcal{H}}_{\mathcal{R}} \in \Re^3$ and the rotation offset $R^{\mathcal{H}}_{\mathcal{R}} \in$ SO(3) from $\mathcal{R}$ to $\mathcal{H}$. See Fig. 5. Now, in order to estimate $p^{\mathcal{H}}_{\mathcal{R}}$ and $R^{\mathcal{H}}_{\mathcal{R}}$, we performed the following reaching-without-seeing task.

A virtual target point $p_t \in \Re^3$ was generated randomly and the subjects were asked to move their finger-tip position $p_f \in \Re^3$ to the target p_t as close as possible. During this task, only the virtual target point t was presented as a gray sphere, while the user's finger-tip position was not rendered (i.e., they moved their finger-tip only relying on their proprioceptive perception). We then measured the position of the user's finger-tip p_f w.r.t. the HMD frame $\{\mathcal{H}\}$ (i.e., $p^{\mathcal{H}}_f$). We can then write the following rigid body transformation equation:

$$R^{\mathcal{H}}_{\mathcal{R}} p^{\mathcal{R}}_f + p^{\mathcal{H}}_{\mathcal{R}} = p^{\mathcal{H}}_f \tag{1}$$

where $p^{\mathcal{R}}_f$ is the position of the finger-tip as measured in the perception reference frame $\{\mathcal{R}\}$, which is unknown as we do not know the location/orientation of the reference frame $\{\mathcal{R}\}$.

Now, consider (1). The perfect calibration between $\{\mathcal{H}\}$ and $\{\mathcal{R}\}$ would then imply that $p^{\mathcal{R}}_f = p^{\mathcal{H}}_t$, that is, the human user's perception of the finger-tip position in the real-world is the exactly the same as that of the virtual target point position in the virtual-world as rendered within the HMD. This then further imply that we can estimate $p^{\mathcal{H}}_{\mathcal{R}}$ and $R^{\mathcal{H}}_{\mathcal{R}}$ by using the following equation:

$$R^{\mathcal{H}}_{\mathcal{R}} p^{\mathcal{H}}_t + p^{\mathcal{H}}_{\mathcal{R}} = p^{\mathcal{H}}_f$$

where $p^{\mathcal{H}}_t, p^{\mathcal{H}}_f$ are given/measurable, and $R^{\mathcal{H}}_{\mathcal{R}}, p^{\mathcal{H}}_{\mathcal{R}}$ are unknown. Thus, by repeating this reaching-without-seeing task many times, we can produce a data set of $p^{\mathcal{H}}_t, p^{\mathcal{H}}_f$. using this data set and the above equation, we can estimate $R^{\mathcal{H}}_{\mathcal{R}}, p^{\mathcal{H}}_{\mathcal{R}}$, thereby, completing the calibration.

For this calibration, we utilized the spherical coordinate system as shown in Fig. 5. The distance, azimuth and elevation of the virtual target point were randomly chosen in the predetermined range: the range of azimuth and elevation was between from -30° to 30° and the range of distance was from 30cm to 50cm. This range of space was chosen, as the majority of our experiments (and other typical tasks in the VR with the HMD) was performed near this area. When a target was randomly generated, the subjects were asked to move their finger-tip to the target as close as possible (i.e., to match $p^{\mathcal{R}}_f$ and $p^{\mathcal{H}}_t$) with no visual information of real finger-tip position. Five subjects participated in this calibration task and took 100 trials each, making total 500 data points. We then used the results in [19] for obtaining least square solution of the rigid-body transformation and obtained:

$$p^{\mathcal{H}}_{\mathcal{R}} = \begin{pmatrix} 3.261 \\ 10.282 \\ -5.069 \end{pmatrix}, \; R^{\mathcal{H}}_{\mathcal{R}} = \begin{bmatrix} 0.9941 & 0.0294 & -0.1042 \\ -0.0297 & 0.9996 & -0.0016 \\ 0.1041 & 0.0047 & 0.9946 \end{bmatrix}$$

with the unit of $p^{\mathcal{H}}_{\mathcal{R}}$ being cm, showing that the translation offset is more prominent than the rotation offset between $\{\mathcal{H}\}$ and $\{\mathcal{R}\}$.

III. Human Subject Study and JND of Visual-Proprioceptive Conflict

A. Experiment #1

The purpose of Experiment #1 was to measure the detection threshold of tracking error (i.e., visual-proprioceptive conflict) human can perceive in the virtual environment. We measured this threshold by asking subjects to discriminate the true position of their finger-tip from the one intentionally perturbed with some position error.

1) Participants: Six human subjects participated in the Experiment #1. They were all male, from the age of 22 to 32, right-handed with no known perception disorder and used their index finger of dominant hand for this experiment.

2) Experimental Settings: The virtual environment, displayed to participants through the HMD, consisted of the the finger sphere and a cylinder as mentioned in II. Also, during the whole trials in Experiment #1, the cutaneous haptic device was turned off to exclude the effect of haptic feedback. Subjects were told to make decisions as soon as possible, but also told that making a correct decision is more important.

3) Procedure: In the beginning of the experiment, the subjects were given enough time to be familiar with the motion in the virtual environment for preventing learning effect. They were able to move their finger-tip sphere in free air or touch the cylinder. They then proceeded Experiment #1, which consists of the three phases: **adaptation phase**, **blind phase**, and **answer phase** as shown in Fig. 6:

In the **adaptation phase**, subjects were guided to swipe the surface of the cylinder from side to side. This adaptation phase lasted for five seconds to reaffirm the information of the mapping between the visual sense in the virtual

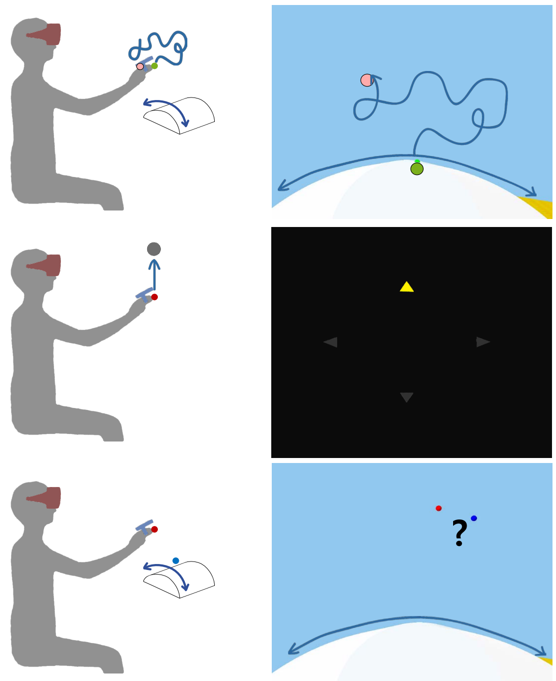

Fig. 6: Procedure for the Experiment #1: (1) **adaptation phase** (top): subjects freely moved their finger sphere to adapt the virtual environment and were asked to swipe the surface of the cylinder; (2) **blind phase** (middle): subjects were instructed to move their finger sphere following the yellow arrows, while all the virtual environment was blacked-out; (3) **answer phase** (bottom): subjects repeated the cylinder swiping task again and answer which sphere represented their real finger-tip position.

environment and the proprioception of the subjects, after the initial familiarization phase.

In the **blind phase**, the virtual environment was blacked out for three seconds, except for the arrows that informed the directions - up, down, left, and right. The directions were displayed to guide the subjects' finger-tip position to be within a desired range same, as did in visual perception reference calibration. This phase was designed to separate the adaptation phase and the answer phase by confusing the subject of their perception of the last position of the true finger sphere before generating the visual feedback of the false finger sphere.

Visual feedback of the virtual environment appeared again in the **answer phase** similar to the adaptation phase. The only difference is that, now, the two spheres were displayed; one representing the true finger-tip, the other representing the false one with a perturbation error of position.

The generated errors were defined as the radial distance from the true finger-tip sphere. In each trial, they were determined randomly within the range of $1.5 \sim 7.5cm$ with the interval of $1.5cm$, in that, we expected the JND to be within this range in our pilot experiment. Whenever the error was generated, the false sphere was visualized randomly in the circle, of which the radius was the error value and the center was the true sphere position. From this random initial position, the false and the correct finger spheres moved together under the human command, except when one (or both) of them made contact with the cylinder, for which the penetration into the cylinder was graphically removed.

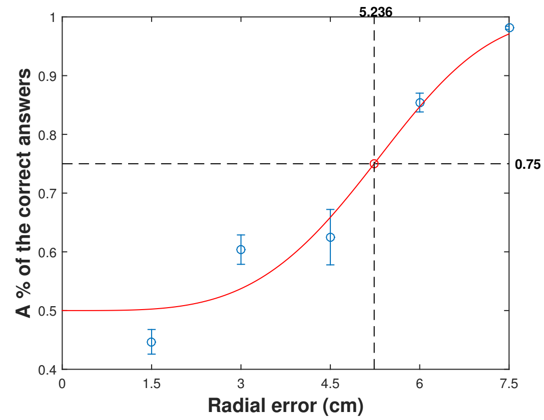

Fig. 7: Results of Experiment #1: average percent of answers where the subjects correctly guessed which sphere corresponds to their true finger-tip. (fitted by the psychometric curve).

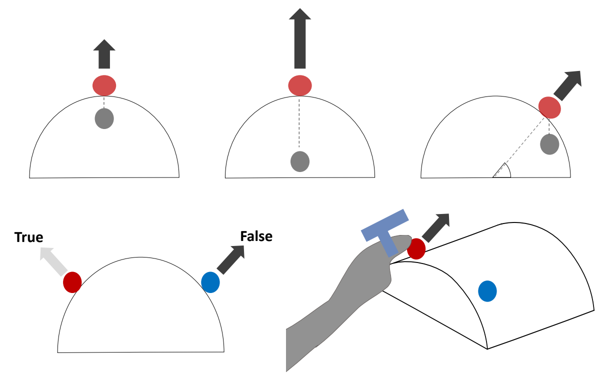

Fig. 8: Experiment #2: haptic feedback was added according to the position of finger sphere (gray) on the cylinder (top); subjects received haptic feedback corresponding to either the randomly-chosen true(red) or false(blue) sphere. In this figure, the false sphere is selected so corresponding haptic feedback is given.

Subjects had to carry out classical Two Alternative Forced Choices (2AFC) with those two spheres. They performed two similar tasks of sliding the finger sphere on the surface of the cylinder. For each task, subjects were instructed to consider as if one of two spheres were their real finger-tip. After taking several trials for each task, subjects were asked to choose which finger sphere represents the true position of their finger-tip; "blue" or "red". 8 repetitions were given for 5 error steps, thus, total 40 trials for each subject were performed in Experiment #1.

4) Result: The average of the correct answer rate over all the subjects was plotted as a blue line and markers in Fig. 7. As expected, the percentage of correct answers of discriminating the sphere of the true finger position increases as the error becomes large. The JND of visual-proprioceptive conflict is determined as the value where 75% correct discrimination occurs [20]. For estimating the error corresponding to 75%, we fit the data to the Weibull function as the psychometric curve [21]. The result of the JND value is $5.236cm$ about the object $30cm$ away from the subject's HMD.

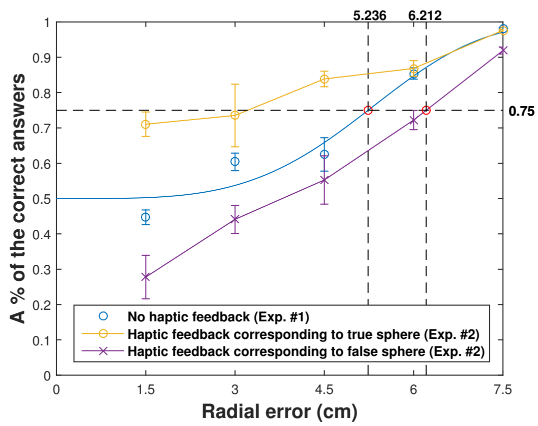

Fig. 9: Results of Experiment #2: percentage of the correct answers in two cases, true haptic feedback and false haptic feedback and comparison with results of Experiment #1 .

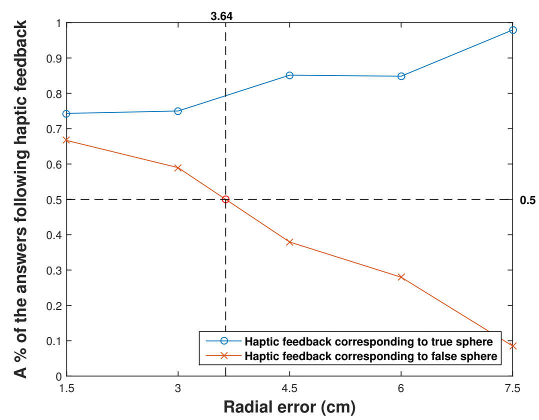

Fig. 10: The percentage of the answers following the haptic feedback when the haptic feedback corresponding to the false or true sphere was delivered.

B. *Experiment #2*

In Experiment #2, haptic feedback was added in the **adaptation phase** and the **answer phase**, to analyze the quantitative effect of the feedback on the JND of the visual-proprioceptive conflict compared to the Experiment #1.

1) Participants: The same as the Experiment #1.

2) Experimental Settings: : The same as the Experiment #1, except that haptic feedback from the cutaneous haptic device was activated.

3) Procedure: The same procedure as the Experiment #1, except the haptic feedback. When the sphere (true sphere in **adaptation phase**, randomly selected one between the true and false spheres in **answer phase**) was contacting with the cylinder surface, the corresponding contact force was given to the subjects with the combination of the normal and shear forces as shown in Fig. 8. Because the haptic feedback might be correct or wrong information w.r.t. the user's true finger-tip position, applying the haptic feedback according to the randomly-chosen sphere enables us to investigate how the true or false haptic feedback affect human' JND of the visual-proprioception conflict. Note that this would be meaningful only when the human subject does not know if the haptic feedback comes from the true or false finger sphere.

4) Result: In the Fig. 9, the effect of the haptic feedback on the perception of error is shown. It can be noticed that the percentage of correct answers is lower than Experiment #1 with the false haptic feedback (i.e., haptic feedback corresponding to the false finger sphere). We also estimated the JND of visual-proprioceptive conflict as the point where 75% correct discrimination occurs. To fit the data set, we used the linear interpolation, not the Weibull function used in Experiment #1, because the condition for Weibull function, 50% of correct answers at no-stimuli point, can not be satisfied because of the randomized haptic feedback stimuli. Accordingly the JND value of visual-proprioceptive conflict with false haptic feedback is observed as $6.212cm$, which is an increased value about $1.1cm$ from the prior result.

IV. Discussion

Psychophysical examinations were proceeded to compute the detection threshold of positional error in virtual environment where visual-proprioceptive confusion usually occurs due to the tracking error. In Experiment #1 where only visual feedback without haptic feedback was given, we obtained the JND value, $5.236cm$, meaning that human users are expected to distinguish their true finger-tip from the false one with the error larger than $5.236cm$. In Experiment #2, haptic feedback via cutaneous haptic device was added when contacting with the virtual cylinder. Because this feedback was randomly chosen from the contact information of true or false finger-tip sphere, subjects did not know whether this haptic feedback was correct information from true finger-tip or not. But our hypothesis was that force feedback corresponding to the false finger-tip can disturb perceiving their real position based on proprioception which leads to the increase of JND. And responses when given the false haptic feedback in Fig. 9 show that the resultant JND value is $6.212cm$, which is larger than that of Experiment #1, confirming our hypothesis.

To closely investigate the effect of haptic feedback, we plot the graph in Fig. 10, which means when haptic feedback corresponding to true or false sphere is delivered, the percentage of answers where subjects chose that sphere as their real finger-tips. As seen from the graph, the aspect of decisions are similar for both true and false haptic feedback at the radial error of $1.5cm$; around 70% of subjects relied on the haptic cue in selection task. However, the results show a completely different tendency as radial error increases. In the case of false haptic feedback, a percentage of choosing the corresponding sphere gradually decreases with an increasing error, while converges to 100% in case of true haptic feedback. This presents clearly the role of the haptic cue in sensing the position when proprioceptive and visual sense conflict. when the error is small, human cannot get enough clue of position senses from the conflict so they are easily prone to rely on haptic cue. As error goes larger than the JND, proprioceptive sense becomes distinguishable from the distorted visual feedback, so subjects can neglect the haptic cues and aware the visual-proprioceptive conflict, which means the haptic feedback lose their role in tracking system. This can be reconfirmed using one-way ANOVA of which independent factor is type of the haptic feedback (no, true, false) and dependant variable is correct answer rate. In the case of $7.5cm$ error, there is no significant difference

($F_{2,15} = 1.6, p > 0.05$) while there is significant difference in $1.5cm$ ($F_{2,15} = 6.9, p < 0.0001$). This also proves our hypothesis that the haptic feedback has a substantial impact on sensing position when the tracking error is small.

This result provides the notable idea for designing a finger-tracking system. As mentioned in Sec. I, mapping the finger-tip position into the VR is quite challenging, since there exists an tracking error due to the imprecision of the sensors. However, using finger-tracking device with the error below the JND value, human users would not able to recognize the disorder in virtual operation, which denotes the system has a good performance of finger-tracking. Furthermore, concerning this result of Experiment #2, the error threshold for the finger-tracking system with cutaneous haptic feedback is allowed to be larger than that for the single finger-tracking system. As a more rigid specification for device design, tolerable error threshold can be defined as a point of 50% correct discrimination which means no one can detect the visual distortion by tracking error. This threshold is extremely different between case without haptic feedback, almost close to zero error, and case with haptic feedback, $3.64cm$ as shown in Fig. 10. This results claim the efficacy of haptic feedback in designing finger tracking system.

The absolute value of our results can depend on the details of the experiments such as the size of finger sphere, scene of virtual environment and so on. One of possible factor varying along tasks is the eye movements, which has a significant role in accuracy and time of finger-reaching task ([22] , [23]), thus, can affect the sense of position. However, seeing the tendency of our results, especially Fig. 10 where the results is extremely different according to the type of haptic feedback, we strongly argue that the contribution of tactile feedback to perceiving tracking error can be generalized and applied to general finger tracking system.

V. CONCLUSIONS

In this paper, we verify the possible efficacy of the haptic feedback to reduce the performance requirement for the tracking error in virtual environment. For this, we performed the Experiment #1 to measure the JND of visual-proprioceptive conflict in virtual environments and analyzed the effect of haptic feedback on this JND in the Experiment #2. The results of Experiment #1 and #2 show that the detection threshold of tracking error (i.e., JND of visual-proprioceptive conflict) can be extended by using haptic feedback in that humans sense of the position is given as the weighted sum of various senses of the human. This result can suggest, in the finger-based tracking system, a design standard of allowable error range and the fact that integration with cutaneous haptic device can alleviate the performance requirement of this finger-tracking system in virtual operation.

The topics for future research can include: 1) the extension of the JND analysis from simple swiping task to general virtual operation such as grasping, manipulating, 2) the effect of avatar graphic on the detection threshold of error. Our final goal is to implement finger-based virtual operation system with ignorable tracking error by combining our cutaneous haptic device and IMU-based finger tracking system, and to validate our results in this paper.

REFERENCES

[1] K. Minamizawa, S. Fukamachi, H. Kajimoto, N. Kawakami, and S. Tachi, “Gravity grabber: wearable haptic display to present virtual mass sensation,” in *ACM SIGGRAPH emerging technologies*, 2007, p. 8.

[2] D. Prattichizzo, C. Pacchierotti, S. Cenci, K. Minamizawa, and G. Rosati, “Using a fingertip tactile device to substitute kinesthetic feedback in haptic interaction,” in *Haptics: Generating and Perceiving Tangible Sensations*. Springer, 2010, pp. 125–130.

[3] M. Solazzi, A. Frisoli, and M. Bergamasco, “Design of a cutaneous fingertip display for improving haptic exploration of virtual objects,” in *Ro-man 2010 19th IEEE International Symposium in Robot and Human Interactive Communication*. IEEE, 2010.

[4] I. Jang and D. Lee, “On utilizing pseudo-haptics for cutaneous fingertip haptic device,” in *IEEE Haptics Symposium*, 2014, pp. 635–639.

[5] Cyberglove systems. CyberGrasp. http://www.cyberglovesystems.com/products/cybergrasp/overview. [Online; accessed 25-January-2015].

[6] Dexta robotics. Dexmo. http://www.dextarobotics.com/products/Dexmo. [Online; accessed 25-January-2015].

[7] M. Fontana, S. Fabio, S. Marcheschi, and M. Bergamasco, “Haptic hand exoskeleton for precision grasp simulation,” *ASME J. Mech. Robot.*, vol. 5, no. 4, p. 041014, 2013.

[8] A. Frisoli, F. Rocchi, S. Marcheschi, A. Dettori, F. Salsedo, and M. Bergamasco, “A new force-feedback arm exoskeleton for haptic interaction in virtual environments,” in *Proc. 1st Joint Eurohaptics Conf. and Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE, 2005, pp. 195–201.

[9] V. Frati and D. Prattichizzo, “Using kinect for hand tracking and rendering in wearable haptics,” in *IEEE World Haptics Conference*, 2011, pp. 317–321.

[10] Leapmotion. https://www.leapmotion.com/. [Online; accessed 25-January-2015].

[11] R. Van Beers, A. C. Sittig, and J. J. D. van der Gon, “The precision of proprioceptive position sense,” *Experimental Brain Research*, vol. 122, no. 4, pp. 367–377, 1998.

[12] E. Foxlin and G. Welch, “Motion tracking: No silver bullet, but a respectable arsenal,” *IEEE Computer Graphics and Appilications*, vol. 22, no. 6, pp. 24–38, 2002.

[13] J. B. Madsen and R. Stenholt, “How wrong can you be: Perception of static orientation errors in mixed reality,” in *IEEE Symposium on 3D User Interfaces*, 2014, pp. 83–90.

[14] M. A. Livingston and Z. Ai, “The effect of registration error on tracking distant augmented objects,” in *Proc. of the 7th Int’l Symp. on Mixed and Augmented Reality*. IEEE Computer Society, 2008, pp. 77–86.

[15] E. Burns, S. Razzaque, A. T. Panter, M. C. Whitton, M. R. McCallus, and F. P. Brooks Jr, “The hand is slower than the eye: A quantitative exploration of visual dominance over proprioception,” in *Proc. of IEEE Virtual Reality Conf.*, 2005, pp. 3–10.

[16] N. P. Holmes and C. Spence, “Visual bias of unseen hand position with a mirror: spatial and temporal factors,” *Experimental Brain Research*, vol. 166, no. 3-4, pp. 489–497, 2005.

[17] K. Drewing and M. O. Ernst, “Integration of force and position cues for shape perception through active touch,” *Brain Research*, vol. 1078, no. 1, pp. 92–100, 2006.

[18] A. Folegatti, F. de Vignemont, F. Pavani, Y. Rossetti, and A. Farnè, “Losing one’s hand: visual-proprioceptive conflict affects touch perception,” *PLoS One*, vol. 4, no. 9, p. e6920, 2009.

[19] P. J. Besl and N. D. McKay, “Method for registration of 3-d shapes,” in *Robotics-DL tentative*. International Society for Optics and Photonics, 1992, pp. 586–606.

[20] S. Allin, Y. Matsuoka, and R. Klatzky, “Measuring just noticeable differences for haptic force feedback: implications for rehabilitation,” in *Proc. of 10th Symp. Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2002, pp. 299–302.

[21] M. Achibet, M. Marchal, F. Argelaguet, and A. Lécuyer, “The virtual mitten: A novel interaction paradigm for visuo-haptic manipulation of objects using grip force,” in *IEEE Symposium on 3D User Interfaces*, 2014, pp. 59–66.

[22] K. Wilmut, J. P. Wann, and J. H. Brown, “How active gaze informs the hand in sequential pointing movements,” *Experimental brain research*, vol. 175, no. 4, pp. 654–666, 2006.

[23] V. Gaveau, L. Pisella, A.-E. Priot, T. Fukui, Y. Rossetti, D. Pélisson, and C. Prablanc, “Automatic online control of motor adjustments in reaching and grasping,” *Neuropsychologia*, vol. 55, pp. 25–40, 2014.