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Displaying Variable Stiffness by Passive Nonlinear Spring Using Visuo-Haptic Interaction

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Abstract— **This paper proposes an immersive visuo-haptic display system composed of an easy-to-carry and light-weight passive haptic device and an HMD. We employ visuo-haptic interaction to control a wide range of perceived stiffness without using mechanical actuators that would inevitably make the device bulky and power-consuming. Via an HMD a user sees his or her own rendered hand with its finger flexion that is appropriately modified in relation to presented virtual stiffness. We experimentally verified that the proposed system could display both a pinchable elastic ball and a rigid undeformable one.**

I. Introduction

Recent rising attention to virtual-reality(VR)-related technologies and applications would be considerably ascribed to the advent of head-mounted-displays (HMDs) that have followability to body movement with an affordable price such as Oculus Rift (Oculus VR, LLC.) [1]. These recent HMDs have provided easily immersive audio-visual VR experiences, which are substantially satisfactory, while their correlated haptic technologies still have much room for further development. The purpose of this research is to develop a compact and low power-consuming system which provides realistic haptic experiences with virtual objects compatible with recent HMDs. A straightforward approach to accomplish realistic haptic presentation would be actively and accurately presenting force to user's fingers in accordance with displayed images using exoskeleton devices [2, 3]. Though this method can precisely present the reaction force to user's motion in principle, it requires a large-sized device consuming large power, especially when haptic feedback with a larger dynamic range is preferred. Therefore a simpler force display device is desired that is usable for general use with recent HMDs.

In case of haptic sensation associated with visual events, a perceptive phenomenon named pseudo-haptics has been reported. It is an effect that a haptic sensation is produced by a visual event with no actual haptic stimulation. It was reported users felt forces while watching a monitor that showed a mouse cursor or virtual objects that visually reacted to their input actions [4, 5, 6]. Thanks to the recent improvement of remote sensing technology of human motions and HMDs, it has become possible to capture the position and posture of users' own hand and render it in the users' sight, where user's own actual hand doesn't get in their sight. In this situation visual modification of displayed users' own hand is possible, which enables illusional perception such as reoriented stretching direction [7], weight or mass misperception [8, 9], warped cognition of surface shape [10] or even the existence of an object that actually is not there [11]. These systems only use generic objects being held by users instead of active actuators providing users with force or torque consuming much energy in operation and consequently are small-sized.

Figure 1. Experimental setup of stiffness display

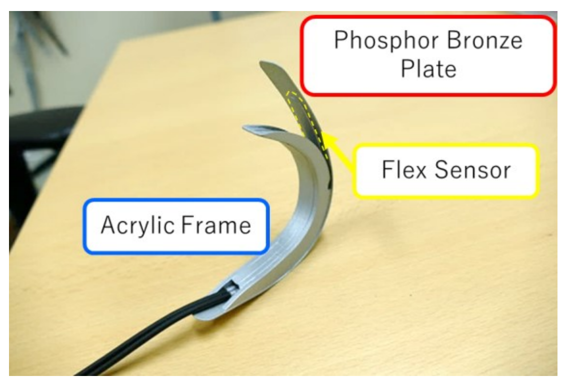

Figure 2. Photo of the prototyped haptic device

One of physical aspects essential in enriching haptic perception would be the dynamic response of objects given to hands. In this research, we focus on displaying virtual

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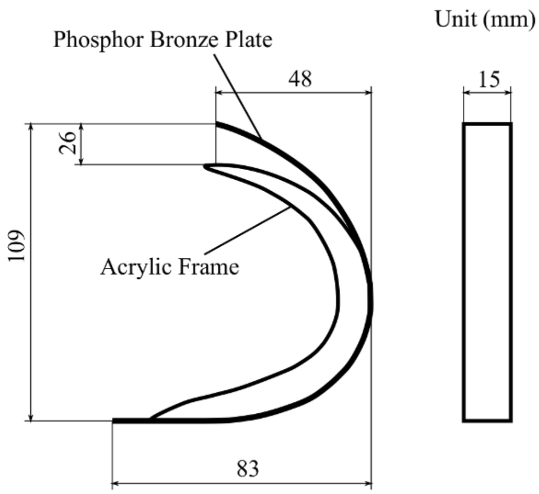


Figure 3. Dimensions of the haptic device

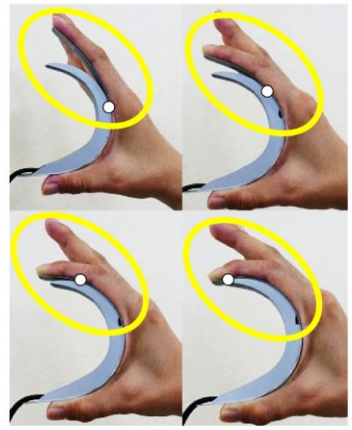


Figure 4. The mechanism of the nonlinear spring

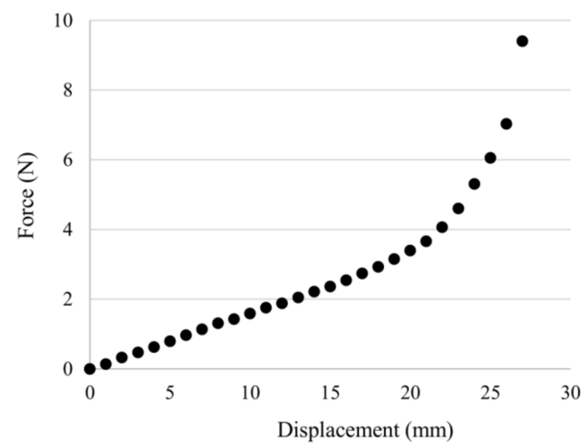


Figure 5. Reaction force vs. displacement

pinchable objects with a wide range of stiffness based on the 'warped self-movement' concept introduced above. We propose a system that the perceived stiffness is controlled by replacing the actual visual flexion images with warped ones that tunes the relation between the finger displacement and resilient force change. The system has a portable haptic device containing a curved beam that presents resilience to the user's fingers in response to the finger flexion. It has a specifically-designed mechanical structure whose equivalent stiffness increases as the flexion of user's finger increases. Users are supposed to hold the device and wear an HMD to see re-rendered their own hand pinching a virtual object. The displayed finger flexion is created based on the actual one measured by the embedded flex sensor in the haptic device.

Our system is based on an assumption that visual perception has priority over proprioception. If the visually displayed finger flexion is perceived as the real one while the perceived force is preserved, the perceived stiffness will be controlled by the relation between the displayed finger displacement and resilient force change.

We have fabricated the very first prototype for this research [12] and what is described in this paper is its more refined version. We refer to a technique concurrently proposed with a concept that is similar to ours [13].

In the following of the paper we describe how the users' stiffness perception was experimentally affected by the change in visual dynamics of the object. The unique challenge in the research is that it covers a very soft objects that is extremely deformable to a completely rigid object that shows no deformation. As its related researches, the device contains no active elements generating regulated force of torque. Therefore our approach can coexist with another haptic/tactile technologies such as vibrotactile textures or electric stimulations, which can offer more complicated tactile experiences.

II. Variable Stiffness Display

A. System Overview

Figure 1 shows a whole picture of the prototype system. This system is composed of a PC, HMD (Head Mounted Display, Oculus Rift by Oculus VR), finger posture sensor (Leap Motion by Leap Motion Inc.) for obtaining the position and posture of user's hand, and the haptic device we propose which physically present resilience to the user's fingers. The virtual objects and user's hand in the HMD are rendered synchronously with the actual user's hand. The user's hand position and orientation is roughly estimated by the finger posture sensor (Leap Motion). The precise motion of the index finger relative to the hand is measured by the flexion sensor on the haptic display device. As the development tool of 3D CG for HMD, we used Unity 5.4.0b25 by Unity Technologies.

B. Varying Stiffness Using Visuo-Haptics Interaction

The above mentioned "haptic device" is a nonlinear plate-spring with a flexion sensor. The user grasps the haptic device with his or her thumb and index finger. The haptic device passively present resilience to the user according to the flexion of user's fingers. The spring constant is low (elastic) at the initial state and very high (rigid) at the most bended state.

Here suppose we change the correspondence between the actual finger flexion angles and visually displayed ones in the HMD. If the finger image in the HMD bends more largely than the actual motion, the user feels a weak reaction force for a large bending motion, where the user will feel the grasped object elastic. If the fingertip image stopped at the "most bended state" of the haptic device, the user will feel a rigid object.

In the ideal case that the perception of the finger flexion angles is completely replaced with the visually displayed one, the actual elastic property of the haptic device

$$f = g(d) \tag{1}$$

where f and d are respectively the reaction force and the displacement of a representative point of the finger, can be replaced with an apparent elastic property

$$f = G(D) \equiv g(h^{-1}(D)) \tag{2}$$

where $D \equiv h(d)$ is the replaced finger displacement by the visual display. If we only consider single-valued monotonic functions, we can produce any function of G by selecting $h(d)$ as $h(d) = G^{-1}(g(d))$. This is the basic principle of the stiffness display. Since the section of G is flexible, we can design a variety of haptic experiences as explained in Graphics section.

The emphasis of our device is the use a nonlinear spring that can cover a wide range of f with a relatively small range of d, which enables a wide range stiffness display by a simple device structure.

This haptic display strategy is based on the uncertainty of the finger angle perception by the muscle spindles. One of the most similar preceding work is [11] where the user with a HMD can feel a virtual ball between the thumb and index finger that are making an "OK gesture." The difference from the previous researches is that a wide-range of stiffness is realistically displayed. Since the physical stiffness changes actually and can be adjusted to a desired value, the perception is stable and convincing.

C. Haptic Device Configuration

The haptic device is composed of an acrylic frame, a phosphor bronze plate, a flex sensor as shown in Figure 2. The mass of the haptic device is 30 g (0.03 kg) and its dimensions are shown in Figure 3. The flexion of user's fingers is captured by the flex sensor attached along with the inside of the phosphor bronze plate. The resistance value changes from 30 kΩ to 35 kΩ corresponding to the flexion of user's fingers. In the measurement circuit, we form a Wheatstone bridge with the reference resistance of 33 kΩ and source voltage of 5 V. The output of flex sensor from Wheatstone bridge is amplified by 20 times by an instrumentation amplifier.

Figure 4 shows the behavior of haptic device when the user grasped it and bended his or her fingers. The white points shown in Figure 4 indicate the final contact points between the phosphor bronze plate and the acrylic frame. The final contact point gradually moves to the tip while the user's finger bends deeply, which results in the increase of the spring constant (the derivative of Figure 5 curve) of the cantilever formed by the final contact point (white point) and the phosphor bronze plate. By this structure, the haptic device can passively present variable spring constant. Figure 5 shows measured relation between the device-top displacement from the original position and the force in y-axis direction presented by the haptic device. The graph shows the spring constant increases monotonically with increase of the displacement.

The important feature of the device is that the perceived stiffness is controlled by the user's spontaneous finger motion led by the visual image, where the flexion force is provided by the user. Although the motion range of the movable part is as small as 26 mm as shown in Figure 3, a wide variety of object shapes and sizes are displayable.

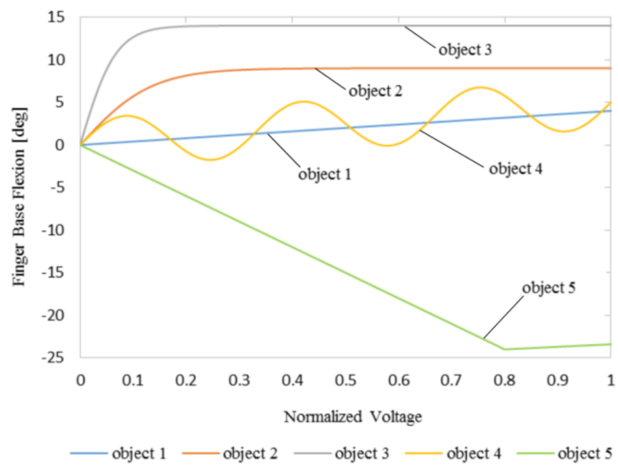
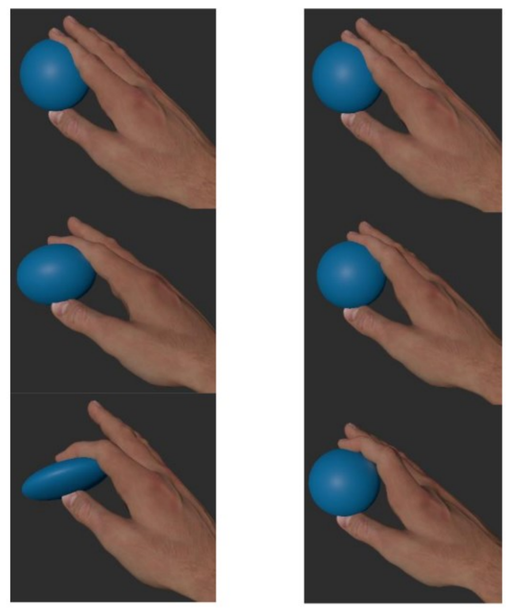


Figure 6. Displayed finger flexion vs. flexion sensor output



Object 1, 2, 3 and 4 | Object 5

Figure 7. Displayed finger

D. Graphics

Users see their own right hand holding a blue virtual ball in their sight that the HMD provides. The wrist posture and hand position of the displayed hand is determined from the actual hand captured by Leap Motion. The ball keeps located between their thumb and index finger as long as the hand is in the sight. Because users are supposed to hold the device with their thumb and index finger and actual finger flexion happens only with their index finger, only the index finger is visually bent according to the sensor voltage in the device. Actual flexion of the other fingers are not reflected on the displayed fingers that are fixed at the predetermined postures.

We prepared following 6 types of virtual objects in this system. First we set the standard object where the deformation of the re-rendered virtual fingers and the virtual object almost matches actual behavior (we refer to this as object 1). Next, we created objects with different deformation profiles, the one whose deformation enlarged in comparison with object 1 (we refer to this soft one as object 2), the one with extremely exaggerated deformation (we refer to this supersoft one as object 3), and the one alternately expand and shrink as the finger flexion goes deeper (we refer to this obviously unnatural one as object 4). We added this object 4 in expectation that it would be an exemplar of 'less effective cases' where the user feel a stronger sense of incongruity with it than with the other objects. We added two rigid objects: neither of them visually deforms. Their difference is that when holding one of them the finger is shown sliding on the surface of the ball (we refer to this as object 5) and when holding the other, finger keeps its initial posture (we refer to this one with no visual feedback as object 6). We expected that object 5 would be the most natural image of rigid-object pinching.

Figure 6 shows the flexion angle of the finger base from its straight position along the normalized sensor voltage with object 1,2,3,4 and 5. Each finger joint is bent with a linearly increasing flexion angle according to the base angle in case of object 1, 2, 3 and 4. The case of object 5 is different from deformable ones. The displayed finger slides on the undeformable object in proximal direction as the sensor bend goes deeper. Accordingly, the other joint angle is implemented in its inherent manner (Fig. 7).

III. Evaluation

We conducted a subjective experiment to evaluate how realistically the proposed system could display variable stiffness of virtual objects with a single device.

A. Participants

The experiment was conducted in cooperation with 10 participants (9 male, 1 female, aged 20's and 30's). Their academic backgrounds were different from ours and they were all naive participants without previous knowledge relating to our research. We got acknowledgement to the participants in advance by explaining about the content of trials and no compensation in this experiment.

B. Method

In the experiment, 6 types of virtual objects described above were presented to the participants. They were asked a common single question that "*Did you feel sense of incongruity between the behavior of your finger holding the displayed object in your sight and the stiffness you perceived?*" every time after they interact with the objects. We evaluated the quality of the visuo-haptic experience with Likert scale by asking them to respond to this question scoring in 7 levels from 1 (extremely feel) to 7 (Don't feel at all).

First, participants were told about the series of this experiment including tasks they perform, question and how to respond to the question. But participants weren't informed of the purpose of this experiment for excluding bias. Second, participants were asked to wear Oculus rift and grasp the haptic device. Then participants were asked to pinch the displayed virtual object of standard image (object 1) with the haptic device. Participants were told to remember the fidelity or incongruity they felt as the reference of score 7 to the question. This procedure is performed in order to standardize the subjective answers. Next participants were asked to pinch each type of 6 virtual objects in random order and orally score the incongruity they felt every time after pinching the displayed virtual object. Participants were asked to repeat this tasks 5 times, resulting in 30 trials in total.

C. Result

Figure 8 shows the scores obtained from all of the participants. The displayed score is averaged among 5 trials with every participant. It is obviously confirmed that object 6 is rated with the lowest score where no visual changes are displayed to users in response to the actual finger movement. The standard object is ranked highest while softer objects are evaluated to have less fidelity compared with that. The score difference between object 2 and 3 indicates that an extreme modification in deformation would yield a stronger sense of incongruity. Object 4 is also scored lower presumably because of its oscillatory reaction.

It should be stated that the overall score of object 5 is higher than object 3 and 4 in spite of no object deformation shown. Another tendency unique to the score of this object is that the largest individual difference is found. Almost half of them clearly felt the discrepancy (scored 3 or more) during their operation with the object 5, while the other half did not. In figure 9 we depict the scores of the 'more-sensitive' five participants and 'less-sensitive' five participants. The more-sensitive ones gave lower score among all kind of objects other than the object 5. The less-sensitive ones scored almost equally for object 2 and 5.

IV. Discussion

In this experiment, most of the participants felt strong sense of incongruity in object 3 and 6. It is supposedly because the behavior of these virtual objects was obviously different from the actual behavior of fingers. Though there are individual differences, the 'less-sensitive' participants felt the comparable level of fidelity with object 2 and 5. Thus, it is shown possible to display a certain stiffness of soft object and a rigid object with no deformation with the same mechanical device.

Another interesting result in the experiment is that the participants were separated in two groups in terms of the incongruence sensitivity. The most definitive difference among them appeared when they touch the rigid object.

It should be noted the Likert scale score is on the incongruity. The subject was asked if they found any unnaturalness in the experiences. At least for the authors, the displayed stiffness of object 2 and 5 was practically realistic and the finger flexion is naturally replaced with the visual flexion. Unclarified is what determines the threshold of the naturalness and the adaptation.

Some of the participants commented that as they got accustomed to the system they gradually lost confidence in their somatosensory cognition.

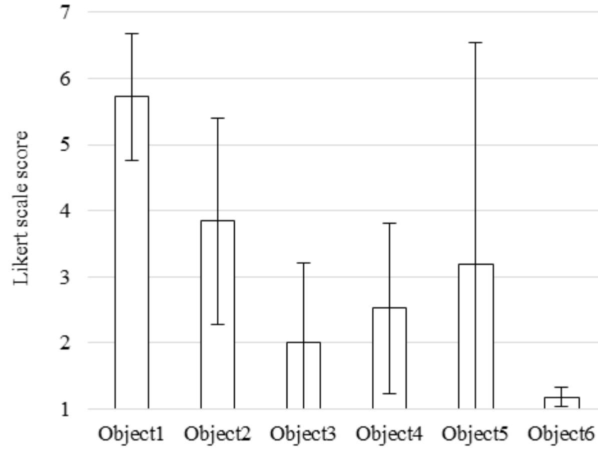


Figure 8. Experimental result

V. Conclusion

In this paper, we proposed an immersive visuo-haptic display system that allows users to interact with virtual objects of various stiffness with a compact setup. Based on the priority of visual information over proprioception, the system incorporated modified visual feedback showing users' own finger movement with a passive haptic device that presents a wide range of resilient force to users. We experimentally demonstrated that the system could offer visuo-haptic interaction with ball-shaped objects in various settings of virtual stiffness without any mechanical actuation. Although the experimental results indicated the existence of nonnegligible perceived discrepancy, the participants perceived both elastic objects and rigid ones using an identical passive device where there was no actual change in mechanical properties of the device.

Toward a more sophisticated version of the system, there are many possible improvements. While operating the current device, some people reported the need of paying attention not to drop it. Another pointed out the mismatch in contact regions with objects between visual (only fingertips are in contact) and actual haptic feedback (whole parts of the index finger and the thumb are in contact). Hence a refined mechanical design of the device that naturally fits users' hand and agrees more faithfully with visual feedback would be an adequate approach. Another possibility would be challenges in superimposing different kinds of physical property such as surface texture, shape, weight and so forth. We expect that there would be room for these because the proposed method is compatible with other tactile stimulation including vibration, electric stimulation or thermal sensations.

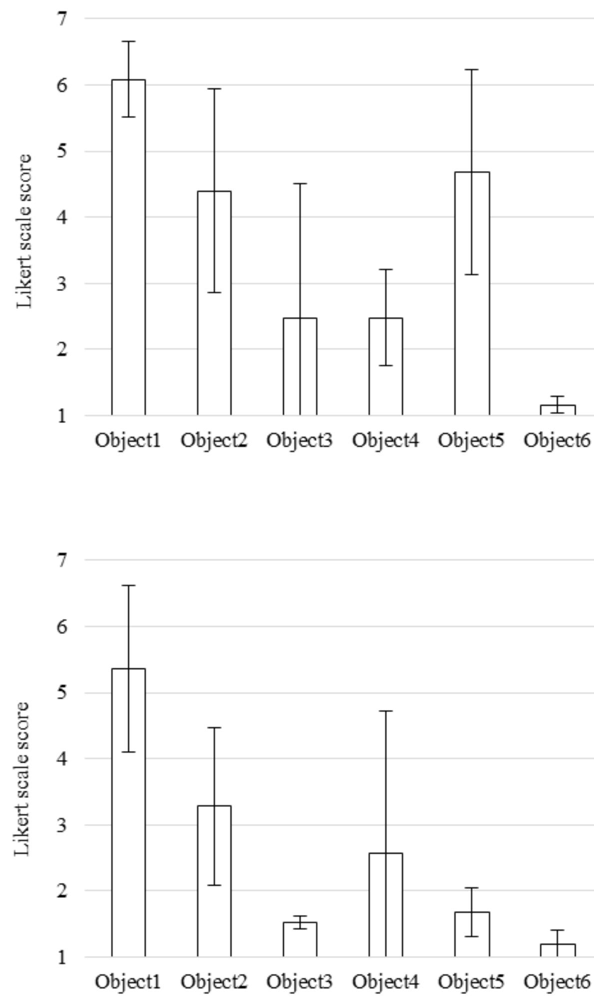


Figure 9. Experimental results of the two groups: 'less-sensitive' (upper) and 'more-sensitive' (lower) participants

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