Wearable Haptic Display to Present Gravity Sensation

Preliminary Observations and Device Design

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Abstract

We propose a wearable ungrounded haptic display that presents a realistic gravity sensation of a virtual object. We focused on the shearing stress on the fingerpads due to the weight of the object, and found that the deformation of the fingerpads can generate a reliable gravity sensation even when proprioceptive sensation on the wrist or arm is absent. This implies that an ungrounded gravity display can be realized by reproducing fingerpad deformation. Based on our observations, we conducted evaluation tests for the device design. We first implemented the prototype device, which has a simple structure comprising dual motors, and then evaluated the recognition ability of the gravity sensation presented on the operator's finger by this method.

1. Introduction

The human hand can perceive the shape and gravity of an object that it grasps. In haptic display design, the discernment of the shape and gravity of an object is considered to be beneficial from the viewpoints of both safety and operability in teleoperation task. However, most conventional haptic displays [1]–[3] are designed to present only the grip forces acting on the fingertips. In some master cockpit systems [4], the gravity is presented to the operator's wrist by a multi-DOF grounded force display. Although the resulting system is large and complex, the presented gravity sensation is not very similar to actual sensation, since the stimulus points in these methods are different from the actual contact surface between the object and the finger. In a grasping task, the gravity of an object is perceived by the proprioceptive sensation on the arm, the wrist and the finger, and the tactile sensation on the fingerpads.

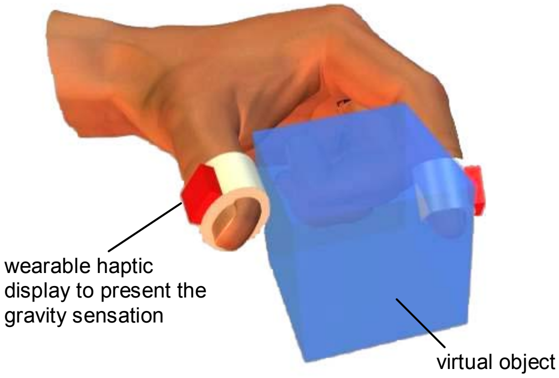

Fig. 1: Conceptual drawing of a wearable haptic display to present the gravity sensation. The weight of the virtual object is presented on the fingerpad of the operator.

In some researches, the slippage between the fingertips and the object has been focused on as a parameter for weight sensation. Johansson [5] showed that partial slippage plays an important role in object grasping, and Maeno [6] showed a method for controlling the grip force by detecting the stick/slip distribution on the fingerpad. Other researches present different perspectives. Inaba [7] showed that simple constrictive pressures on the fingers replicate the grip sensation. Yao [8] showed that the dynamics of a rolling object can be displayed by presenting only the rolling noise and impact. These researches indicate that the dynamics of an object can be presented in a simple manner by reproducing the elements of motion.

We aimed to develop a haptic display that can present the gravity of objects (Fig. 1). To simplify the mechanism, we focused on the shearing stress on the fingerpads caused by the weight of an object.

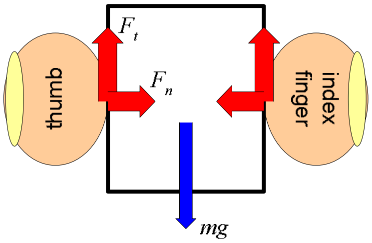

Fig. 2: Vertical stress (F_n) and shearing stress (F_t) between finger and object in grasping. In this figure, F_n is the grip force and F_t is the gravity of the object.

As shown by Forssberg [9] it is considered that gravity sensation is perceived as an integration of proprioceptive and tactile sensations. However, how would gravity sensation be perceived when only the tactile sensation is presented and the proprioceptive sensation is not? The forces that are perceived on the fingerpads can be categorized into vertical and shearing stresses. In Figure 2, for example, it is assumed that the vertical stress (F_n) is the grip force on the hand and the shearing stress (F_t) is the gravity of an object. We observed that a realistic gravity sensation of an object can be presented, even when the proprioceptive sensation on the wrist or arm is absent, by reproducing these stresses on the fingerpads, which are the interfaces between the human and the object. This in turn implies that an ungrounded device can be realized.

In this paper, we propose a wearable ungrounded haptic display to present the gravity sensation of a virtual object. We conducted experiments to study the device design. Further, we also studied the human weight discrimination ability on fingerpad without proprioception, and evaluated the reproducibility of the gravity sensation by the shearing stress in order to substantiate our proposal. We will design and implement the prototype system based on the results of the experiments.

2. Experiments to Evaluate Device Design

2.1. Weight discrimination ability on fingerpad without proprioception

In order to evaluate the limitation of our proposed method, we measured the difference limen in weight detection on the fingerpads without proprioceptive sensation. This experiment was performed under two conditions (with and without proprioception). In the with-proprioception session, the subjects set their forearm on an armrest while their wrist was free. The subjects could perceive the proprioceptive sensation on their wrist and fingers. In the without-proprioception session, the subjects' wrists and the sides of their thumbs and index fingers were fixed, as shown in Figure 3, in order to ensure that they perceived the gravity of an object only by the tactile sensation on the fingerpads. Four blindfolded subjects, aged 21 to 31 years, participated in these experiments.

Fig. 3: Experimental setup for with-proprioception sessions.

The procedure for this experiment was the constant method. The subjects were first asked to grasp one of the standard objects (50, 100, 200 gf) for 2 sec as a standard stimulus. After a 2-sec interval, the subjects grasped a test object for 2 sec as a comparison stimulus. And more than 5-sec interval was given between each trial. The subjects then stated whether the test object was “heavy”, “similar” or “light” in comparison to the standard object, according to a three-alternative forced-choice procedure. Each experimental session comprised four series of trials for each standard stimulus. Two sessions were performed for each condition and an interval of more than 3 min was provided between each session.

Figure 4 shows the average rate of “heavy” responses obtained in trials where the standard stimuli were 100 g. The blue circles (with proprioception) and red triangles (without proprioception) represent the average of each of 16 trials for all subjects in two conditions. A blue line and dotted red line indicate the fitted line with cumulative normal distribution. The 75 percent difference limen (75 % DL) was derived from the difference between PSE and the 75 percent discrimination threshold. Table 1 shows the 75 % DL for each standard stimulus in two conditions of with/ without proprioception. According to this result, it is confirmed that the tactile sensation on fingerpads provides certain perception to discriminate the weight without proprioceptive sensation.

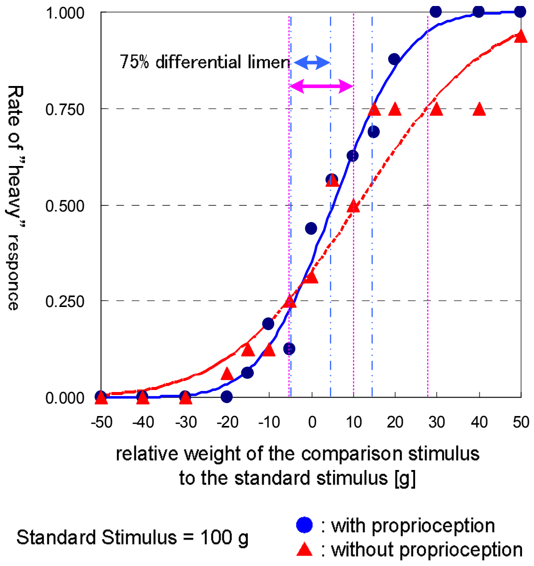

Fig. 4: Average rate of "heavy" response for a 100-g standard stimulus. The blue dash lines and pink dotted lines indicate the PSE and the 75 % correct lines in with and without proprioception.

Table 1: 75% difference limen for three kind of standard stimulus with / without the proprioceptive sensation on wrist and fingers

standard stimulus	75 % DL with prop.	75 % DL without prop.
50 gf	8.1 gf	9.3 gf
100 gf	9.3 gf	16.5 gf
200 gf	13.9 gf	23.6 gf

2.2. Virtual weight using a grounded setup

In this experiment, we evaluated the reproducibility of the gravity sensation by the shearing stress on the fingerpads. A grounded experimental setup was used so as to inhibit the effect of ungrounded condition.

To reproduce the deformation pattern generated by the weight of an object, we used the experimental setup shown in Figure 5. The experimental devices were attached to the subject's fingers, as shown in Figure 6. The subjects were asked to grasp test objects of predetermined weights with the naked index finger and thumb of their left hand. On their right hand, a pair of experimental devices was attached and the shearing stress was generated by belts that were connected to two motors. The subjects were asked to adjust the torque strength exerted by the motors in order to perceive the weight of the test object; the virtual gravity was observed to be the same. The result is shown in Figure 7.

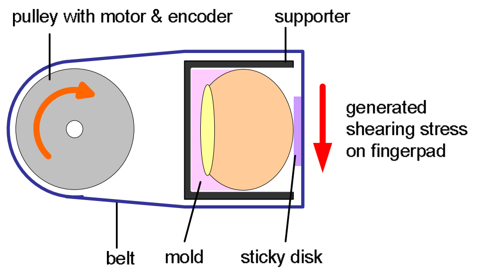

Fig. 5: Schematic representation of the experimental device to generate shearing stress on the fingerpad. The setup comprises a belt, a motor with an encoder (Maxon Motor Corp., RE25, 20 W, gear ratio = 18:1), and a supporting frame to limit the motion direction of the belt to generate the correct shearing stress. A sticky disk is placed between the fingerpad and the belt to inhibit slippage.

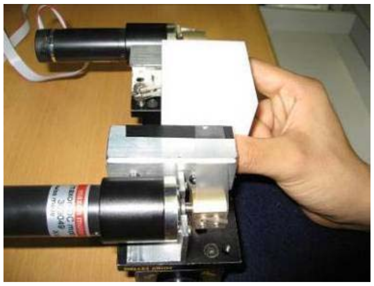

Fig. 6: Displaying gravity sensation to the index finger and the thumb using a pair of experimental devices (described in Fig. 6). The dorsal sides of the fingers are fixed by molds so that they do not move. A styrofoam cube (2 g, 5 cm on one side) is grasped to fix the position of the fingers.

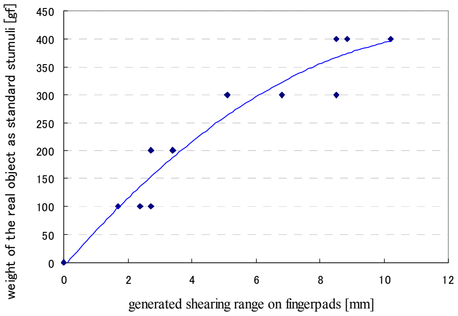

Fig. 7: Results of the experiment to present gravity sensation on the fingerpad using a grounded setup shown in figure 6. The blue line is the least-squares-estimated curve.

2.3. Reflexive response to virtual weight

In this experiment, we confirmed the reality of the presented gravity sensation. We examined the reflexive response of the gripping force in a situation where the weight of the object suddenly increases. If no significant difference is observed between the result of the reflexive response to increments in the real weight and the virtual weight, the gravity sensation presented by our proposed method can be described as essentially similar to the actual gravity sensation.

First, the subjects were asked to grasp a test object whose weight was counterbalanced. The counterbalance was then suddenly removed and the subjects perceived a sudden increase in real weight. The reflexive change in the grip force was measured by two force sensors (Nitta Corp., FlexiForce A201) placed on the padding surface of the index finger and thumb. Second, when the subjects were wearing the experimental devices shown in Figure 5, a certain shearing stress was suddenly produced. The magnitude of this shearing stress was determined so as to present the same gravity sensation as that of the test object according to the least-squares-estimated curve shown in Figure 7.

Figure 8 shows the result for a case where the weight of the test object is 300 gf. On comparing the two graphs in this figure, we observe that the increments in the grip force in both cases are 80 gf and they change in 0.4 s. Figure 9 shows the grip force increments in the reflective responses using test objects of various weights. This result shows that the reflexive responses to the virtual and real weights exhibit the same tendency.

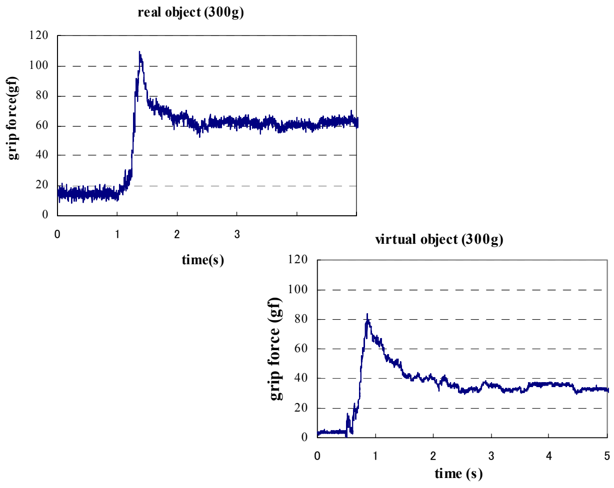

Fig. 8: The grip force rates in the reflective responses to the real weight (top) and the virtual gravity presented by the device (bottom).

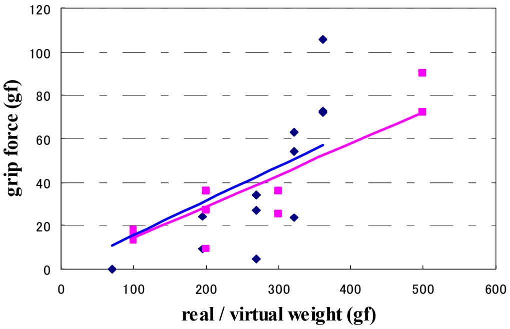

Fig. 9: Increment of grip force in reflexive responses by various changes in real (red squares) and virtual (blue circles) gravity.

2.4. Summary of the experiments

Table 1 shows that the tactile sensation on fingerpad is sufficient to allow people to perceive the gravity sensation even when the proprioceptive sensation is absent, although the discrimination threshold is inferior to integration of tactile and proprioceptive sensation. In Figure 7, we determined the relation between the gravity sensation and the fingerpad deformation due to the shearing stress. The result shown in Figure 9 further supports the assumption that the gravity sensation presented by our proposed method is essentially the same as the weight of a real object, though the resolution is inferior. These results indicate that the gravity sensation can be presented with the shearing stress on fingerpad without the proprioceptive sensation. In the following section, we will describe the prototype device design, which is based on these observations.

3. Prototype Device

3.1. Design of the prototype device

We modified the mechanism proposed by us as a haptic display for the middle phalanx using dual motors in [10], and designed the prototype device shown in Figure 11; this device has a simple construction and a small size. To present the grip sensation, the dual motors are driven in opposite directions of rotation so that they roll up the belt. A vertical stress is then generated on the fingerpad of the operator. On the other hand, to present the gravity sensation, the motors are driven in the same direction of rotation. In the figure on the right in Figure 10, for example, the belt is rolled up on the left side and rolled out on the right side. The shearing stress is then generated form right to left on the fingerpad. We implemented the prototype device shown in Figure 12.

The device comprises a belt (width = 20 mm), a pair of motors (Maxon Motor Corp., RE 10, 1.5 W, $\phi = 10$ mm, gear ratio = 1:16) and brass shafts ($\phi = 6$ mm), and a body made of ABS resin. The body functions to guide the belt so as to provide a good tangential force on the fingerpad. The device is fixed on the middle phalanx of the finger by a Velcro strap. The bottom surface of the device is flushed with the dorsal side of the finger by a mold so that the reactive force from the body of the device is widely distributed and barely perceptible.

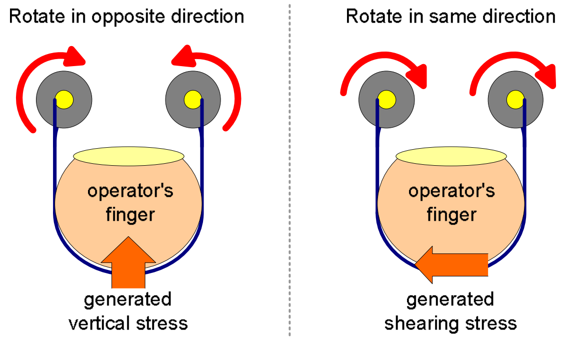

Fig. 10: A method for generating vertical stress (left) and shearing stress (right)

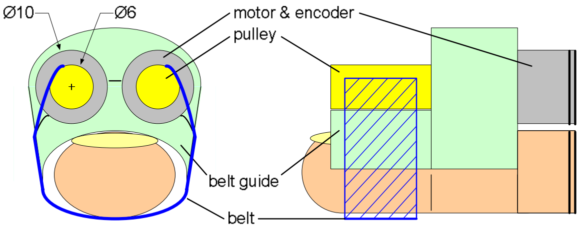

Fig. 11: Conceptual drawing of the prototype device

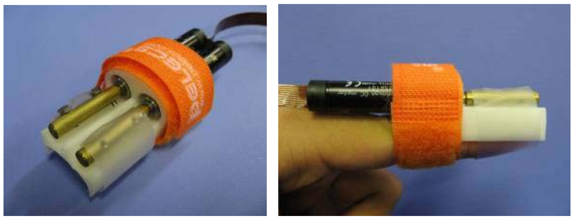

Fig. 12: Implemented prototype device

3.2. Evaluation of the prototype device

We evaluated the recognition ability of the virtual weight presented by the prototype devices in a static grasping situation. The subjects fixed their arm on an armrest, attached the prototype devices on their index finger and thumb, and grasped a light-weight styrofoam cube (2 g, 5 cm on a side) to fix the position of their fingers, as shown in Figure 13. The gravity sensation was then presented as a shearing stress on the index finger and the thumb simultaneously with the same power for 2 sec. The subjects stated how much they perceived the weight of the object to be in comparison to various weights of real objects with a similar appearance. Figure 14 shows the result that the perceived virtual weight has good linearity with the generated shearing stress.

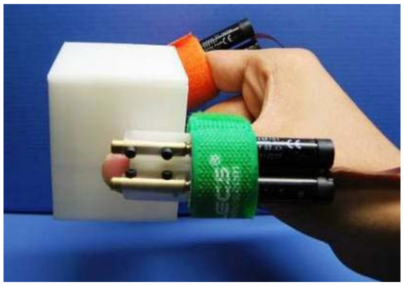

Fig. 13: Displaying augmented weight on a light-weight styrofoam cube.

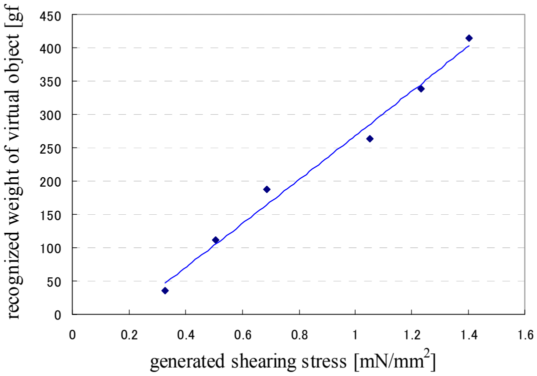

Fig. 14: Perceiving virtual weight in static grasping. The shearing stress is theoretically calculated from the applied current values, motor specifications, and device structures.

4. Discussion

In order to present virtual gravity sensation in a virtual reality or teleoperation system, our proposed method should be extended to present the mass sensation of a virtual object during active movement. In situations where the operator moves his/her hand actively and the object is set in motion, the force should be presented according to its acceleration. We briefly tested the recognition of a virtual weight during some operations such as shaking and rotating as shown in Figure 15: we have not, however, conducted quantitative evaluations thus far. During rotation, for example, the weight of a virtual object is presented evenly on the index finger and the thumb, a as shown in Figure 15 (c). As the object is rotated position (d), disproportionate weight ins perceived on the index finger. Then, at position (e), the weight is presented evenly once again. However, the stress direction is opposite to that in (c). In these cases, the perception of gravity sensation was clearer than that in static grasping described in section 3.2. The operator could perceive certain weights such as 50 g or 100 g from a light-weight styrofoam cube according to the change in the vertical and shearing stresses generated by the devices, although the actual weight of the cube was just 2 g. According to these observations, it is considered that our proposed method is applicable for presenting not only static gravity but also the inertia of a virtual object in active motion.

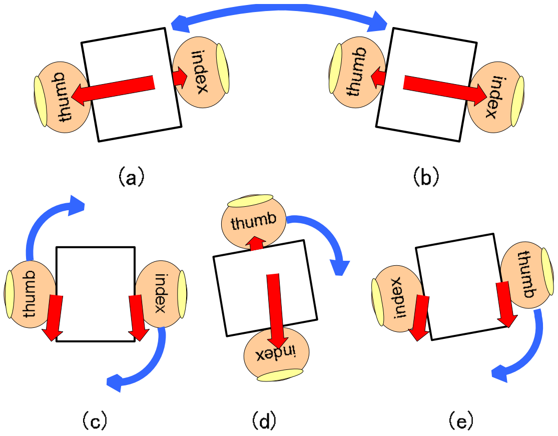

Fig. 15: Change in the force directions in grasping during shaking from (a) to (b) and rotation from (c) to (e). Blue arrows indicate the direction of motion and the red arrows indicate the combined force vectors —grip force, the gravity, and the inertia— which should be reproduced.

5. Conclusions

In this paper, we focused on the shearing stress on the fingerpads during grasping and proposed a wearable ungrounded haptic display to present the gravity sensation of a virtual object. To validate the possible realization of our proposed method, we measured the difference limen for weight detection on the fingerpads without proprioceptive sensation. The relation between the gravity sensation and the shearing stress was evaluated to design the prototype device. We then implemented the prototype devices and confirmed that the presented virtual weight has good linearity with the generated shearing stress.

This paper presented the evaluation of the prototype only in a static grasping situation. In our next study, we will evaluate whether our proposed method is applicable to only the gravity sensation in static grasping or to the sensation of inertial force in active motion as well. In addition, we need to study the relativity between tactile sensation and proprioceptive sensation in perceiving gravity in order to investigate the possibility of realizing our proposed haptic display.

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