Gravity Grabber: Wearable Haptic Display to present Virtual Mass Sensation

Kouta Minamizawa[*1]
The University of Tokyo

Souichiro Fukamachi[*2]
The University of Tokyo

Hiroyuki Kajimoto[*3]
The University of Electro-Communications

Naoki Kawakami[*4]
The University of Tokyo

Susumu Tachi[*5]
The University of Tokyo

Executive Summary

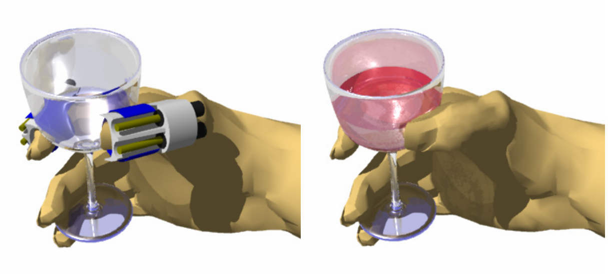
We propose a wearable haptic display to present the weight sensation of a virtual object, which is based on our novel insight that the deformation on fingerpads makes a reliable weight sensation even when the proprioceptive sensation is absent. This device will provide a new form of ubiquitous haptic interaction.

1. Project Overview

In recent times, there have been a number of computer user interface devices that have some haptic feedback functions, such as the DUALSHOCK controller [Sony Computer Entertainment, Inc. 1997] or the Wii Remote [Nintendo Co., Ltd. 2006]. However, their haptic feedback is limited to only the vibration function since there is no other method to provide haptic feedback that can be implemented with a small and inexpensive device. However, there is an increasing demand for realistic haptic feedback; thus, a simple and inexpensive method for a highly realistic haptic display is required. To meet this requirement, we focused on the mass of a virtual object, which contributes to the weight and the inertia mass in haptic interaction. If the virtual mass is presented by a haptic device, the user can perceive a more realistic sensation of the virtual object by grasping than the vibration feedback.

We propose a wearable haptic display to present the mass of a virtual object as shown in Figure 1. In our previous researches [Minamizawa et al., 2006; Minamizawa et al., 2007], we investigated the possibility of realizing a simple haptic display on the basis of finger deformation. Conventionally, it is believed that it is necessary to reproduce the proprioceptive sensation in order to present a weight sensation and thus a large grounded device is required. However, we found that the deformation of the fingerpads due to the weight of an object can generate a reliable weight sensation even when the proprioceptive sensations on the wrist and arm are absent. This implies that a simple ungrounded display for presenting the virtual mass can be realized by reproducing the fingerpad deformation. Based on our observations, we designed the mechanism of the haptic display as shown in Figure 2, which has a simple structure comprising dual motors.

We implemented the prototype device shown in Figure 3 and then confirmed the recognition ability of the weight sensation presented on the user's finger by this method.



Real world:
holding a empty glass with
wearing our proposed devices

Virtual world:
the user can perceive
the weight of the virtual water

Figure 1: *Conceptual representation of our proposed device. By wearing our proposed devices on the index finger and the thumb, the user can feel the augmented weight and inertia of the water that is virtually filled in the actually empty glass.*

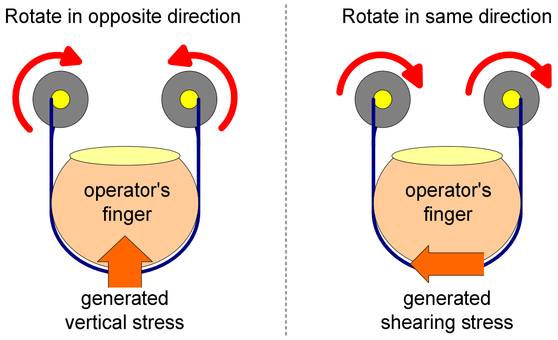


Figure 2: *Our proposed method for generating vertical stress (left) and shearing stress (right).*

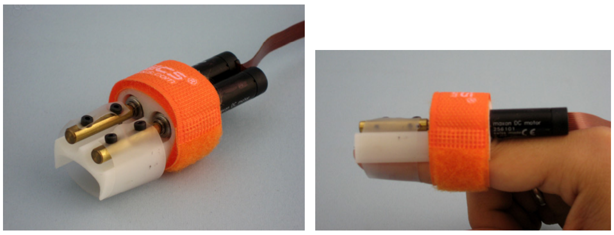


Figure 3: *Implemented prototype device.*

[*1] e-mail: kouta_minamizawa@ipc.i.u-tokyo.ac.jp
[*2] e-mail: souichiro_fukamachi@ipc.i.u-tokyo.ac.jp
[*3] e-mail: kajimoto@hc.uec.ac.jp
[*4] e-mail: kawakami@star.t.u-tokyo.ac.jp
[*5] e-mail: tachi@star.t.u-tokyo.ac.jp

By wearing our proposed devices on the index finger and the thumb, the user can perceive the grip force and the mass of a virtual object. In Figure 4, for example, the grip force, gravity, and inertia mass of a virtual object are presented on the user's fingerpads during shaking and rotational motion.

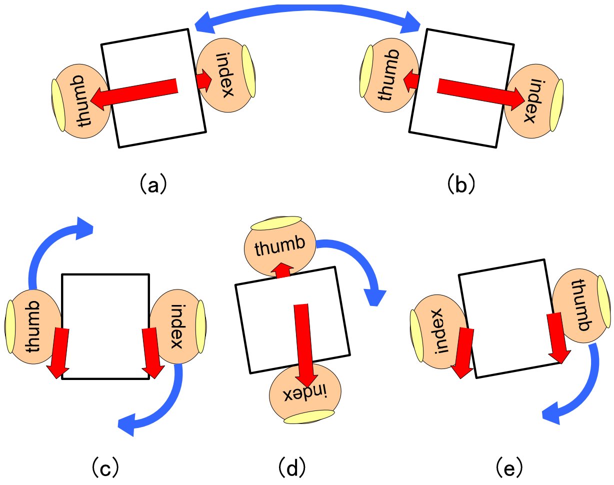


Figure 4: *Displayed force directions while grasping: shaking from (a) to (b) and rotation from (c) to (e). The blue arrows indicate the direction of motion and the red arrows indicate the combined force vectors—grip force, gravity, and inertia— that should be reproduced.*

2. Context and Vision

The ultimate goal of our project is to introduce high realistic haptic interactions in our daily life.

Grasping is the most important function of the human hand. There are several haptic displays to present grasping sensations. Conventional haptic displays [Immersion Co., Ltd., 2000; Nakagawara et al., 2003] have been designed to correctly reproduce the physical phenomenon on the interface between fingertips and an object while grasping. It induces a highly realistic sensation, but it tends to require a complex and expensive mechanism; therefore, these haptic devices are used only in a few professional fields such as 3D-CAD designing, surgical operations, and education in schools. In some master cockpit systems [Tachi et al., 2003], 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 the actual sensation since the stimulus points in these methods are different from the actual contact surface between the object and the finger.

On the other hand, there has been an increasing number of researches from other perspectives in recent times. These researches aim to achieve the practical use of human perceptual characteristics and perceptual illusions in the design of haptic devices. Some researches have focused on the slippage between the fingertips and the object as a parameter for weight sensation. Johansson and Westling [1984] showed that partial slippage plays an important role in grasping an object, and Maeno et al. [2000] showed a method for controlling the grip force by detecting the stick-slip distribution on the fingerpad. Inaba and Fujita [2006] showed that simple constrictive pressures on the fingers replicate the grip sensation. Yao and Hayward [2006] 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.

In our proposed method, we considered the human perceptual characteristics that the weight perception is effected by the fingerpad deformation and then designed a simple mechanism for a haptic display. This method can provide sufficient high-definition haptic sensations (grip force, weight, and inertia) from a virtual object so that the user can have a highly realistic perception of the virtual object. In addition, it is easy to put on and take off this device.

In our proposed haptic display, the grasping experience of a virtual object is more realistic than the conventional vibration function. In the near future, this device can be downsized and unwired according to the evolution of motors and batteries. The device can then be used in daily life, for example, as a grasping controller in entertainment systems or as a force-feedback device for operating a virtual reality environment in a computer. This device can be used in combination with the contemporary mouse-based user interfaces, since it is small enough to be used with a mouse while the device is worn on the operator's fingers. This device also realizes a ubiquitous teleoperation, since the wearable and wireless device can be used to manipulate a robot from any location. In this project, we will provide alternative experiences of ubiquitous haptic interactions and telecommunications.

3. Principle and Device Design

We introduce mainly two technical innovations in this project. Firstly, we find that the deformation at the fingertips leads to weight perception even without the proprioceptive sensations on the arm and wrist. This enables the realization of a simple wearable haptic display for virtual weight. Secondly, we designed a mechanism to reproduce the fingerpad deformation using a simple method that employs a pair of motors and a belt. We describe the abovementioned in detail in the subsequent sections.

3.1. Weight discrimination ability on a fingerpad without the proprioception

Weight sensation is perceived as the integration of the proprioceptive sensation on the arm and the tactile sensation on fingerpad. Most conventional haptic displays for presenting virtual weight are designed to reproduce the proprioceptive sensation, due to which heavy grounded devices are required. However, how can weight sensation be perceived when only the tactile sensation is presented and the proprioception is not?

The forces that are perceived on the fingerpads can be categorized into vertical and shearing stresses. In Figure 5, 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 equal to the gravitational force acting on the object. We observed that the realistic gravity sensation of an object can be presented, even when the proprioceptive sensation on the wrist or arm is absent. This can be done by reproducing these stresses on the fingerpads, which are the interfaces between the user and the object. This in turn implies that an ungrounded device can be realized.

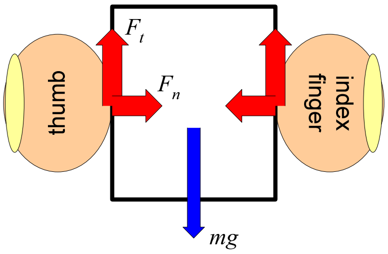


Figure 5: *Vertical stress (F_n) and shearing stress (F_t) between the finger and object while grasping. F_n is the grip force and F_t is equal to the gravitational force acting on the object.*

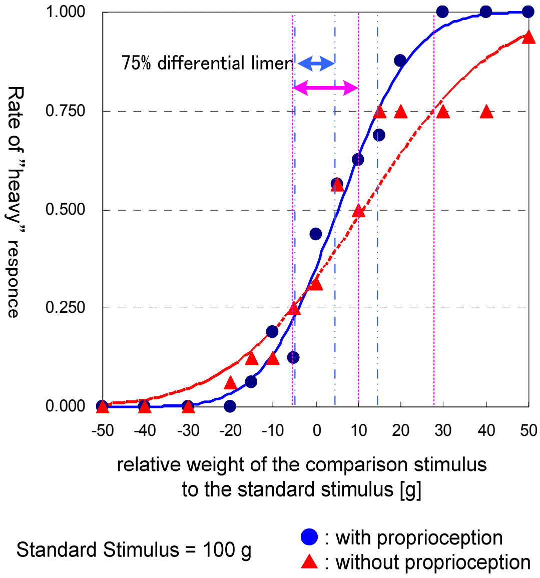


Figure 6: *Average rate of "heavy" response for a 100-g standard stimulus. The blue dashed lines and pink dotted lines indicate the PSE and the 75 % correct lines in the with- and without-proprioception sessions.*

Table 1: *75% DL for three kinds of standard stimulus with/without the proprioceptive sensation.*

Standard stimulus	75% DL with proprioception	75% DL without proprioception
50 gf	8.1 gf	9.3 gf
100 gf	9.3 gf	16.5 gf
200 gf	13.9 gf	23.6 gf

In order to evaluate the limitation of our proposed method, we measured the difference limen (DL) of the weight detection on the fingerpads without any 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 in order to ensure that they perceived the gravity of an object only by the tactile sensation on the fingerpads. The constant method was used for this experiment. The subjects stated whether the test object was "heavy," "similar," or "light" in comparison to the standard object, according to a three-alternative forced-choice procedure. Figure 6 shows the average rate of "heavy" responses obtained in the trials in which the standard stimuli were 100 g. Table 1 shows the 75 % DL for each standard stimulus under two conditions. According to these results, it is confirmed that the tactile sensation on the fingerpads provides certain perception to discriminate the weight without proprioceptive sensation.

3.2. Design of the prototype device using dual motors

On the basis of the observation described in section 3.1, we designed the mechanism shown in Figure 2; 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. , For example, in Figure 2, the belt in the figure on the right 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 7. The device comprises a belt (width = 20 mm), a pair of motors (Maxon Motor Corp., RE 10, 1.5 W, ϕ =. 10 mm, gear ratio = 1:16), brass shafts (ϕ =. 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. This 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.

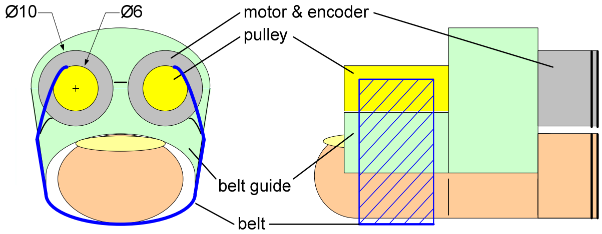


Figure 7: *Detail drawing of the prototype device.*

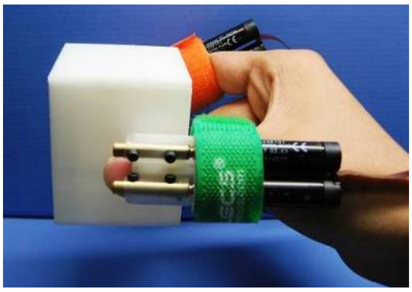


Figure 8: *Displaying augmented weight on a light-weight cube.*

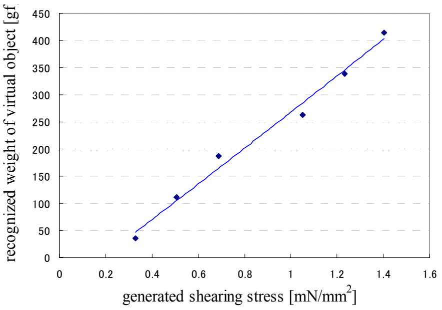


Figure 9: *Perceiving virtual weight in static grasping. The shearing stress is theoretically calculated from the applied current values, motor specifications, and device structures.*

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 side length) to fix the position of their fingers, as shown in Figure 8. The gravity sensation was then presented as a shearing stress on the index finger and the thumb simultaneously. 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 9 shows the result that the perceived virtual weight has good linearity with the generated shearing stress.

4. User Experiences

In SIGGRAPH 2007 Emerging Technologies, we will provide two kinds of the experience of “Gravity Grabbing”. First is to operate a virtual reality environment with the augmented mass sensations by our proposed devices. As shown in Figure 1, for example, the participant can perceive the ruffle of the water in a glass although he/she actually has an empty glass. Second is a videogame-based entertainment system with the haptic interaction of the virtual mass.

5. Conclusion

We found that the vertical and sharing stresses on the fingerpads due to the weight of the object can generate a reliable weight sensation even when the proprioceptive sensation on the wrist or arm is absent. On the basis of this observation, we designed a wearable ungrounded haptic display to present the gravity sensation of a virtual object using dual motors and a belt.

This method is simple and it can be introduced in daily-life. We then implemented the prototype devices and confirmed that virtual mass sensations can be presented with good linearity. By wearing our proposed devices on the index finger and the thumb, a user can perceive the grip force, gravity, and inertia of a virtual object.

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