A Wearable Haptic Display to Present the Gravity Sensation

- Preliminary Observations and Device Design -

Kouta Minamizawa*, Hiroyuki Kajimoto†, Naoki Kawakami*, Susumu Tachi*

(*) The University of Tokyo, Japan
(†) The University of Electro-Communications, Japan
E-mail: kouta_minamizawa@ipc.i.u-tokyo.ac.jp, kajimoto@hc.uec.ac.jp,
kawakami@star.t.u-tokyo.ac.jp, tachi@star.t.u-tokyo.ac.jp

Abstract

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

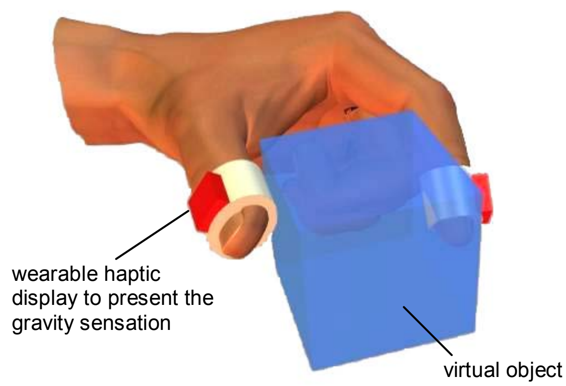

Fig. 1: Conceptual drawing of a wearable haptic display to present the gravity sensation. The weight of the virtual object is presented on the fingerpad of the operator.

1. Introduction

Human hand can perceive the shape and the gravity of an object when grasping the object. In designing haptic displays, it is supposed to be useful both for safety and operability of tele-operation tasks to indicate the gravity of the object as well as the shape. However, most of conventional haptic displays [1]–[3] are designed to present only the grip forces on the fingertips. In some master cockpit system [4], the gravity is presented to the operator's wrist by a multi-degree-of-freedom grounded force display. Although the resulting system is huge 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 of the object and the finger. In a grasping task, the gravity of an object is perceived with the proprioceptive sensation on the arm and the finger, and the tactile sensation on the fingerpads.

In some researches, slippage between the fingertips and the object has been focused as weight sensors. Johansson [5] showed that partial slippage has an important role for grasping the object, and Maeno [6] showed a method for control the grip force by detecting stick/slip distribution on fingerpad. Other researches have different perspectives. Inaba [7] showed that simple constrictive pressures on fingers make 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 imply that it is possible to display the dynamics of an object in simple way of reproducing the elements of the 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 that caused by the weight of an object.

Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)
0-7695-2738-8/07 $20.00 © 2007 **IEEE**

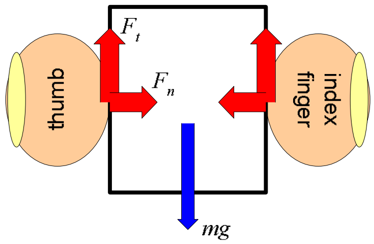

Fig. 2: Vertical stress (F_n) and shearing stress (F_t) between finger and object in grasping. In this figure, F_n implies the grip force and F_t implies the gravity of the object.

As Forssberg [9] showed, it is considered that gravity sensation is perceived as integration of proprioceptive and tactile sensations. However, how the gravity sensation is perceived when the tactile sensation is only presented and the proprioceptive sensation is absent? The forces that are perceived on the fingerpads of the hand can be categorized in vertical stress and shearing stress. In Figure 2, for example, it is supposed that the vertical stress (F_n) implies the grip force of the hand and the shearing stress (F_t) implies the gravity of an 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, by reproducing these stresses on the fingerpads which are the interfaces between the human and the object. This implies that a non-grounded device is available.

In this paper, we propose a wearable, ungrounded haptic display to present the gravity sensation of a virtual object. We conducted the experiments for device design. Human weight discrimination ability on fingerpad without proprioception and the reproducibility of gravity sensation by shearing stress were evaluated so as to substantiate our proposal. Based on the result of the experiments, we will design and implement the prototype system.

2. Experiments for Device Design

2.1. Weight discrimination ability on fingerpad without proprioception

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

Fig. 3: Experimental setup for with-proprioception experiments

The procedure for this experiment was the constant method. The subjects were firstly asked to grasp one of the standard objects (50, 100, 200 g) for 2 sec as standard stimulus. After a 2 sec interval phase, the subjects grasped a test object for 2 sec as a comparison stimulus. And more than 5 sec interval time was given between each trial. The subjects then answered whether the test object was "heavy", "similar" or "light" compared to the standard object in three-alternative-forced-choice procedure. One session of the experiments consisted of four series of trials for each standard stimulus. Four sessions were performed for each subject (two sessions for each condition) and more than 3 minute's interval time was given between each session.

Figure 4 shows the average rate of "heavy" responses obtained in the 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 makes certain perception to discriminate the weight without proprioceptive sensation.

Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)
0-7695-2738-8/07 $20.00 © 2007 IEEE

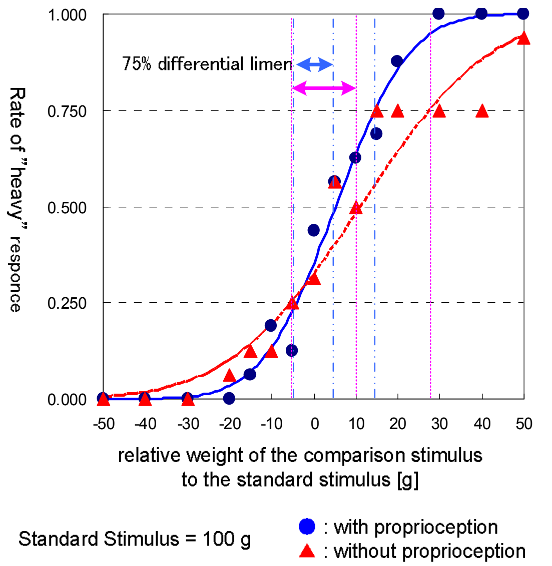

Fig. 4: Average rate of "heavy" response for the 100 g standard stimulus and the 75 % DL

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 g	8.1 g	9.3 g
100 g	9.3 g	16.5 g
200 g	13.9 g	23.6 g

2.2. Virtual weight using a grounded setup

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

To reproduce the deformation pattern caused 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 the 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 and the virtual gravity was founded to be the same. The result is shown in Figure 7.

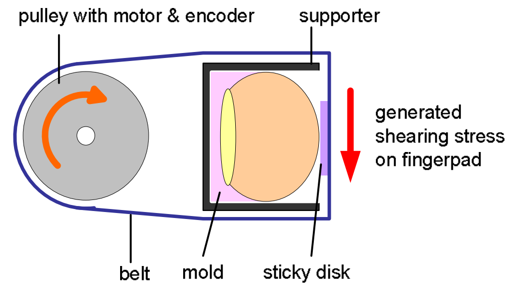

Fig. 5: Schematic representation of the experimental device to generate the shearing stress on the fingerpad. The setup comprises a belt, a motor with an encoder (Maxon Motor Corp., RE25, 20 W, gear ratio = 18:1), and a supporting frame to limit the motion direction of the belt to generate the correct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

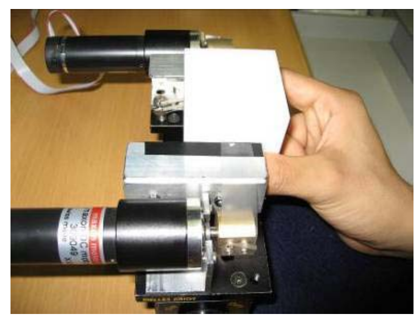

Fig. 6: Displaying gravity sensation to the index finger and the thumb using a pair of experimental devices (described in Fig. 6). The dorsal sides of the fingers are fixed by molds so that they do not move. A styrofoam cube (2g / 5cm on a side) is grasped to fix the position of the fingers.

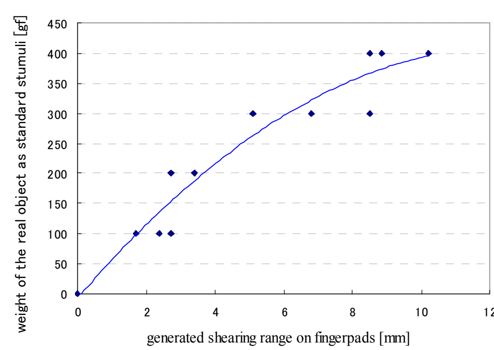

Fig. 7: Results of the experiment to present gravity sensation on fingerpad by grounded setup (Fig. 4). The line is the least-squares estimated curve.

Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)
0-7695-2738-8/07 $20.00 © 2007 IEEE

2.3. Reflexive response to virtual weight

In this experiment, we will confirm 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 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 felt a sudden increase in real weight. The reflexive change in the grip force was measured by two force sensors (Nitta Corp., Flexi Force 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 in Figure 7.

Figure 8 shows the result for a case where the weight of the test-object is 300 gf. Comparing two graphs in this figure, we observed that the increments in the grip force in both cases are 80 gf and changed in 0.4 sec. Figure 9 shows the grip force increments in the reflective responses using test objects of various weights. This result shows that the reflexive response to the virtual weight exhibits the same tendency as the reflexive response to the real weight.

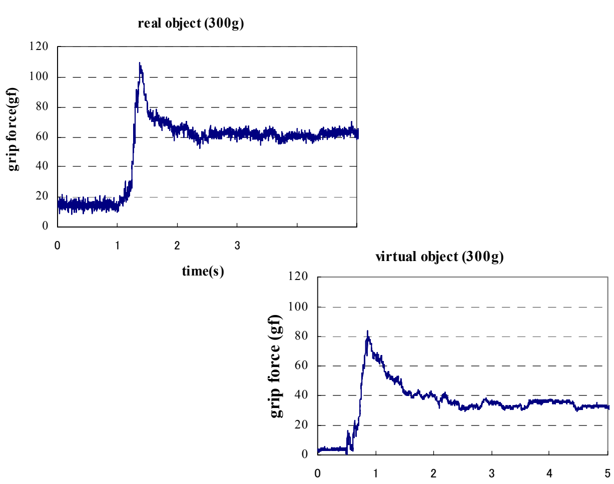

Fig. 8: The grip force rate during the experiment of displaying sudden change of the virtual gravity presented by the experimental devices.

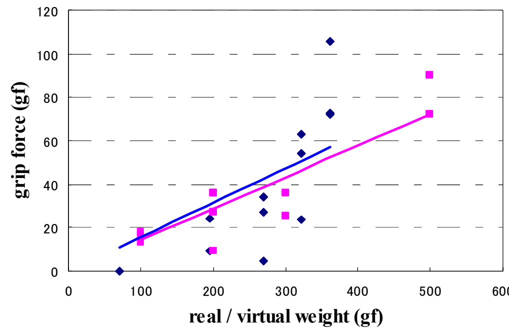

Fig. 9: Increment of grip force in reflexive responses by various change portions of real (red dots) and virtual (blue dots) gravity.

2.4. Summary of the experiments

Table 1 showed 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 deformation of fingerpads due to the shearing stress. The result in figure 9 further supports that the gravity sensation by 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 shearing stress on fingerpad without proprioceptive sensation. In the following section, we will design the prototype device based on these observations.

3. Prototype Device

3.1. Design of the prototype device

We modified the mechanism that we proposed as a haptic display for middle phalanx using dual motors in [10], and designed the prototype device shown in Figure 11, which has simple construction and small size. To present the grip sensation, the dual motors are driven in opposite direction of rotation to roll up the belt, and then vertical stress is generated on the fingerpad of the operator. In other hand, to present the gravity sensation, the motors are driven in same direction of rotation. In the right figure at Fig. 10, for example, the belt is rolled up at left side and rolled out at the right side, then the shearing stress, form right to left, is generated on the fingerpad. We implemented the prototype device shown in figure 12. The device consists of a belt (width = 20mm), a pair of motors (Maxon Motor Corp., RE10, 1.5W, $\phi = 10$

Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)
0-7695-2738-8/07 $20.00 © 2007 IEEE

mm, gear ratio = 1:16) and brass shafts ($\phi = 6$ mm), and a body made of ABS resin. The body has a function to guide the belt so as to provide a good tangential force on fingerpad. The device is fixed on the middle phalanx of the finger by Velcro strap. The bottom surface of the device conforms to the dorsal side of finger by mold so that the reactive force from the device is widely distributed and hardly recognized.

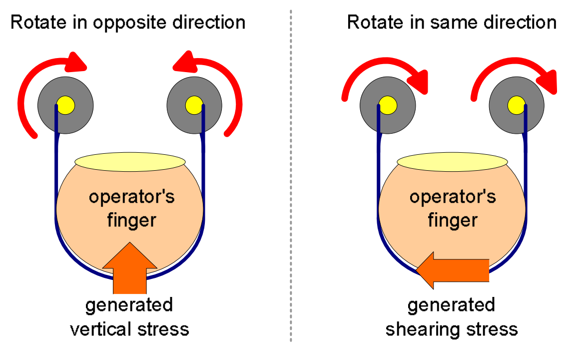

Fig. 10: A method for generating vertical stress (left fig) and shearing stress (right fig.)

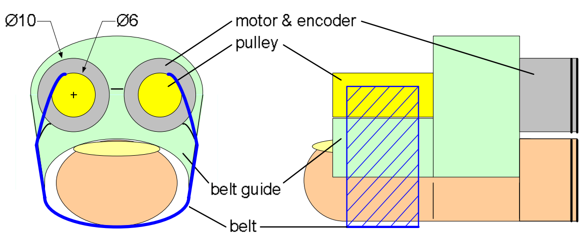

Fig. 11: Construction drawing of the prototype device

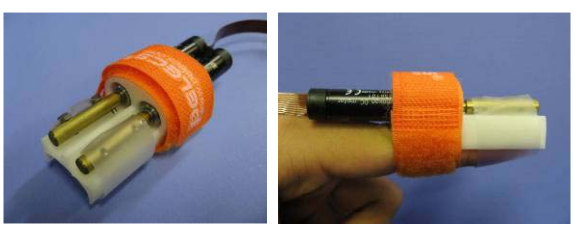

Fig. 12: The implemented prototype device

3.2. Evaluation of the prototype device

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

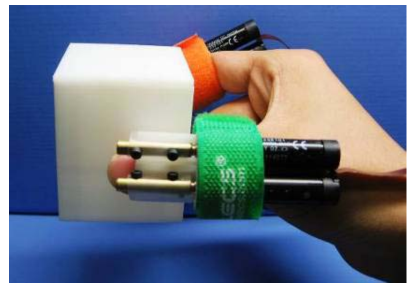

Fig. 13: Displaying augmented weight on a light-weight Styrofoam cube.

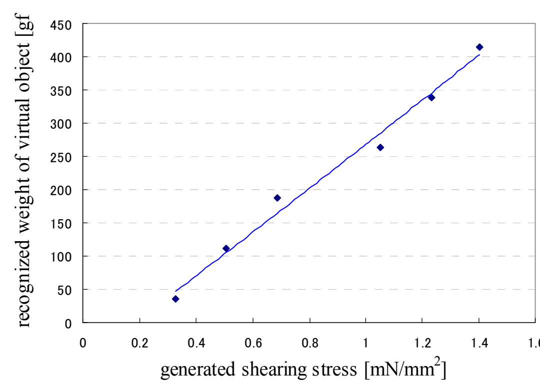

Fig. 14: Recognition of virtual weight in static grasping. The shearing stress is theoretically calculated from applied current values, motor specifications and device structures.

4. Discussions

To display the virtual gravity sensation in virtual reality or tele-operation system, our proposed method should be extended to present the mass sensation of the virtual object in active movement. In the situations that the operator moves its hand actively and the object is put in motion, the force should be presented according to its acceleration. We briefly tested the recognition of the virtual weight during some operations such as shaking motion and rotating motion shown in figure 15, although quantitative evaluations have not been supplied yet. In the rotation

Second Joint EuroHaptics Conference and Symposium on Haptic
Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)
0-7695-2738-8/07 $20.00 © 2007 IEEE

motion, for example, the weight of a virtual object is presented evenly on index finger and thumb in figure 15 (c). As the object is rotated to (d), it becomes to place disproportionate weight on index finger. And then in (e), the weight evenly divided again. But the stress direction is opposite from (c). In these cases, the recognition of gravity sensation was clearer than in the static grasping described in section 3.2. The operator could feel certain weights such as 50 g or 100 g from a light-weight cube made with styrofoam according to change of the vertical and sharing stress generated by the devices, although the actual weight of the cube was just 2 g. According to these observations, it is supposed that our proposed method is applicable for presenting not only the static gravity but also the inertia of a virtual object in active motion.

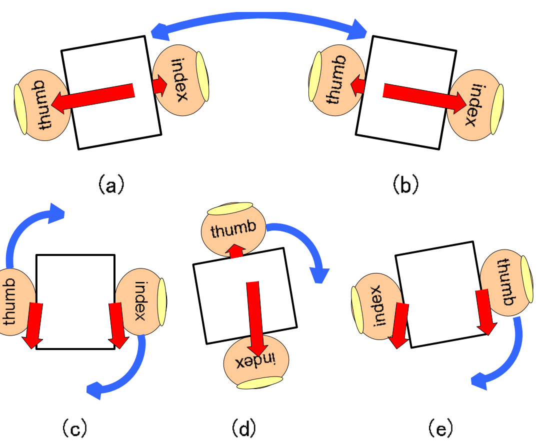

Fig. 15: Change of the force directions in grasping during shaking motion from (a) to (b) and rotating motion from (c) to (e). Blue arrows show the motion and the red arrows are expressing the force vectors combined the grip force, the gravity, and the inertia, which should be reproduced.

5. Conclusions

In this paper, we focused on the shearing stress on fingerpads in grasping, and then proposed a wearable, ungrounded haptic display to present the gravity sensation of a virtual object. To show the possibility of our proposed method, we measured the difference limen for weight detection on fingerpads without the proprioceptive sensation. The relation between the gravity sensation and shearing stress was evaluated to design the prototype device. And then, we implemented the prototype devices and it was confirmed that the presented virtual weight has good linearity to the generated shearing stress. This paper showed the evaluation only in static grasping situation. Our next study is to evaluate that the proposed method is applicable for not only the gravity sensation in static grasping but also the sensation of inertial force in active motion. Furthermore, we need to study the relativity between the tactile sensation and the proprioceptive sensation in perceiving gravity, in order to investigate the possibility of our proposed method.

References

[1] Y.Yokokohji and T.Yoshikawa: "Maneuverability of Master-Slave Telemanipulation Systems", *Trans. SICE*, Vol. 26, No. 5, pp. 572–579, 1990.

[2] Immersion Co., "The CyberGrasp: Groundbreaking haptic interface for the entire hand", (online) http://www.immersion.com/3d/products/, 2003.

[3] S. Nakagawara, H. Kajimoto, N. Kawakami, S. Tachi, and I. Kawabuchi: "An Encounter-Type Multi-Fingered Master Hand Using Circuitous Joints", *Proc. IEEE International Conference on Robotics and Automation (ICRA2005)*, Barcelona, Spain, 2005.

[4] S. Tachi, K. Komoriya, K. Sawada, T. Nishiyama, T. Itoko, M. Kobayashi, and K. Inoue: "Telexistence Cockpit for Humanoid Robot Control", *Advanced Robotics*, Vol. 17, No. 3, pp. 199-217, 2003.

[5] S. Johansson and G. Westling: "Roles of Glabrous Skin Receptors and Sensorimotor Memory in Automatic Control of Precision Grip When Lifting Raugher or More Slippery Objects", *Experimental Brain Research*, vol. 56, pp. 550-564, 1984.

[6] T. Maeno, S. Hiromitsu and T Kawai: "Control of Grasping Force by Detecting Stick/Slip Distribution at the Curbed Surface of an Elastic Finger", *Proc. IEEE International Conference on Robotics and Automation (ICRA2000)*, San Francisco, USA, 2000.

[7] G. Inaba and K. Fujita: "A Pseudo-Force-Feedback Device by Fingertip Tightening for Multi-Finger Object Manipulation", *Proc. EuroHaptics Int. Conf. 2006*, pp. 275-278, Paris, France, 2006.

[8] H. Y. Yao and V. Hayward: "An Experiment on Length Perception with a Virtual Rolling Stone", *Proc. EuroHaptics Int. Conf. 2006*, pp. 275-278, Paris, France, 2006.

[9] H. Forssberg, A.C. Eliasson, H. Kinoshita, R.S. Johannson, and G. Westling: "Development of human precision grip I: Basic coordination of force", *Experimental Brain Research*, Vol. 85, pp. 451-457, 1991.

[10] K. Minamizawa, K. Tojo, H. Kajimoto, N. Kawakami, and S. Tachi: "Haptic Interface for Middle Phalanx Using Dual Motors", *Proc. EuroHaptics Int. Conf. 2006*, pp. 235-240, Paris, France, Jul. 2006.

Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)
0-7695-2738-8/07 $20.00 © 2007 IEEE