

## Method for Displaying Partial Slip used for Virtual Grasp

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### Abstract

*A method is presented to display partial slip in precision grip of humans. Partial slip is important information for precision grip of humans, because the human controls grasping force by detecting expansion of the partial slip area. Therefore, a device that displays partial slip will make it easier for remote controlled mechanical hands to grasp objects, irrespective of the friction coefficient between the mechanical hand and object. To design the device displaying partial slip, we analyzed the deformation of a finger when in contact with a rigid plate using a finite element model. We also analyzed the deformation of the finger section model when in contact with the device that displays partial slip. As a result of the analyses, it is confirmed that there is a possibility in displaying partial slip using a tactile display device, which stimulates the finger through deformation of an elastic body.*

### 1 Introduction

Demands for dexterous remote controlled robot hands are increasing for use in medicine, space and other extreme environments [1]-[3]. Various remote control devices displaying remote or virtual force have been developed [4]-[8]. However, direction of the feedback force is usually normal to the contact surface between the device and the object touched. Tangential force must also be detected and displayed when humans handle a remote or virtual object without dropping it. Authors have indicated that the detection and display of partial slip is especially important.

When we grasp an object with our fingers, the contact area of the fingers and the object can be divided into two areas. One is the stick area where the fingers stick to the surface of the object. The other is the partial slip area in which the finger slips on the surface of the object [9]. Figure 1 shows the distribution of the stick area and the partial slip area in the contact area between the finger and the grasped object. The stick/slip distribution in the contact area between the finger and the object is important information for precision grip of humans. If humans increase the lifting force without changing grasping force, the partial slip area expands and the stick area narrows.

Expansion of the partial slip area means that the object may slip out of the fingers' grasp. In other words, when the whole contact area becomes the partial slip area, the grasped object will fall. However, humans can increase the grasping force before the grasped object slips through the fingers, because afferent signals from mechanoreceptors that are sensitive to the expansion of the partial slip area works on the human to increase grasping force [10]. This means that humans actually know the expansion of partial slip area and adequately control grasping force.

Therefore, we can suppose a master-slave device that detects and displays partial slip information is useful for tele-operation systems. The slave device is a tactile sensor that detects stick/slip information. There have been numbers of researches to develop distributed tactile sensors [11]-[13]. On the other hand, the master device must be a tactile display that displays partial slip information. This is what authors propose in the present study for dexterous remote/virtual manipulation. When the tactile sensor of the slave device senses the expansion of the partial slip area between the slave device and the grasped object, the tactile display stimulates the finger to display the partial slip information. In this way, the tactile device displaying partial slip can inform the risk of dropping the grasped remote/virtual object. Hence, the tactile device displaying partial slip makes easier for remote controlled mechanical hands to grasp objects, irrespective of the friction coefficient between the mechanical hand and object. In the present study, stick/slip condition and response of Meissner's corpuscles are calculated using the FE (finite element) analysis between a section of a finger and a rigid plate. It is shown that response patterns of Meissner's corpuscles change when the partial slip area changes. Then, a tactile display is

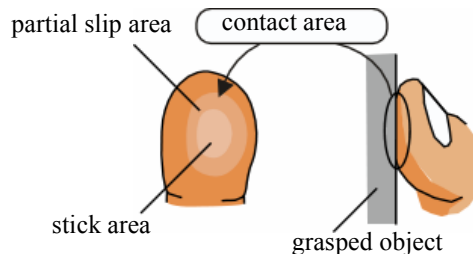


Figure 1: Stick/slip distribution

designed by using the FE analysis between the section of a finger and proposed tactile devices in which a part of the device moves in a tangential direction. Effectiveness of this device is confirmed by showing that the response pattern of Meissner's corpuscles is similar to that of the finger/plate contact.

## 2 Contact Analysis between Rigid Plate and Finger

There are four types of mechanoreceptors embedded in human fingers, Meissner's corpuscles, Pacinian corpuscles, Merkel cell-neurite complexes, and Ruffini endings. Of the four, Meissner's corpuscles are considered the most sensitive mechanoreceptors in detecting the surface state. Meissner's corpuscles activate nerve signals at a high rate when the partial slip area expands [9]. It is known that humans increase grasping force when afferent signals from the Meissner's corpuscles increase [10]. Therefore, the device that displays partial slip should make the Meissner's corpuscles activate the nerve impulses much like those caused by the expansion of partial slip area when a remote object touches a finger. However, it is difficult to experimentally measure the deformation of a finger and the nerve impulses of Meissner's corpuscles. However, it is confirmed that the firing rate of mechanoreceptors correlates closely with the

strain energy measured at the locations of mechanoreceptors [14]-[15]. Therefore, we analyze the deformation of a finger and the strain energy at the locations of Meissner's corpuscles using the finite element model of the finger section [14] when the finger is in contact with a rigid plate to show changes in the response pattern of Meissner's corpuscles as the partial slip region changes. Nodes at the surface of nail and bone are constrained in the  $x$ - and  $y$ -direction.

### (a) Method

To reproduce the deformation of a finger when the partial slip area expands, we brought the rigid plate into contact with the finger section model. The rigid plate shown in Figure 2 moves in the negative  $y$ -direction for 1mm first, and then moves in  $x$ -direction maintaining contact with the finger section model. When the rigid plate moves in the negative  $y$ -direction, the rigid plate moves 0.02mm per step, and when the rigid plate moves in  $x$ -direction, the rigid plate moves 0.04mm per step. The friction coefficient between the finger and rigid plate is 0.25, 0.50, and 0.75. The circular marks shown in Figure 2 and Figure 3 indicate the locations of nodes that are located at the center of the epidermal ridge (ER nodes), and triangular marks shown in figure 2 and figure 3 indicate the locations of nodes at Meissner's corpuscles (MC nodes). We defined the ER nodes as  $ER_i$  ( $i=1, 2, 3, \dots, 26$ ) and defined the MC nodes as  $MC_i$  ( $i=1, 2, 3, \dots, 52$ ) as shown in Figure 3. We also defined the stick rate as the ratio of the total number of ER nodes that stick to the rigid plate and the number of ER nodes that slide on the rigid plate. The firing rate of Meissner's corpuscles correlates closely with the velocity of deformation of finger. Therefore, we analyzed the absolute value of strain energy change per step ( $\Delta E$ ) measured at the locations of Meissner's corpuscles to estimate its firing rate.

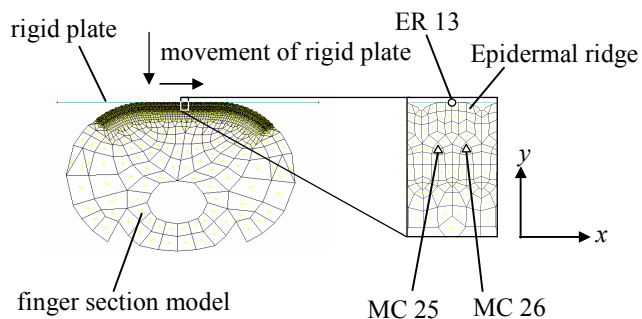


Figure 2: Finite element model of finger and rigid plate

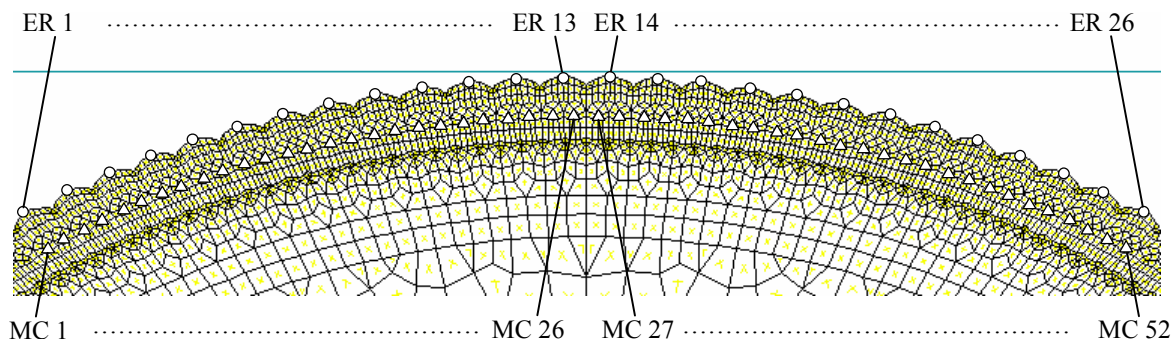
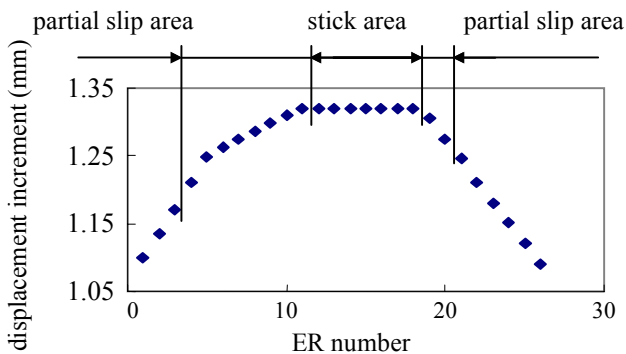


Figure 3: location of Epidermal ridges and Meissner's corpuscles

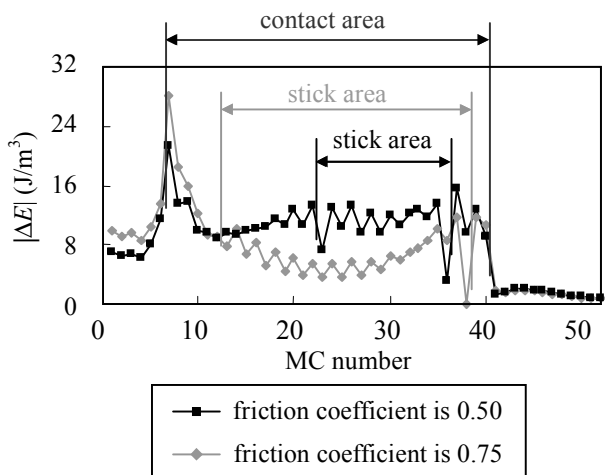
## (b) Result

The positional change of ER nodes in the  $x$ -direction is the most important value when analyzing the deformation of a finger section model when the partial slip area expands. When the rigid plate moves 1mm in the negative  $y$ -direction without moving in the  $x$ -direction, the ER nodes not only move in the negative  $y$ -direction but also in the  $x$ -direction, and not until then do we define the positions of each ER node as a datum point to measure its positional change in the  $x$ -direction. The displacement increment of ER nodes shown in Figure 4 is the positional change of ER nodes in the  $x$ -direction from the datum points. For Figure 4, the displacement of rigid plate in the negative  $y$ -direction is 1mm and in the  $x$ -direction is 1.32mm. The horizontal axis shown in Figure 4 is the number of ER nodes. The displacement increment of ER nodes in the partial slip area is smaller than those in the stick area. Similar tendencies can be seen when the friction coefficient is 0.25 and 0.75.

Figure 5 shows the absolute value of  $\Delta E$  at Meissner's



**Figure 4:** Displacement increment of epidermal ridge (friction coefficient is 0.5 and stick/slip rate is 40%.)



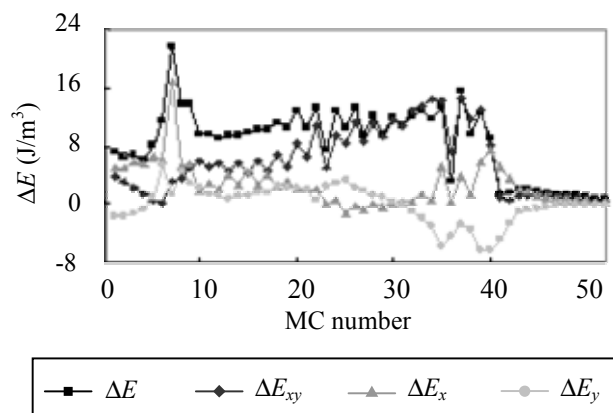
**Figure 5:** Distribution of  $|\Delta E|$  at meissner's corpuscles

corpuscles ( $|\Delta E|$ ). The smaller the friction coefficient is, the smaller the stick rate becomes, while  $|\Delta E|$  at  $MC_i$  ( $i=16, 17, \dots, 35$ ) increase, and  $|\Delta E|$  at  $MC7$  decreases as shown in Figure 5.  $|\Delta E|$  differ according to the changes of stick/slip distribution. We must now consider which of the  $|\Delta E|$  is most influenced by the changes of stick/slip distribution. Figure 6 shows the changes of three separate elements ( $\Delta E_{xy}$ ,  $\Delta E_x$  and  $\Delta E_y$ ) of strain energy at Meissner's corpuscles.  $\Delta E_{xy}$  is the strain energy change caused by the change of shear stress and shear strain.  $\Delta E_x$  and  $\Delta E_y$  are changes of strain energy caused by the change of normal stress and normal strain in the  $x$ -direction and  $y$ -direction. The value of  $\Delta E$  at  $MC7$  mainly depends on  $\Delta E_x$  as shown in figure 6. The total friction force largely influences the normal stress and the normal strain in the  $x$ -direction at  $MC7$ . Therefore, there is no use in trying to obtain the hint to stick/slip distribution by measuring the value of  $|\Delta E|$  at  $MC7$ . However,  $\Delta E$  at  $MC_i$  ( $i=10, 11, \dots, 40$ ) mainly depend on the  $\Delta E_{xy}$ . Hence,  $MC_i$  ( $i=10, 11, \dots, 40$ ) can be considered to be most influenced by the change of friction force caused by the expansion of the partial slip area. Therefore, the stimuli that makes the value of  $\Delta E$  at  $MC_i$  ( $i=10, 11, \dots, 40$ ) larger can display the partial slip.

## 3 Contact Analysis between finger and tactile displays

### 3.1 Display using three separate rigid plates

In this section, a device to display partial slip is designed which stimulates Meissner's corpuscles similarly to when a finger touches the rigid plate. The displacement increment of ER nodes in the partial slip area is smaller than those in the stick area as shown in Figure 4. The stick area is around the center of the contact area, and the partial



**Figure 6:** Distribution of  $\Delta E$ ,  $\Delta E_{xy}$ ,  $\Delta E_x$  and  $\Delta E_y$  at meissner's corpuscles

slip area is around the stick area. Therefore, if the moving distance of the central stimulating part is longer than that of other stimulating parts shown in Figure 7, there is a possibility in displaying partial slip using the three stimulating parts.

**(a) Method**

The three stimulating parts move 1mm in the negative  $y$ -direction first, and then move in  $x$ -direction maintaining contact with the finger section model. The friction coefficient between the finger section model and the stimulating parts is 1.0. Displacements of stimulating parts in the  $x$ -direction are set referring to the displacement increment of ER nodes obtained in the contact analysis of the finger section model and the rigid plate.

**(b) Result**

Figure 8 shows the displacement increment of ER nodes. Displacement increments of ER nodes that are in contact with the central stimulating part are close to the results of the contact analysis. However, the increments of ER nodes in contact with the other stimulating parts differ from those of the contact analysis between the finger section model and the rigid plate. Therefore, arranging the stimulating parts in a discrete manner would mean distribution discontinuity of displacement increments of the ER nodes.

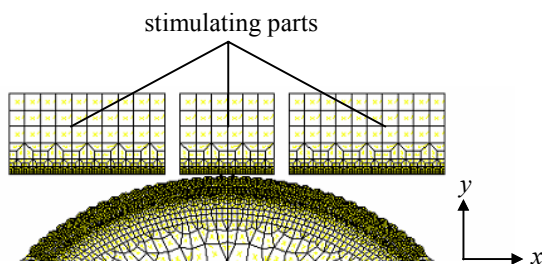


Figure 7: Stimulating parts in contact with finger directly

Figure 9 shows  $|\Delta E|$  at Meissner’s corpuscles. The horizontal axis is the number of MC nodes. There are two peaks that are nonexistent in  $|\Delta E|$  of the contact analysis between the finger section model and the rigid plate. Therefore, it is hard to display partial slip with discretely arranged stimulating parts. Furthermore, the positions of the two peaks exist between the stimulating parts. Therefore, the two peaks of the contact analysis between the finger section model and the three stimulating parts are caused by the discreteness of the stimulating parts. Hence, the increment of ER nodes must be distributed continuously to display partial slip.

**3.2 Display using separate rigid parts inside an elastic body**

When the finger section model is in contact with the stimulating parts, humans might feel the discreteness of stimulating parts, because there are two peaks of  $|\Delta E|$  between the stimulating parts that do not exist in the result of the contact analysis between the finger section model and

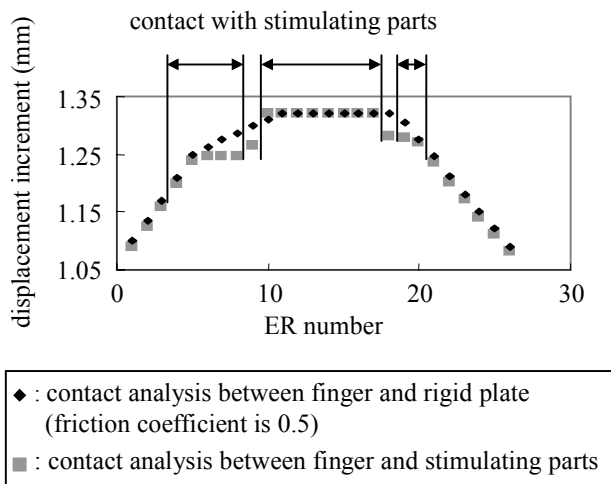


Figure 8: Displacement increment of epidermal ridge as the result of contact analysis between finger and stimulating parts

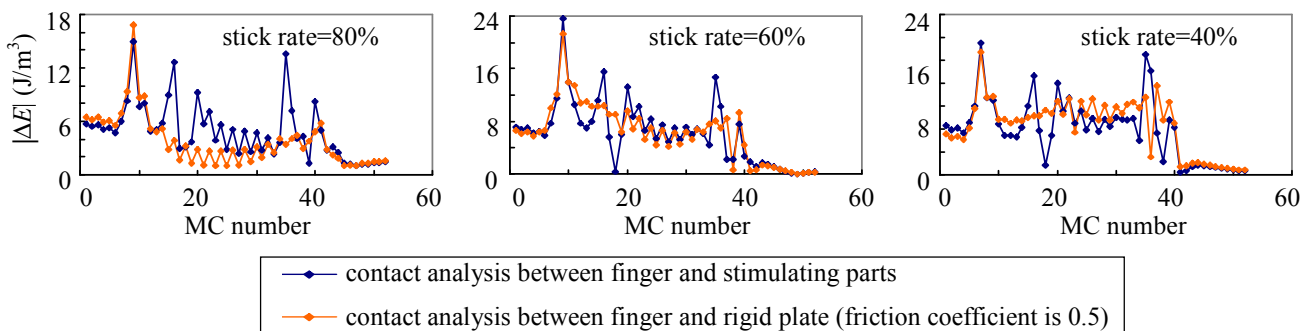


Figure 9: Distribution of  $|\Delta E|$  at Meissner’s corpuscles in contact analysis between finger and stimulating parts

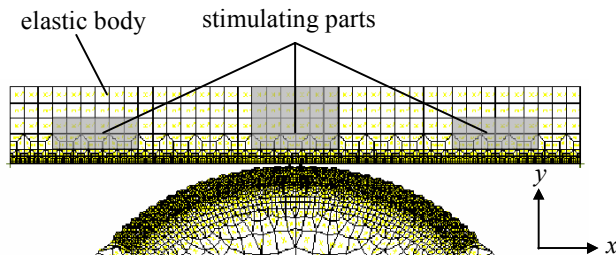
the rigid plate. Displacement increments of ER nodes are also distributed discontinuously among the stimulating parts. Therefore, if the displacement increments of ER nodes are distributed continuously humans may not feel discreteness of the stimulating parts. Hence, we propose a tactile device with three stimulating parts inserted in an elastic body as shown in Figure 10. If the tactile device stimulates the finger section model through continuous deformation, displacement increments of ER nodes should distribute continuously as shown in Figure 4.

**(a) Method**

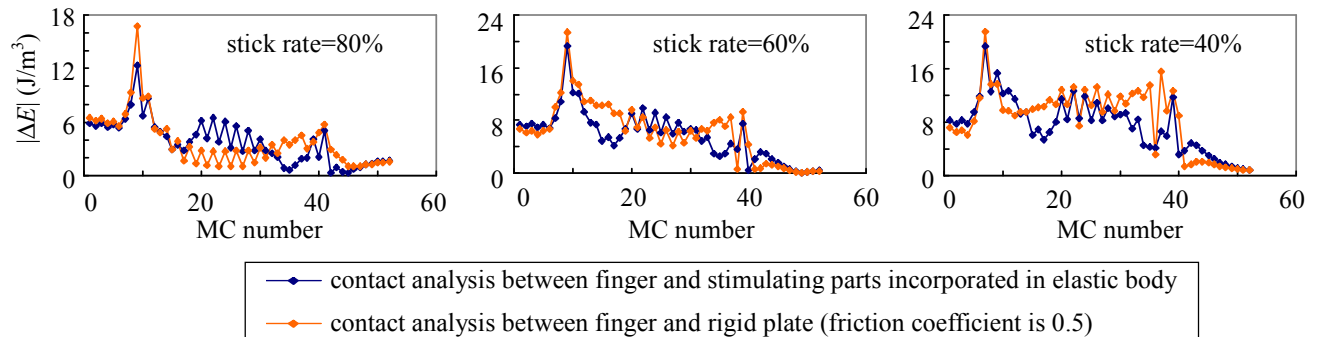
The three stimulating parts shown in figure 10 move 1mm in the negative  $y$ -direction and then move in the  $x$ -direction. We set the displacement of stimulating parts in the  $x$ -direction referring to displacement increments of ER nodes that are results of the contact analysis between finger section model and the rigid plate. The Young's modulus of an elastic body is 2.06Mpa, and the Poisson's ratio is 0.45. The depth of stimulating parts is 0.5mm from the surface that contact with the finger section model. Clearance of the stimulating parts is 4mm.

**(b) Result**

Figure 11 shows displacement increments of ER nodes. Although increments of ER nodes located around the center of the contact area is close to the result of the contact analysis between the finger section model and the



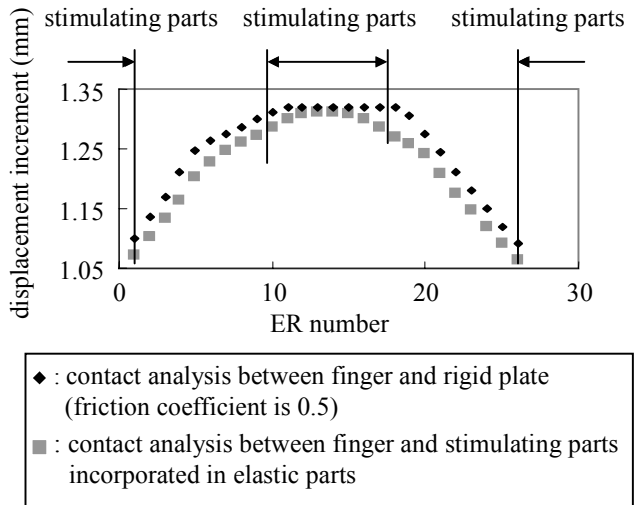
**Figure 10:** Stimulating parts incorporated in elastic body



**Figure 12:** Distribution of  $|\Delta E|$  at Meissner's corpuscles in contact analysis between finger and stimulating parts incorporated in elastic body

rigid plate, overall displacement increments of ER nodes are smaller than those of the contact analysis between the finger section model and the rigid plate. However, compared with the contact analysis between the finger section model and the three stimulating parts, displacement increments of ER nodes are distributed continuously. Therefore, it is true that the displacement increment of ER nodes between the stimulating parts is smaller than that of ER nodes under the central stimulating part, but humans do not feel the discreteness of the stimulating parts.

Figure 12 shows the  $|\Delta E|$  at Meissner's corpuscles. There are no large peaks between the stimulating parts unlike the result of the contact analysis previously discussed. Therefore, it is unlikely for humans to feel the discreteness of the stimulating parts.  $|\Delta E|$  of the contact analysis between the finger section model and the elastic body is closer to  $|\Delta E|$  of contact analysis between the finger section model and the rigid plate than  $|\Delta E|$  of the contact analysis between the finger section model and the



**Figure 11:** Displacement increment of epidermal ridge as the result of contact analysis between finger and stimulating parts incorporated in elastic body

discretely arranged stimulating parts. Similar tendencies can be seen when the friction coefficient is 0.25 and 0.75. Therefore, the method of stimulating the finger through continuous deformation of an elastic body is an effective method to display partial slip

### 3 Conclusions

We proposed a tactile displaying device for teleoperation systems by using partial slip information that can be obtained when traction is applied between an elastic finger and a virtual object. It is confirmed that the proposed method is effective in displaying partial slip by stimulating the finger through the continuous deformation of the elastic body. We plan to design the tactile displaying device in detail and to manufacture the device. In future studies, we can then confirm the effectiveness of the method to experimentally stimulate the finger through the deformation of an elastic body using the tactile device.

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