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Softness Display by a Multi-Fingered Haptic Interface Robot*

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Abstract— **When we touch a human body, the flesh yields to our touch and we feel a sensation of softness. In virtual training systems for medical procedures such as palpation, the display of softness at the fingertips is essential. This paper proposes a softness-display device using a flexible sheet, and we present the concept of softness display at multiple fingers by combining the developed softness-display device and a multi-fingered haptic interface robot consisting of a five-fingered hand and an arm. Further, we carried out several experiments, the results of which show the validity of the proposed system and its great potential.**

I. Introduction

Haptic interfaces allow users to communicate with a virtual reality (VR) environment using the sense of touch. The user of the haptic interface can feel force and tactile sensations from the VR environment; further, the user can provide force, tactile and position information to the VR environment. Therefore, the haptic interface provides a bidirectional interaction between the user and the VR environment. Haptic interfaces have become key input/output devices for communication with highly realistic sensations and have been used in many application areas (for example, see [1]–[4]).

One application area is virtual training systems in medicine, manufacturing, and other fields requiring skilled use of the hands. For example, in the medical field, expert skills such as palpation are obtained by long-term training, and this skill is normally acquired by the experience of working with actual patients. However, it is difficult for residents and medical students to train directly on actual human bodies due to patient safety issues, and training with animals is also problematic because of ethical concerns [5], [6]. Creating a virtual human model in a VR environment with a haptic interface eliminates the need for actual patients, and a trainee can gain skills based on realistic touch sensation. For gaining skills such as palpation through such a virtual training system, the softness display at human multiple fingertips is critical. Thus, a haptic interface that can present the sensation felt when human touches soft, yielding objects, such as human flesh, is required.

Our perceived softness when we touch a soft or yielding object with fingers is based on a combination of kinesthetic information [7] (force/position information) and cutaneous information [8] (surface deformation information of fingertip) [9], [10]. In fact, the softness of the object is perceived by cutaneous information, which is obtained by changing the contact area of a fingertip, namely skin deformation, and kinesthetic information, which is obtained by the force from the object and the position of the finger. It has been found that cutaneous information is more dominant than the kinesthetic information in the perception of softness [11]. It is desirable to present both types of information simultaneously for realistic softness display.

Although there are many kinds of research on softness display, if we focus attention on haptic interfaces, which can present the softness feeling at the fingers using both kinesthetic and cutaneous information, they can be roughly divided into two groups: haptic interfaces which control the contact area between the finger and the virtual soft object (for example, [12]–[14]) and haptic interfaces which display/ prepare a substitute with the same softness as a real object (for example [15]–[17]). In [12]–[14], the developed haptic interfaces consist of cutaneous information display, which controls the contact area, and a force-reflecting device for kinesthetic information display. In particular, control of the contact area at the fingertips was carried out using a rubber membrane and air pressure in [12], by a set of cylinders of different radii in [13], and by arrayed pins in [14]. However, the physical parameters of the user's finger and the displayed object are indispensable to the derivation of the contact area; human physical parameters have large individual differences, and identification of the parameters is required for each user. Further, the size of the devices is large, and the extension to the display at multiple fingers is difficult. On the other hand, for haptic interfaces using a substitute with the same softness as the target object, a breast palpation simulator has been developed [15]. In their system, a pneumatic parallel manipulator was installed in the inside of a commercially available breast model made of silicon. In this setting, the user can feel a realistic touch sensation of the cutaneous surface; further, the system can present a lump at any position by introducing the manipulator. Although their system specializes in breast palpation and is considered to be useful, it is lacking in versatility. Another softness-display device has been developed using a large flexible sheet [16]. Both ends of the sheet were connected to the manipulators, and tension is applied to the sheet by pulling these ends; thus, the system could vary the softness in the sheet-normal direction. Touching this flexible sheet, the user feels the same softness as he or she would touch a real object. However, the device is large-sized, and the system has difficulty simulating situations in which the object is not uniform but has a complicated form and where the softness differs with each finger. The FEELEX in [17] can display a substitute with the same softness as the target object; namely, the system can present a deformable surface using many separate sets of piston-crank mechanisms, but its workspace is limited and is small.

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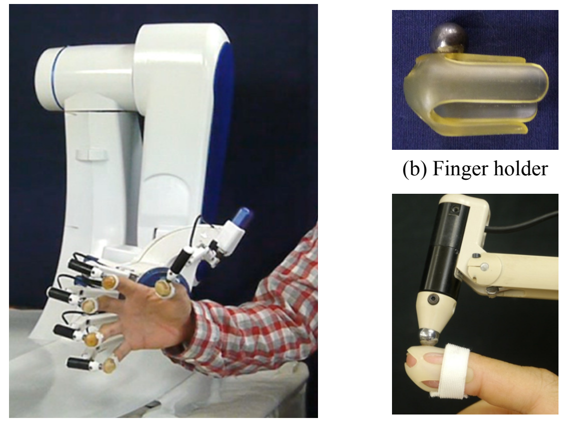
We previously developed a side-faced-type multi-fingered haptic interface robot [18], which can present three-directional forces at all five human fingertips. To manipulate the haptic interface, the user wears a finger holder on each fingertip, as shown in Fig. 1 (b). The connection between the haptic interface and the user is realized through the finger holder as shown in Fig. 1 (a). Here, the finger holder is slightly hard; thus, it is considered that, compared with touching an actual soft object, different cutaneous information (surface deformation) is displayed at the fingertip by the above haptic interface. In fact, it is known that the perception ability of the fingertip, including the finger's ability at palpation, declines when the finger is equipped with a rigid fingertip sheath [19]. From these points of view, in this paper, we developed a new finger holder installing a tension-controllable flexible sheet into the finger holder. And, by integrating the side-faced-type multi-fingered haptic interface robot and the newly developed finger holder, we propose the concept of softness display at multiple fingers. That is, the tension is applied to the flexible sheet in the new finger holder by pulling both ends of the sheet, and the sheet has same softness as the target object. Then, the sheet is displayed/prepared to a user's multiple fingers by the side-faced-type multi-fingered haptic interface robot. Thereby, in addition to the display of a softness feeling at multiple fingertips, the situation where the softness differs with each finger can be realized. We also can ensure a large workspace.

In the next section, we introduce the side-faced-type multi-fingered haptic interface robot. Section III presents the developed finger holder for the softness display (henceforth, the "softness-display device") and presents the integration of the softness-display device and the side-faced-type multi-fingered haptic interface robot. Experimental results are shared in section IV. Finally, section V presents our conclusions.

II. Side-Faced-Type Multi-Fingered Haptic Interface Robot

A side-faced-type multi-fingered haptic interface robot [18] shown in Fig. 1, can present three-directional forces at the user's five fingertips. The specifications of the robot are shown in Table I. The robot can be briefly summarized as follows.

The haptic interface robot consists of an arm and a five-fingered haptic hand. The arm has 6 joints allowing 6 degrees of freedom (DOF). The haptic hand is constructed of five haptic fingers. Each haptic finger has 4 joints allowing 3 DOF. The first joint relative to the hand base allows abduction/adduction, while the second and the third joints allow flexion/extension. The fourth joint is interlocked with the third joint through a closed-loop mechanism, and the haptic hand has 15 DOF. Further, a three-axis force sensor is installed at the top of each haptic finger. To manipulate the haptic interface, the user wears a finger holder on each fingertip, as shown in Fig. 1 (b). The finger holder has a steel sphere, and the haptic finger has a permanent magnet at its fingertips. By means of the magnet force, the finger holder can be connected to the interface, as shown in Fig. 1 (c). Here, note that the sphere forms a passive spherical joint when attached to the permanent magnet at the force sensor tip. Its role is to



(a) Overall system (b) Finger holder (c) Finger holder and its connection to haptic finger

Figure 1. Side-faced-type multi-fingered haptic interface robot.

TABLE I. Specifications of Side-Faced-Type Multi-Fingered Haptic Interface Robot

Degrees of Freedom	Hand: 15 DOF (Number of haptc fingers: 5)
	Finger: 4 joints allowing 3 DOF
	Arm: 6 joints allowing 6 DOF
Performance	Maximum output of finger: over 3.8 N
	Maximum displayable stiffness: 6kN/m
	Frequency response: 9 Hz
	Sampling time of control: 1kHz

adjust for differences between the human and haptic finger orientations. Furthermore, the magnet connection breaks if the user pulls his or her finger with a force of about 4.3N. For more technical details, please see [18].

III. Softness-Display System

A. Design Concept and Mechanical Design

The aim of this paper is to realize a haptic interface that can display the softness at multiple human fingertips. To realize this aim, we combined a softness-display device (namely, the new finger holder) and the side-faced-type multi-fingered haptic interface robot. In this setting, the softness-display device realizes a substitute with same softness as the target object, and the side-faced-type multi-fingered haptic interface robot displays the substitute (namely, the softness-display device) to a user's fingers.

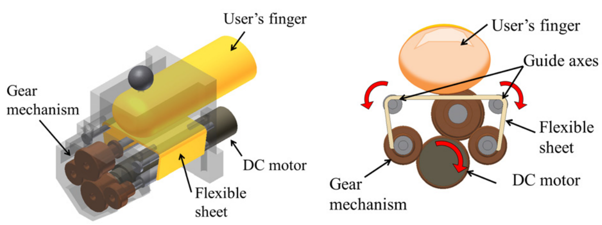
First, we introduce the developed softness-display device, which can have the same softness as the target object by installing the tension-controllable flexible sheet into the finger holder. In choosing the flexible sheet, we carried out a preliminary experiment to examine whether a sheet could present softness like that of human flesh. We used the hyper-gel sheet [20] (Exseal Co.), which has a thickness of 1 mm and a hardness of 30 as measured using an ASKER durometer (Type C). Further, since the device must be deployed at the human fingertips, we had to consider the miniaturization of the device and shortening of the device width.

The mechanical structure of the developed softness-display device is shown in Fig. 2. For the miniaturization of the device, we used one motor (maxon DC motor RE10), and the rotation of the motor was transmitted to both ends of the sheet through the gear mechanism. To enable shortening of the device width, both ends of the flexible sheet were connected to the gear mechanism through the guide axes. When the motor rotates as shown in Fig. 2 (b), the parts of the sheet at the guide axes rotated in the opposite direction by gear mechanics, respectively. Thus, we can adjust the tension of the sheet by pulling the sheet from both ends. The domain on the sheet which a user touches is 20 mm × 20 mm. The maximum penetration depth of the sheet is 7 mm.

The developed softness-display device is shown in Fig. 3. The device is connected to the side-faced-type multi-fingered haptic interface robot through the steel sphere installed at the top of the device. For example, Fig. 3 (c) shows the case in which a user connected his thumb and index finger to the haptic interface using two softness-display devices. If we use five softness-display devices, we can display the softness at the user's five fingertips. The weight and size of the developed device are 49g and 26 mm × 37.5 mm× 60 mm, respectively.

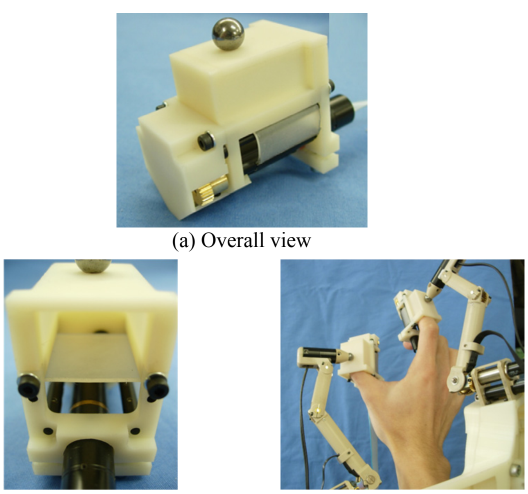
B. Control System for Softness-Display System

The control of the softness-display system consists of the control of the softness-display device and the control of the side-faced-type multi-fingered haptic interface robot. First, we describe the control of the softness-display device. In the softness-display device, the tension of the flexible sheet is controlled by the motor, and the change of the tension drives the change of the Young's modulus of the sheet. We used the



(a) Overall view (b) Front view

Figure 2. The mechanical structures of the softness-display device.



(a) Overall view

(b) Back view (c) The connection to thumb and index fingers

Figure 3. The developed softness-display device.

PID control of the rotational angle of the motor. The control system consists of a control PC, an up/down counter (CNT), a digital-to-analogue convertor (D/A), and a motor driver. The control PC reads the value of the encoder through the CNT and outputs the control signal through the D/A, and the rotational angle of the motor is controlled by the PID control of the angle

$$\tau(t) = k_1 e(t) + k_2 \int_0^t e(s)\mathrm{d}s + k_3 \dot{e}(t), \tag{1}$$

where $\tau(t)$ is the torque of the motor, $\theta(t)$ is the rotational angle of the motor, $\theta^d(t)$ is the desired rotational angle, and $e(t) = \theta^d(t) - \theta(t)$. Furthermore, k_i, $i = 1, 2, 3$ is the positive feedback gain. The sampling time of the control is 1 ms.

Next, we explain the control of the side-faced-type multi-fingered haptic interface robot. In particular, we explain it by dividing the free space case, where there is no contact between the fingertip and the virtual object, and the constraint space case, where the fingertip has contact with the virtual object.

In the free space, the haptic fingers of the side-faced-type multi-fingered haptic interface robot are controlled by force control

$$\begin{aligned}\boldsymbol{\tau}_{\boldsymbol{F}}(t) = \boldsymbol{K}_1 \boldsymbol{J}_{\boldsymbol{F}}^T \boldsymbol{F}_{\boldsymbol{e}}(t) + \boldsymbol{K}_2 \boldsymbol{J}_{\boldsymbol{F}}^T \int_0^t \boldsymbol{F}_{\boldsymbol{e}}(s)\mathrm{d}s \\ + \boldsymbol{J}_{\boldsymbol{F}}^T \boldsymbol{F}_{\boldsymbol{d}} - \boldsymbol{K}_3 \dot{\boldsymbol{q}}_{\boldsymbol{f}}(t),\end{aligned} \tag{2}$$

where $\boldsymbol{\tau}_F = \mathrm{col}[\boldsymbol{\tau}_1,\ldots, \boldsymbol{\tau}_5] \in R^{15}$ is the joint torque of the haptic finger, $\boldsymbol{J}_F$ is a Jacobian, $\boldsymbol{F} = \mathrm{col}[\boldsymbol{F}_1,\ldots, \boldsymbol{F}_5] \in R^{15}$ is a force at the fingertip, $\boldsymbol{F}_d = \mathrm{col}[\boldsymbol{F}_{d1},\ldots, \boldsymbol{F}_{d5}] \in R^{15}$ is the desired force, $\boldsymbol{F}_e = \boldsymbol{F}_d - \boldsymbol{F}$, $\boldsymbol{q}_f = \mathrm{col}[\boldsymbol{q}_1,\ldots, \boldsymbol{q}_5] \in R^{15}$ is a joint angle of the haptic finger, and $\boldsymbol{K}_i$, $i = 1, 2, 3$ is the positive feedback gain matrix [21]. In (2), the third term is a feed-forward term for the reaction force and the last term is the velocity feedback to employ the active damping. Here, note that we did not consider the influence of the gravity of the softness-display device because the device is light. Since we consider the manipulation of the haptic finger in the free space, the desired forces at the five fingertips were set as $\boldsymbol{F}_d = \boldsymbol{0}$. Then, the user's finger does not penetrate into the sheet, and the user can manipulate his or her finger freely with the same feeling as in a conventional finger holder [18]. Here, the stiffness of the flexible sheet in the softness-display device must be controlled at a high level by giving tension to the sheet when the stiffness of the sheet is very low.

On the other hand, in the constraint space, the side-faced-type multi-fingered haptic interface robot is controlled by force control (2) with $\boldsymbol{F}_d = K \times d$ N, where d is the penetration depth of the finger into the virtual object and K is the stiffness. Here, note that the value of K is arbitrary constant if the value of $\boldsymbol{F}_d$ becomes high value. By doing this, the haptic finger's tip positions are constrained on the surface of the virtual object (namely, the fingertips of the haptic fingers do not penetrate the virtual object, and it is possible to let the fingertips slide on the surface of the virtual object). Further, the softness-display device controls the tension of the flexible sheet according to the stiffness of the real soft object. Even if a user of the haptic interface pushes the virtual object, the fingertips are on the surface of the virtual object, and the user can feel the softness by pushing the sheet of the softness-display device. That is, the flexible sheet has the same softness as the actual object. By using the above control methods, softness display at multiple fingers is accomplished. For more details of the control system of the side-faced-type multi-fingered haptic interface, please see [18].

IV. Experiments

To evaluate the developed system, we carried out three experiments.

A. Experiment 1: Measurements of Displayed Softness

To evaluate the displayable softness of the developed device, we measured the relationship between force and displacement. Note that this experiment measures the displayable softness of the softness-display device; thus, we considered the performance of the developed device without using the side-faced-type multi-fingered haptic interface robot.

The measurement system is shown in Fig. 4. It consists of a force gauge, a gauge stand with manual height control, and a tape measure. The top of the softness-display device was connected to the force gauge. A steel sphere with an 8 mm diameter was fixed to the aluminum flat bar, and the bar was fixed to a base. The measurement procedure is as follows: i) the motor of the device is rotated at the desired angle (every 90 deg from 0 to 360 deg) and we give the tension at the flexible sheet of the device. Then the height of the force gauge is adjusted so that the surface of the flexible sheet and the surface of the steel sphere are in agreement. ii) By using the tape measure installed in the stand, we move the height of the sheet only the desired distance (every 1 mm from 0 to 7 mm), and measure the reaction force to the steel sphere using the force gauge. Three readings were averaged to derive the mean.

The measurement results are shown in Fig. 5. In this figure, the vertical and the horizontal axes show the average value of the reaction force and the displacement, respectively. Further, Rot i for i = 0 to 360 means the rotational angle of the motor. From this figure, it turns out that the softness of the flexible sheet can be made variable by controlling the sheet's tension (namely, by changing the rotational angle of the motor). Further, the relationship between the force and the displacement is nonlinear, and we also found that the device can display an object of nonlinear softness like a human body. For example, the relationship between the force and the displacement in the commercially available breast model made of silicon becomes as shown in Fig. 8 (b), which is mentioned later (for comparison, the response of the softness-display device at 270 deg is shown), and we can also see that the relationship in the silicon breast model resembles the relationship in the developed device.

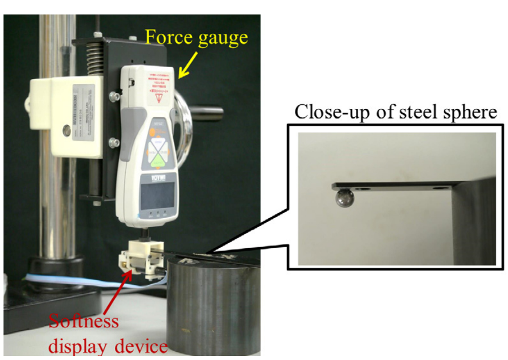


Figure 4. Measurement system of Experiment 1.

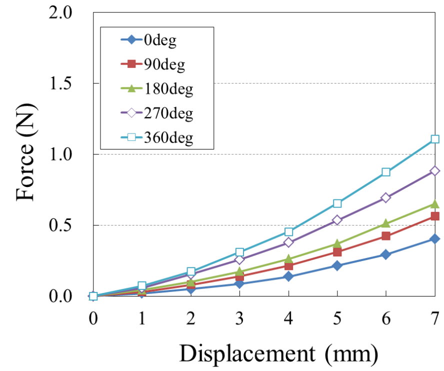


Figure 5. Force and Displacement of the softness-display device.

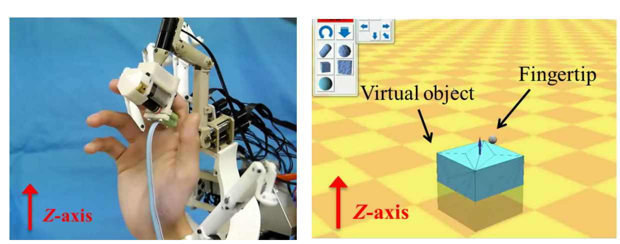
B. Experiment 2: Contact Experiment

We integrated the softness-display device and the side-faced-type multi-fingered haptic interface robot, and carried out a contact experiment where the user touches a virtual soft object in the VR environment.

In the experiment, a user connected his index finger to the device and pushed a virtual soft object several times. Here, we did not use the interface arm part of the haptic interface. The control method in section III-B was used. To avoid the penetration of the finger all the way to the virtual object, we set $\boldsymbol{F}_d$ = 1 kN/m × d in (2) for the constraint space case, where d is the penetration depth. Further, to adjust the tension of the flexible sheet, we set the θ^d = 360 deg in (1) for the free space case and θ^d = 270 deg in (1) for the constraint space case.

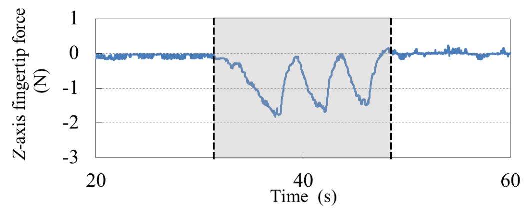
Fig. 6 shows the experimental environment. Fig. 6 (a) shows the real environment, and (b) shows the VR environment. In this figure, the small sphere corresponds to the user's index fingertip position and the blue cube is the virtual soft object. In the experiment, the user connects his index finger to the softness-display device, which is connected to the haptic index finger, and pushes a virtual soft object several times. Here note that we consider only the motion in the vertical direction (z-axis), and the user can feel the force in the normal direction of the sheet.

Fig. 7 shows the experimental results. Fig. 7 (a) shows the z-axis force response of the haptic index finger, (b) shows the

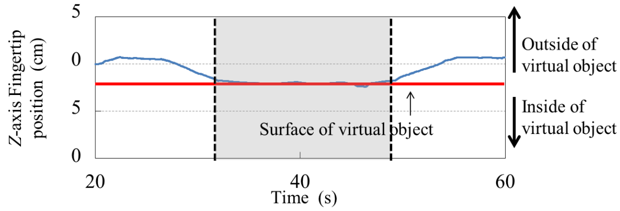


(a) Real environment (b) VR environment

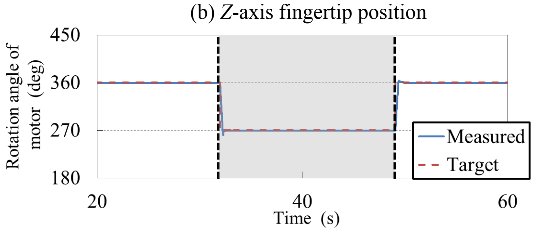
Figure 6. Experimental Environment of Experiment 2.



(a) *Z*-axis fingertip force



(b) *Z*-axis fingertip position



(c) Rotational angle of the motor

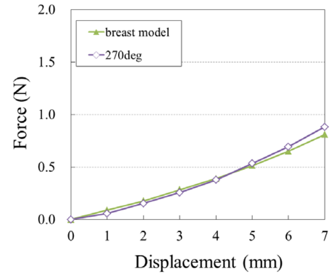
Figure 7. Results of contact experiment.

z-axis position response of the index finger, and (c) shows the rotational angle of the motor, which pulls the flexible sheet. In addition, the gray portions surrounded by the dotted line in the figures show the time intervals where the finger contacts the virtual object. In the interval where the index finger did not contact the virtual object, the angle of the motor converged to the desired angle, $\theta^{d} = 360$ deg (the average angular error was 0.02 rad), and we also see that the index finger did not penetrate through to the virtual object. Further, there were no big changes in the responses of the fingertip force (the average force error was 0.06 N) even if the user moved his index finger in that case. On the other hand, in the intervals where the finger contacts the virtual object, the rotational angle of the motor was controlled at 270 deg (the average angular error was 0.02 rad), and this derives the changing softness at the time of the user pushing on the sheet. In this case, there was a big change in the response of the fingertip force, but there were no changes in the fingertip position. So it is inferred from these facts that the fingertip position of the haptic finger is restrained on the object surface and the softness display was made by the softness-display device. These results showed that integrating the softness-display device and the side-faced-type multi-fingered haptic interface robot can produce a realistic softness sensation of the virtual object.

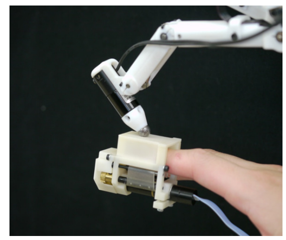
C. *Experiment 3: Comparing the displayed softness and the softness of the actual object*

Here, we conducted a psychological test to compare the displayed softness and the softness of the actual object. In the experiment, the participants touched both the actual object and the virtual object constructed in the VR environment, and subjectively evaluated the similarity of the touch sensations.

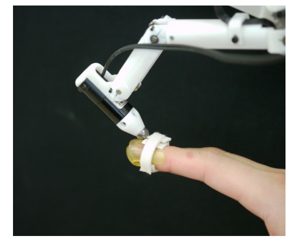
(a) Breast model



(b) Force and displacement of the breast model.



(c) Softness-display device case



(d) Finger holder case

Figure 8. Experimental Environment of Experiment 3.

When the subjects touched the virtual object, we carried out two methods: method 1 used the conventional haptic interface (previous finger holder) and method 2 used the developed softness-display device (newly developed finger holder).

We measured the relationship between the force and the displacement of the breast palpation model (Fig. 8 (a)) using a force gauge before the experiment. The measurement result is shown in Fig. 8 (b). For the comparison, we show the response of the softness-display device at 270 deg in Fig. 5 (the average error between the responses of the breast model and the softness display device was 0.03 N). The stiffness of the model was about K=100 N/m from the experimental results. When we display the softness using method 1, the haptic finger is controlled using (2) and we set $\boldsymbol{F}_d = K \times d$ N, where d is the penetration depth. On the other hand, when we display the softness using method 2, we set the followings: the softness-display device is controlled using (1) and we set θ^{d} = 270 deg, and the haptic finger is controlled using (2) and we set $\boldsymbol{F}_d = \tilde{K} \times d$ N, where $\tilde{K}$ = 1 kN/m.

In the experiment, the subject touches the actual object/virtual object using his index finger as shown in Fig. 8 (a). Eight people in their twenties participated in this experiment and we divided the participants into two groups, A and B. (All participants were male and are right-handed.) To eliminate any effect caused by the sequence of experiments, we set up the order of the method in each group as shown in Table II. The participants carried out the experiments in the following manner: (1) First the participant touched the actual object using his index finger, and memorized the touch sensation. Here, note that the place the participant touched was where the stiffness of the model was measured. When we touch an actual object, the object's shape is deformed, but the

TABLE II. THE SEQUENCE OF METHOD IN EXPERIMEN 3

Order of methods	Group A	Group B
1	Method 1	Method 2
2	Method 2	Method 1

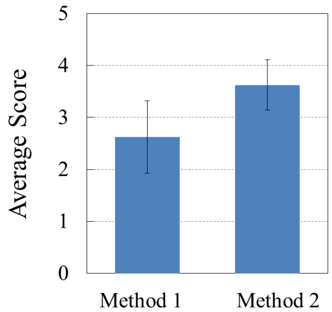


Figure 9. Results of questionnaire.

virtual object is not visibly changed when it is touched. So, we eliminated the sight information of the participant to remove the influence of softness perception by visual information. Further, in the case of the actual object and the virtual object, the participant was instructed to push the object using the same speed. (2) the participant touched the virtual object using the corresponding method. After the experiment, the participant was asked to rate the similarity of the two touch sensations on a five-point scale, in which 1 is the lowest rating and 5 is highest The order of the presentations varied: for example, the participants in group A carried out the experiment outlined in steps (1) to (2) using Method 1. After 30 minutes passed, the participants carried out the experiment in steps (1) to (2) using Method 2.

Fig. 9 shows the results of the questionnaire. In this figure, the horizontal axis shows the method, and the vertical axis shows the average score. The vertical bar shows the standard variation of the corresponding value. A Wilcoxon signed-rank test was carried out for methods 1 and 2. The test showed a significant difference between the method 1 and method 2 ($Z=-1.99$, N=8, $p=0.046<0.05$). This shows that the proposed softness-display device is more effective for softness display than the conventional haptic interface (previous finger holder). Further, we obtained the following comments from the participants: The softness-display system presents the feeling which surrounds the finger, and it is similar to the experience of touching a real object; the textures at the time of finger contact are alike in the softness-display system. On the other hand, we obtained the following comments for the conventional haptic interface: the participant has a feeling that the contact surface is small; there is a feeling of pushing a spring. For this reason, the proposed softness-display system can display the sensation of softness with high precision compared with the conventional haptic interface. Moreover, differences in the softness can be perceived more clearly.

V. CONCLUSION

In this paper, we describe a haptic interface for softness display at multiple fingertips. To accomplish this aim, we developed a softness-display device using a flexible sheet, and present the concept of softness display by combining the developed softness-display device and the side-faced-type multi-fingered haptic interface robot for softness display to multiple fingers. In addition, this setting can ensure a large workspace and can realize the case where the softness differs with each finger. Further, the control method of the softness-display system, and the results of an experimental evaluation are presented. Through the experiments, we found that the proposed system has a remarkable softness display performance compared with our earlier method; thus, the proposed system can be considered effective for softness display at multiple fingers.

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