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A finger skill transfer system using a multi-fingered haptic interface robot and a hand motion image

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SUMMARY

The teaching of how to exert fingertip forces and how to move the fingers is essential for transferring skill using the fingers to perform fine motor tasks. In this paper we accomplish the transfer of fingertip forces and positions in three-dimensional space by combining a multi-fingered haptic interface robot, which can measure and present the three-dimensional forces and positions at five fingertips, and an image display system that records a trainer's hand image and displays it to a trainee. Several experimental results show a high fingertip force and position transferability and the great potential of our proposed transfer system.

KEYWORDS: Haptic interfaces, Man–machine systems, Virtual reality, Fine motor skill in fingers, Skill transfer, Hand motion image.

1. Introduction

The expert skill transfer from a trainer to a trainee has become one of the most important issues in various fields. For example, in the manufacturing industry in Japan, in addition to the aging of skilled engineers and shortage of successors, the problem of experts' skill transfer is expanded under the influence of the falling birthrate and the aging population.[1,2] In the medical field, expert skills, such as palpation and surgical techniques, are obtained by long-term training, and the skill is normally acquired by the experience of working with actual patients. However, it is difficult for residents and medical students to train directly with actual human bodies due to patient safety issues, and training with animals is also problematic because of ethical concerns.[3,4] Analyzing skill transfer for human palpations has been studied for a long time in various applications (e.g., Foulke[5] examined the mechanics of reading in Braille). The teaching of how to exert fingertip forces and how to move fingers is essential for transferring skills using fingers for fine motor tasks. However, the trainee cannot capture exact fingertip force and position information by simply watching and imitating the trainer's motion in the apprenticeship system or by following instructions in books or delivered by a teacher.

Because of these challenges, a skill transfer system that uses virtual reality (VR) and haptic interface technologies has been researched aggressively (e.g., see refs. [6–14] and references in survey papers by Maclean and Hayward,[15] and Marchal-Crespo and Reinkensmeyer[16]). When instructed by a training model in the VR environment, the trainee feels realistic force sensation when touching virtual models in the VR environment through a haptic interface. Further, the movement of the trainer's hand and force can be recorded, and thus the accurate force and position information, which can be transmitted without the use of words or images, can be displayed to the trainee using a screen and haptic interface. This training method is known as a record-and-replay strategy.[6] A skill transfer system that uses VR and haptic interface technologies could dramatically increase the efficiency of skill transfer. In fact, studies in the field of psychology have shown that feedback or presentation of performance to trainee is important for skill acquisition.[17,18]

Several studies have examined the transferring of the force and position information about human hand.[10–14] Henmi and Yoshikawa[10] developed a virtual calligraphy system using a brush-type haptic interface. In this system, based on the record-and-replay strategy, the position and force trajectories of the teacher's writing brush are recorded, and then these trajectories are displayed to the student using the haptic interface and the visual display. Saga *et al.*[11] also developed a haptic teaching system to teach a handwriting task. In this system, the force exerted by an expert with a brush is recorded, and the force is displayed to the trainee in the opposite direction, and the force transfer is enabled by training so that the trainee tries to cancel the force. Note that these systems considered the transferring of one-dimensional force and two-dimensional position. Okuda *et al.*[12] proposed a skill transfer system designed for transferring one-dimensional finger position and one-dimensional finger force. Williams II *et al.*[13] developed a two-mode playback training system for palpation of human back. In mode 1, the trainee is guided to the recorded expert's position trajectory. In mode 2, the recorded expert's position trajectory is displayed on a monitor by a ball. The trainee moves his/her fingertip so that his/her fingertip is in agreement with the displayed ball, which is the expert's fingertip position. If the trainee can touch exactly the same position as the expert, the trainee can learn the same force as the expert's fingertip force. This system considered the transfer of one fingertip force and one fingertip position. Morris *et al.*[14] showed that the visuohaptic training is an effective tool for teaching an abstract motor skill. In their system, the trainee is guided along a two-dimensional position trajectory by the haptic interface, and he/she is asked to learn a sequence of one-dimensional force, which

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is displayed in visual display. However, in many studies, including those described above, the force display is limited to one point/place and it is not aimed at teaching the force of two or more fingers as occurs in actions such as palpation. There have been studies of work using multiple fingers,[19–24] but these systems use a simulator, and the methodology about the transfer of multiple fingertip forces and positions is not shown. Therefore, in a three-dimensional space, the skill instruction using multiple fingers is not yet realizable.

Using a multi-fingered haptic interface robot named HIRO III,[25] which can display and measure three-dimensional forces and positions at five fingertips, we developed a skill transfer method in which the recorded trainer's multiple fingertip positions and forces in a three-dimensional space are transferred to the trainee.[26] In this skill transfer method, the aim of the trainee is to make his/her five-fingertip positions and forces track the trainer's five-fingertip positions and forces, respectively. To accomplish this, we proposed a skill transfer system consisting of visual and force cues. The visual cue was used for the tracking of fingertip positions. For the tracking of fingertip forces, HIRO III alternately presents the reaction force, $\mathbf{F}_r$, which the trainee feels from the virtual object, and the trainer's force, $\mathbf{F}_t$ to the trainee. In our earlier study[26] we showed that this method allows the transferring of multiple fingertips' forces and positions. However, for force tracking, this method did not transfer multiple fingertips' forces well when the fingertip forces and positions changed a lot at a high speed with significant changes in the direction of the forces. We believe that this is because the posture information of the trainer's fingers was not transferred to the trainee. For example, even if all the fingertip positions are the same, the directions of the fingertip forces that can be presented changes depending on finger postures. We believe that we can improve on our previous developed skill transfer method by displaying the recorded trainer's hand to the trainee. By looking at the trainer's hand image, the trainee realizes difference between the operation of his or her own fingers and the operation of the trainer's fingers, thus improving learning. Here note that to grasp/manipulate a complicate-shaped object stably, the magnitude and the direction of the fingertip force are important. For this reason, the transferring of the magnitude and the direction of the fingertip force is essential.

Here we describe our plan for an improved skill transfer system using expert's recorded hand image and a multi-fingered haptic interface robot, and we accomplish the transfer of fingertip forces, which includes the magnitude and the direction, and positions in a three-dimensional space. Furthermore, we describe our experimental investigation of the performance using the proposed method and show this method's great potential.

This paper is organized as follows: In Section 2 a multi-fingered haptic interface robot, HIRO III, and our previous skill transfer method are introduced. Section 3 presents a newly developed skill transfer method, and Section 4 introduces the experimental measures to examine the experimental results. The experimental results are described in Sections 5 and 6. Finally, Section 7 presents our conclusions.

2. Multi-Fingered Haptic Interface Robot and Previous Skill Transfer Method

2.1. Multi-Fingered haptic interface robot

Multi-fingered haptic interface allows multipoint contact between user and virtual environment, and it has great potential for various applications than do single-point haptic interfaces. In particular, a haptic interface consisting of arm and fingertips can be used in a large workspace.[27–30] However, most of these consist of a hand-exoskeleton-and-arm or a hand-and-arm-exoskeleton system. In general, these induce oppressive feelings in users because of the hard fixing of the interface hand. Further, it is difficult to present three-directional forces or the weight of virtual objects through fingertips because the hand mechanism is mounted on the back of a human hand, and the exerted force is only a one-directional force. From these points of view, we developed a multi-fingered haptic interface robot, named HIRO III,[25] which is shown in Fig. 1. HIRO III can present three-dimensional forces at an operator's five fingertips and can measure three-dimensional forces and positions at the

(a) HIRO III (Haptic Interface RObot III). (b) Finger holder.

Fig. 1. (Colour online) Multi-fingered haptic interface robot, HIRO III, and a finger holder. (a) Haptic Interface RObot III (HIRO III). (b) Finger holder.

Table I. Specifications of HIRO III.

Degrees of freedom (DOF)	Hand: 15 DOF (number of haptic fingers: 5) Arm: 6 DOF
Performance	Maximum output force of haptic finger: over 3.6 N Maximum displayable stiffness: 5 kN/m Frequency response: 8 Hz Sampling time of control: 1 kHz

operator's five fingertips. Further, it should neither cause an oppressive feeling when attached to the user's hand nor represent its own weight. The specifications of HIRO III are shown in Table I.

HIRO III consists of an arm and a haptic hand. The arm consists of an upper arm, a lower arm, and a wrist. The arm has 3 degrees of freedom (DOF) at the arm joint and 3 DOF at the wrist joint. The arm, therefore, has six joints allowing 6 DOF. The haptic hand is constructed of five haptic fingers. Each haptic finger has three 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 total DOF of HIRO III is 21, and its working space covers VR manipulation on the space of a desktop. HIRO III has motors, including an encoder at each joint, and a three-axis force sensor, which is installed on the top of each haptic finger to display force sensations and measure forces and positions at the operator's five fingertips. To manipulate HIRO III, operator wears a finger holder, a sample of which is shown in Fig. 1(b), on each of his/her fingertips. The finger holder has a steel sphere, and the haptic finger has a permanent magnet at its fingertips. By means of magnet force, the finger holder can be connected to HIRO III, as shown in Fig. 1(a). Here, note that the sphere when attached to the permanent magnet at the force sensor tip forms a passive spherical joint. Its role is to adjust for differences between the human and haptic finger orientations.

HIRO III is controlled by a combinational approach with Proportional and Integral (PI) force control for haptic finger and position control for arm. Each haptic finger is independently controlled by a PI force control using a force error at fingertips. In the arm position control, a desired hand posture is determined to maximize the hand manipulability measure to respond to operator's various hand poses. The hand manipulability measure is defined as follows:

$$\begin{aligned}\mathrm{CPI} = \sum_{i=1}^{5} (\alpha_i \, |\det(\boldsymbol{J}_{Fi})| + \beta_i \, P_i) \\ - \frac{1}{2} \left(\boldsymbol{q}_{Ad} - \boldsymbol{q}_A\right)^T \boldsymbol{\Gamma} \left(\boldsymbol{q}_{Ad} - \boldsymbol{q}_A\right),\end{aligned} \tag{1}$$

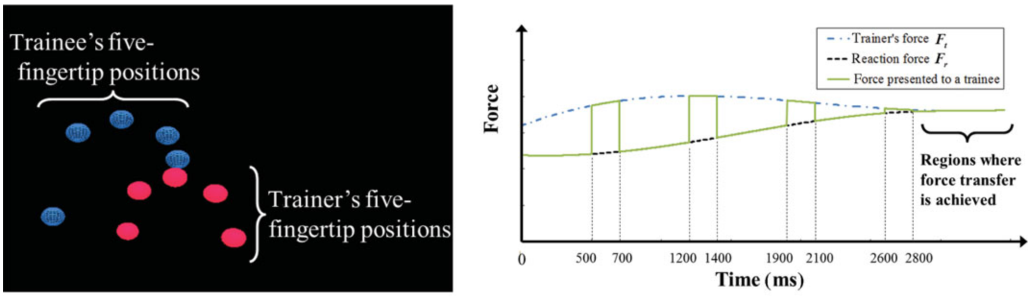
$$P_i = -\sum_{j=1}^{3} \gamma_j [\exp\{-\mu(q_{ij} - a_{ij})\} + \exp\{(\mu(q_{ij} - b_{ij})\}], \tag{2}$$

where CPI means the Control Performance Index, α_i and β_i are the weighting coefficients, $\boldsymbol{J}_{Fi}$ is the Jacobian of the ith haptic finger, P_i is the penalty function to keep the haptic finger joint angles within the movement range, γ_i is the weighting coefficient, μ is the parameter to adjust an exponential function, a_{ij} and b_{ij} are the lower and upper limits of the jth joint angle of the ith finger, respectively, $\mathbf{q}_A \in R^6$ is the arm joint angle, $\mathbf{q}_{Ad} \in R^6$ is the desired arm joint angle, and $\boldsymbol{\Gamma}$ is the weighting matrix. The desired arm joint angle is defined so as to maximize Eq. (1). The second term on the right-hand side of Eq. (1) is added to prevent a large arm motion, which sometimes confuses the operator because it creates the illusion that the device is malfunctioning. The optimum arm joint angle is computed by the conjugate gradient method. Therefore, the arm is controlled so that the hand manipulability index contributes to keeping a better position and orientation of the haptic hand. For more details, see Endo *et al.*[25]

2.2. *Our previous skill transfer system*

Our skill transfer system is based on the record-and-replay strategy, and thus the trainer's work is recorded and then reproduced in the VR space. The trainee's goal is to make his/her fingertip positions and forces track the trainer's positions and forces, respectively. Our previously proposed skill transfer system[26] consists of a fingertip positions tracking part and a fingertip forces tracking part.

For fingertip positions tracking, we used the visual cues shown in Fig. 2(a). The five-fingertip positions of the trainer and trainee are shown as small spheres in the VR space, and the trainee controlled his/her fingertip positions to track the trainer's positions. On the other hand, in the skill transfer system, there are two kinds of forces transferred to the



(a) Visual cues for position tracking.

(b) Force presented to a trainee.

Fig. 2. (Colour online) Our previous skill transfer method. (a) Visual cues for position tracking. (b) Force presented to a trainee.

trainee: the reaction force, $\mathbf{F}_r$, from the virtual object, and the force that a trainer exerts on an object, $\mathbf{F}_{\text{trainer}}$. (when we presented this force to the trainee, we considered the force in the opposite direction, that is $-\mathbf{F}_{\text{trainer}}$. In the following, the force $-\mathbf{F}_{\text{trainer}}$ is called the trainer's force, $\mathbf{F}_t$.). For the fingertip forces tracking, $\mathbf{F}_r$ and $\mathbf{F}_t$ were presented to the trainee and were switched over time as shown in Fig. 2(b). Here a dashed-dotted line presents $\mathbf{F}_t$, a dashed line presents $\mathbf{F}_r$, and a solid line is the force presented to the trainee, and $\mathbf{F}_r$ and $\mathbf{F}_t$ are alternately presented to the trainee. In practice if the force such as the one shown in Fig. 2(b) was presented to the trainee, the trainee would feel the pulse force that is the difference between the recorded trainer's force and the trainee's force. Thus, if the trainee regulates his/her fingertip forces so that the pulse forces become small, the force transfer is achieved. As an example, we have marked regions in Fig. 2(b) where force transfer is achieved. Here note that the pulsating force is simply a replay of the recorded force acquired from the trainer given in the opposite direction. Therefore, if the trainee touches the same position as that of the trainer, then the trainee can feel the same force as that of the trainer, and we assumed that the trainee can control position error small by the visual cues, as in Williams II *et al.*[13] Furthermore, $\mathbf{F}_t$ is not presented to a trainee when the trainee is not touching the virtual object. This is because the trainee will be confused if the pulsing force is presented when the trainee is not touching the virtual object. However, it turned out that it was extremely difficult for the trainee to understand difference in direction between the trainer's fingertip forces and trainee's fingertip forces, even if the position and the magnitude of the force were understood.

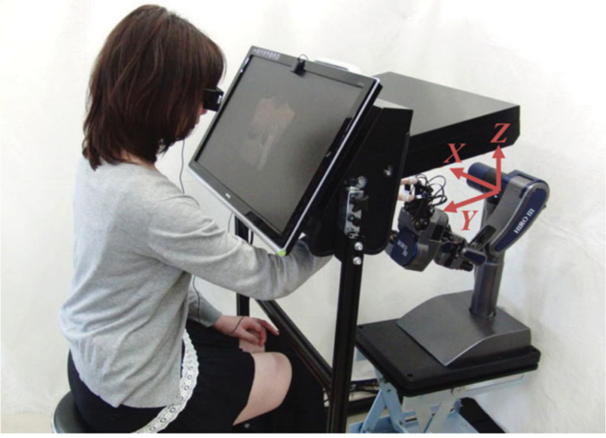


Fig. 3. (Colour online) Finger skill transfer system.

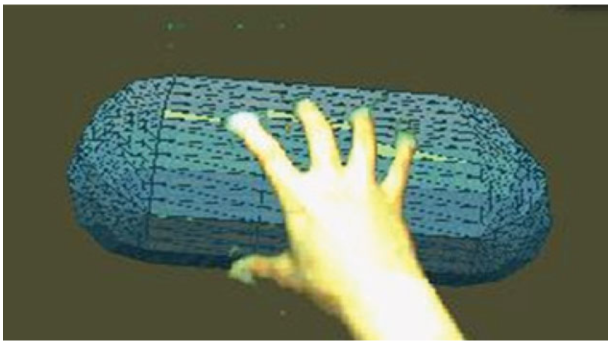


Fig. 4. (Colour online) The screen in the finger skill transfer system.

3. Finger Skill Transfer System

In our earlier research, we presented the trainer's fingertip forces by HIRO III and displayed the trainer's fingertip positions as small spheres to the trainee, and then we tried to transfer the trainer's fingertip force and position information to the trainee. Although we could transfer the fingertip forces' magnitude and positions using this method, the directions of the forces were not transferred well. In particular, this method did not transfer multiple fingertips' forces well when the fingertip forces and positions changed a lot at high speed and with large changes in direction. We think this was because the fingertip position information was displayed by using small spheres visually. The sphere has position information but no orientation information. Therefore, the trainer's finger posture was not transferred to the trainee, leading to the above problem. For example, even if all fingertip positions are the same, the directions of the presented fingertip forces may change depending on the fingertip posture. To solve this problem, we recorded the trainer's hand motion image and displayed it to the trainee. Using the expert's recorded hand image and a multi-fingered haptic interface robot, we accomplished the transfer of human fingertip forces, which included the magnitude and the direction, and positions in three-dimensional space. Further, by displaying the trainer's hand image to the trainee, the trainee realizes the difference between the operation of his or her own fingers and the operation of the trainer's fingers, resulting in better learning.

3.1. System architecture

Figure 3 shows the newly developed finger skill transfer system. This system uses HIRO III as a haptic interface. Further, as the image display system presenting the stereoscopic image of a VR environment to an operator, we used the immersive stereoscopic display manufactured by Tokyo System Composition Technology Co. Ltd., shown as the black housing part in Fig. 3. The CCD camera is built into the display system, and the image of the computer-generated VR environment and the camera-recorded image of the operator's hand of HIRO III are superimposed, and the created image is displayed at the operator's fingertips. This leads to the correct visual/haptic registration.[31] This image shows the stereoscopic image through the use of shutter glasses technology. We show the screen in the finger skill transfer system in Fig. 4.

3.2. Proposed transfer method

The proposed transfer method is based on the record-and-replay strategy, and the trainee's goal is to make his/her fingertip positions and forces track the trainer's positions and forces, respectively. To accomplish this, we propose the transfer method of fingertip forces and positions in three-dimensional space by combing a multi-fingered haptic interface robot and a hand motion image display.

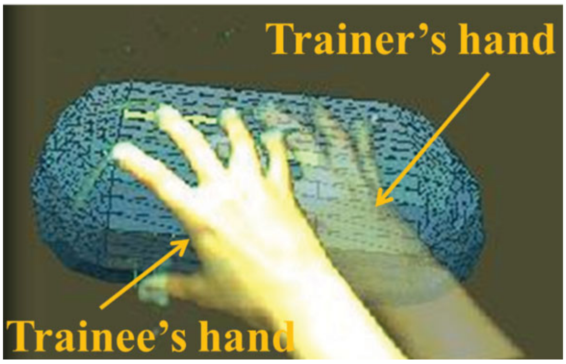


Fig. 5. (Colour online) Hand motion images in the proposed transfer method.

3.2.1. Fingertip position transfer. For fingertip position transfer, the trainer's hand motion image is recorded, and the image is displayed to the trainee. In addition, to distinguish the trainee's own hand motion image and the expert's hand image during training, the expert's hand motion image is displayed translucently as shown in Fig. 5. The trainee controls his/her fingertip positions by copying those of the trainer, by which the transferring of the fingertip position and posture can be expected.

3.2.2. Fingertip force transfer. For fingertip force transfer, we use the recorded trainer's fingertip force, $\mathbf{F}_t$ (note that $\mathbf{F}_t = -\mathbf{F}_{\text{trainer}}$), and the fingertip force that is the reaction force from the virtual object, $\mathbf{F}_r$. We set HIRO III to present $\mathbf{F}_r$ to the trainee for 500 ms and then to present $\mathbf{F}_t$ to the trainee for 200 ms and then repeat the process as shown in Fig. 2(b). For more details, see Endo *et al.*[26] When the force such as the one shown in Fig. 2(b) was presented to the trainee, the trainee would feel the pulse force that is the difference between the recorded trainer's force and the trainee's force. Thus, if the trainee regulates his/her fingertip forces so that the pulse forces become small, the force transfer is achieved. If the trainee does not touch the virtual object, namely, when $\mathbf{F}_r = 0$, the trainer's force $\mathbf{F}_t$ is not presented to the trainee. We can use the image of the recorded trainer's hand motion to transfer information about the fingertip force direction to the trainee.

4. Experimental Measures

To examine the experimental results, we presented the following three items: (i) the average integral value of fingertip force error norm, (ii) the average integral value of absolute fingertip force angle error, and (iii) the average integral value of fingertip position error norm.

To determine the magnitude error between the trainer's fingertip forces and those of the trainee, we calculate the average integral value of fingertip force error norm (FEN) as follows:

$$\text{FEN} = \frac{1}{5}\sum_{i=1}^{5}\int_{T_1}^{T_2} \left\| \boldsymbol{f}_i^{\text{trainer}}(t) - \boldsymbol{f}_i^{\text{trainee}}(t) \right\| dt, \qquad (3)$$

where $\boldsymbol{f}_i^{\text{trainer}}$ is the ith fingertip force vector of the trainer, $\boldsymbol{f}_i^{\text{trainee}}$ is the ith fingertip force vector of the trainee, T_1 is the start time of the task, and T_2 is the final time of the task. If this value is small, the magnitude error between the trainer's fingertip force and the trainee's fingertip force is small.

To determine the direction error between the trainer's fingertip forces and the trainee's fingertip forces, we calculate the average integral value of the absolute fingertip force angle error. When we use polar coordinates, we can express the force $\mathbf{F} = [F_x, F_y, F_z]^T$ by using two angle variables, θ and φ, for example, $F_x = ||\boldsymbol{F}||\sin\theta\,\cos\varphi$, $F_y = ||\boldsymbol{F}||\sin\theta\,\sin\varphi$, $F_z = ||\boldsymbol{F}||\cos\theta$. Thus, we derived the following average integral value of the absolute fingertip force angle error (FAE):

$$\text{FAE} = \frac{1}{5}\sum_{i=1}^{5}\int_{T_1}^{T_2} \frac{1}{2}\Big[\left|\theta_i^{\text{trainer}}(t) - \theta_i^{\text{trainee}}(t)\right| + \left|\varphi_i^{\text{trainer}}(t) - \varphi_i^{\text{trainee}}(t)\right|\Big] dt, \qquad (4)$$

where $\theta_i^{\text{trainer}}$ and $\varphi_i^{\text{trainer}}$ are the two angle variables of the trainer's ith fingertip force, and $\theta_i^{\text{trainee}}$ and $\varphi_i^{\text{trainee}}$ are the two angle variables of the trainee's ith fingertip force. If this value is small, the direction error between the trainer's fingertip force and the trainee's fingertip force is small.

To determine the position error between the trainer's fingertip positions and the trainee's fingertip positions, we calculate the average integral value of the fingertip position error norm (PEN) as follows:

$$\text{PEN} = \frac{1}{5}\sum_{i=1}^{5}\int_{T_1}^{T_2} \left\| \boldsymbol{p}_i^{\text{trainer}}(t) - \boldsymbol{p}_i^{\text{trainee}}(t) \right\| dt, \qquad (5)$$

where $\boldsymbol{p}_i^{\text{trainer}}$ is the ith fingertip position vector of the trainer and $\boldsymbol{p}_i^{\text{trainee}}$ is the ith fingertip position vector of the trainee. If this value is small, the position error between the trainer's fingertip position and the trainee's fingertip position is small.

5. Experiment 1: The Effect of a Hand Image on Force Tracking

To verify the effectiveness of the proposed transfer method, we performed an assessment experiment to investigate the effect of the trainee viewing a hand image on force tracking.

5.1. Experimental setup

In the experiment, we used the finger skill transfer system as shown in Fig. 3. The transfer methods we compared were our earlier method (Method 1) and the proposed method (Method 2). In Method 1, the fingertip positions of the trainer and the trainee are shown as small spheres, and the fingertip forces of the trainer and the trainee are presented by using the method described in Section 2.2. In Method 2, the hand motion images of the trainer and the trainee are shown, and the fingertip forces of the trainer and the trainee are alternately presented as described in Section 3.2. In addition, to confirm the effect of displaying the trainer's hand motion image, we carried out Method 3, where the expert's fingertip forces were not presented to the trainee (namely, $\mathbf{F}_t$ was not presented and $\mathbf{F}_r$ was presented), but the hand motion images of the trainer

Table II. Experimental methods.

	Position tracking	Force tracking
Method 1	Small spheres	$\mathbf{F}_r$ and $\mathbf{F}_t$ are alternately presented
Method 2	Hand motion images	Same as Method 1
Method 3	Same as Method 2	$\mathbf{F}_r$ is only presented

and trainee were shown. To clarify the differences between the methods, we have summarized the methods (Method 1, Method 2, and Method 3) in Table II.

In the experiment, the trainer touches the virtual object using five fingers in the VR environment, and the trainer applies forces to the virtual object without moving his or her fingertip position. The total time of the task is 8.6 s. The virtual object is a blue polyhedron as shown in Fig. 4. The force displayed at the *i*th finger when the operator touches the virtual object is calculated as $\boldsymbol{f}_i = \boldsymbol{f}_i^c + \boldsymbol{f}_i^f$, where $\boldsymbol{f}_i^c$ and $\boldsymbol{f}_i^f$ are the constraint and the friction force, respectively. In the experiment, we set $\boldsymbol{f}_i^c$ and $\boldsymbol{f}_i^f$ using the following equations:

$$\boldsymbol{f}_i^c = K\boldsymbol{a}_i^n + D\boldsymbol{v}_i^n, \tag{6}$$

$$\boldsymbol{f}_i^f = \begin{cases} \eta_i \left\| \boldsymbol{f}_i^c \right\| \boldsymbol{t}_i + d_i \boldsymbol{v}_i^t \\ \quad \text{(in the case of the static friction force)} \\ \lambda_i \left\| \boldsymbol{f}_i^c \right\| \boldsymbol{t}_i + \gamma_i \boldsymbol{v}_i^t \\ \quad \text{(in the case of the dynamic friction force)} \end{cases}, \tag{7}$$

where the penetration depth vector of the *i*th finger into the virtual object is decomposed to the normal directional vector, $\boldsymbol{a}_i^n$, and the frictional directional vector, $\boldsymbol{a}_i^t$; $\boldsymbol{v}_i^n$ and $\boldsymbol{v}_i^t$ are the normal and the frictional directional relative speeds between the fingertip velocity and the virtual object velocity, respectively; K is the stiffness of the virtual object; and D is the damping coefficient of the object. Furthermore, η_i is the coefficient of static friction given by $\eta_i = ||\boldsymbol{a}_i^t||/||\boldsymbol{a}_i^n||$, d_i is the damping coefficient, λ_i is the coefficient of the dynamic frictional force, γ_i is the damping coefficient at the dynamic friction state, and $\boldsymbol{t}_i$ is the unit vector of the frictional force direction. In this experiment, we set $K = 350.0$, $D = 5.0 \times 10^{-3}$, $d_i = \gamma_i = 0.03$, and $\lambda_i = 0.1 \times 10^{-3}$ (for technical details, see Kawasaki *et al.*[32])

Before we carried out the experiment, the person who acted as the trainer performed the task. This person was not included among the six participants in the experiment described below. After we obtained the force and position information of the trainer's fingertips, we set the trajectories of the fingertip force and position and the hand motion image to match those of the trainer. For example, the fingertip force trajectories of the trainer's thumb are shown in Fig. 6. In this figure, F_x, F_y, and F_z are *X*-, *Y*-, and *Z*-axis fingertip force responses, respectively (see the axes in Fig. 3.)

Table III. The sequence of transfer method in Experiment 1.

Order of methods	Group A	Group B	Group C
1.	Method 1	Method 3	Method 2
2.	Method 2	Method 1	Method 3
3.	Method 3	Method 2	Method 1

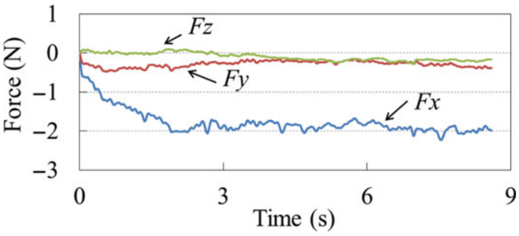


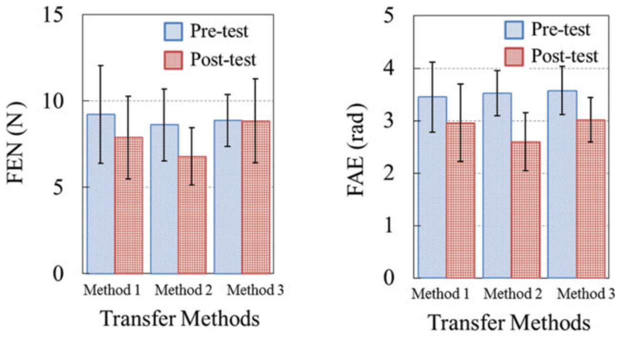
Fig. 6. (Colour online) The fingertip force trajectories of the trainer's thumb in experiment 1.

Six people in their twenties participated in this experiment, and we divided the participants into three groups: A, B, and C (all participants had no experience in medical/surgical training, and their major area of study was robotics or haptics (study of the haptic training was not contained). All participants are right-handed.) To eliminate any effect caused by the sequence of experiments, we set up the order of the transfer method in each group as shown in Table III. The participants carried out the experiments in the following manner: (1) To become familiar with HIRO III and the image display system, the participants practiced with them until they became comfortable, which happened within 10 min in all the cases. (2) The participant confirmed the trainer's trajectory. That is, the fingertip positions of the trainer were shown as small spheres graphically in the VR environment, and the participant saw and confirmed the trajectory of the trainer's fingertips. (3) The fingertip positions of the trainer and the trainee were shown graphically as small spheres in the VR environment, and the trainee carried out the task based on this visual information. This was performed twice, and we measured the initial errors. These data corresponded to the error before training. (4) The participant carried out the task for 10 times continuously using the corresponding transfer method. (5) The participant carried out the task under the same condition as in step (3). This was performed twice, and we measured the final errors. These data corresponded to the errors after training. For example, the participants in group A carried out the experiment outlined in steps (1) to (5) using Method 1. After enough time passed, the participants carried out the experiment in steps (1) to (5) using Method 2, and then using method 3. Here, note that we used the same settings for familiarization and instruction as well as the pre-test and post-test sessions in all methods. That is, steps (1), (2), (3), and (5) were the same in Methods 1, 2, and 3.

To examine the experimental results, we calculated FEN (Eq. (1)) and FAE (Eq. (2)), where we set $T_1 = 0$ s and $T_2 = 8.6$ s in Eqs. (1) and (2).

5.2. *Experimental results*

Figures 7(a) and (b) show FEN and FAE values, respectively. In each figure, the horizontal axis shows the transfer method, and the vertical axis shows the corresponding result. The blue bar graph is the result of the pre-test, and the red bar graph is the result of the post-test. The vertical bar shows the standard deviation (SD) of the corresponding value.



(a) FENs. (b) FAEs.

Fig. 7. (Colour online) Experimental results in experiment 1. Error bars show ± SD. (a) FENs. (b) FAEs.

For FEN, as shown in Fig. 7(a), we conducted a two-way repeated measures ANOVA on FEN value, with the training effect (before or after the training) and training method (Methods 1, 2, or 3). We found a significant effect of training ($F(1, 66) = 3.912$, effect size $\eta^2 = 0.052$, $p = 0.052 < 0.1$), but there was no significant effect for training method ($F(2, 66) = 1.653$, $\eta^2 = 0.044$, $p = 0.199$) and there was no interaction between the training effect and the training method ($F(2, 66) = 0.990$, $\eta^2 = 0.026$, $p = 0.377$). Further, a two-tailed paired t-test was carried out for pre-test and post-test for each transfer method. The t-test showed a significant difference between the pre-test (9.22) and the post-test (7.89) in Method 1 ($t = 2.77$, DOF $= 11$, $p = 0.018 < 0.05$), and Method 2 also had a significant difference between the pre-test (8.63) and the post-test (6.78) ($t = 2.31$, DOF $= 11$, $p = 0.041 < 0.05$). There was no significant difference between the pre-test (8.89) and the post-test (8.85) for Method 3 ($t = 0.06$, DOF $= 11$, $p = 0.952$). Thus, we found that there was a training effect for Methods 1 and 2, and the training decreased the magnitude error of the fingertip force. On the other hand, we considered that there was no training effect for Method 3.

Next, for FAE, as shown in Fig. 7(b), we carried out a two-way repeated measures ANOVA with the training effect and training method. We found a significant effect of training ($F(1, 66) = 22.829$, $\eta^2 = 0.246$, $p = 1.03 \times 10^{-5} < 0.01$), but there was no significant effect for training method ($F(2, 66) = 1.453$, $\eta^2 = 0.031$, $p = 0.241$) and there was no interaction between the training effect and the training method ($F(2, 66) = 0.496$, $\eta^2 = 0.011$, $p = 0.611$). Here we carried out a two-tailed paired t-test. In Method 1, there was a significant difference between the pre-test (3.53) and the post-test (2.96) ($t = 2.78$, DOF $= 11$, $p = 0.018 < 0.05$). There was also a significant difference between the pre-test (3.45) and the post-test (2.60) in Method 2 ($t = 4.80$, DOF $= 11$, $p = 5.51 \times 10^{-4} < 0.01$), and between the pre-test (3.57) and the post-test (3.02) ($t = 3.16$, DOF $= 11$, $p = 0.006 < 0.01$) in Method 3. Therefore, for the force direction of the fingertip, unlike the case of the force magnitude error, all methods had a training effect, and we found that the direction error of the fingertip force decreased with training.

Based on the two evaluation items described above, we conclude that Methods 1 and 2 have a training effect, while Method 3 has no training effect. In this experiment we considered the performance of a task that involves pushing the fingertips straight to the virtual object, and thus there were no big changes in the fingertip forces (Fig. 6). Thus, we consider that the transfer of the fingertip forces' magnitude and the direction was possible by our previous method (Method 1). However, the errors after training in Method 2 were small compared with Method 1, and the training effect of Method 2 was the largest. Here note that when many pieces of information are visually displayed to human beings, retention is not as good and the training is not effective.[33] In the proposed method (Method 2), the trainer's and trainee's hand motion images were used instead of the visual cues shown in Fig. 2(a), which shows the trainer's and trainee's fingertips (Method 1), and thus there was the possibility to increase the information displayed to the trainee. However, Method 2 has a training effect, and we believe that the image does not exert wrong influence on the transferring of the fingertip force. On the other hand, a remarkable training effect was not seen in Method 3. This is considered to be the result of expressing the following explicitly: the trainee cannot catch the exact force information by using only the images.

In this part of our experimentation, we considered a task in which the fingertips apply force to the virtual object while keeping the fingertip position immobile. We investigated the effect of viewing a hand image on force tracking. We next considered breast palpation as a task using multiple fingers, and we investigated the effect of viewing a hand image on skill transfer through the assessment experiment.

6. Experiment 2: The Movement in Breast Palpation

This section deals with breast palpation as a task that requires the use of multiple fingers. Unlike the previous task, the fingertip position changes during the performance of this task. Using a specific task, we consider the effectiveness of the proposed method.

6.1. Experimental setup

In the experiment we used the finger skill transfer system shown in Fig. 3, which is the same as that described in Section 5.1. We compared Method 1 (our earlier method), Method 2 (the proposed method), and Method 3 (the expert's fingertip forces are not presented to the trainee but the hand motion images of the trainer and trainee are shown). The methods used are the same as the methods described in Section 5.

The task of the trainer is breast palpation, during which one uses hand to apply pressure using two or more fingertips, moving the fingers radially. In this section, as an example, we considered the task of moving a finger while applying force diagonally to the right from the center of a breast. For this task, we used index finger, middle finger, and ring finger. Figure 8 shows the VR environment used in the experiment (Method 2 was used as the transfer method in the figure). The virtual breast was a spring-damper model like the virtual object used in the experiment in Section 5. Thus, the force displayed at the ith finger when the operator touches the virtual breast is calculated using Eqs. (6) and (7). In the

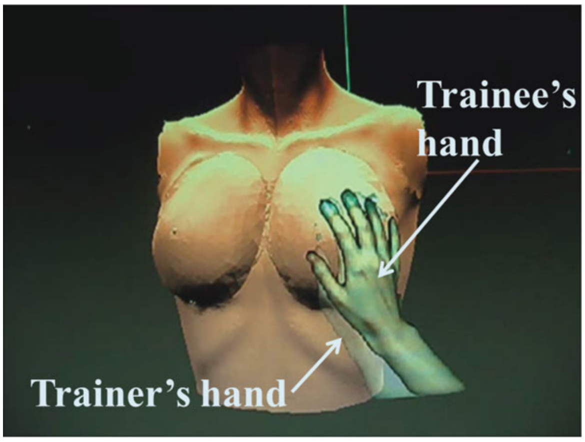


Fig. 8. (Colour online) Virtual environment in experiment 2 with method 2.

experiment, we set $K = 230.0$, $D = 2.0 \times 10^{-3}$, $d_i = \gamma_i = 0.03$, and $\lambda_i = 0.5$.

Before we carried out our experiment, the person who acted as the trainer performed the task. This person was not included among the six participants in the experiment described below. After we obtained the force and position information of the trainer's fingertips, we set the trajectories of the fingertip force and position and the hand motion image to the trainer's values. For example, the force and the position trajectories of the trainer's index finger are shown in Figs. 9(a) and (b), respectively. For the axis in this figure, see the axes in Fig. 3.

Six people in their twenties participated in this experiment, and we divided the participants into groups A and B (all participants had no experience in medical/surgical training, and their major area of study was robotics or haptics (study of haptic training was not contained). All participants are right-handed). Although there was no problem in the task with a fixed fingertip in Section 5 if the proposed method (Method 2) and Method 3 were performed ahead of Method 1, there was a possibility that the participants may memorize the image. The hand image had no influence on performance of the task in which the fingertips were fixed, but an influence was expected in the task with finger movement. In consideration of this, for the experimental sequence we set up the order of the transfer method in each group as shown in Table IV. The participants carried out the experiments in the same manner as in Experiment 1, that is, the participants carried out the experiments outlined in steps (1) to (5) in Section 5.1.

Table IV. The sequence of transfer method in Experiment 2.

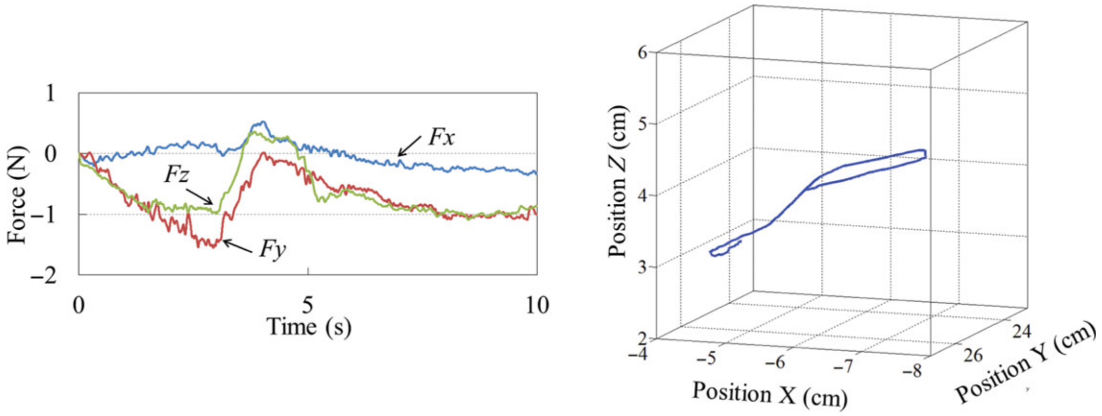
Order of method	Group A	Group B
1.	Method 1	Method 1
2.	Method 2	Method 3
3.	Method 3	Method 2

To examine the experimental results, we considered FEN (Eq. (3)), FAE (Eq. (4)), and PEN (Eq. (5)). Here we evaluated the data from 2 to 6 s, which was the time interval when the fingertip forces and positions made a high change at a high speed. That is, we derived evaluation items FEN, FAE, and PEN using data from 2 to 6 s.

6.2. *Experimental results*

Figures 10(a)–(c) show FEN, FAE, and PEN values, respectively. In each figure, the horizontal axis shows the transfer method and the vertical axis shows the corresponding result. The blue bar graph is the pre-test result, and the red bar graph is the post-test result. The vertical bar shows SD of the corresponding value.

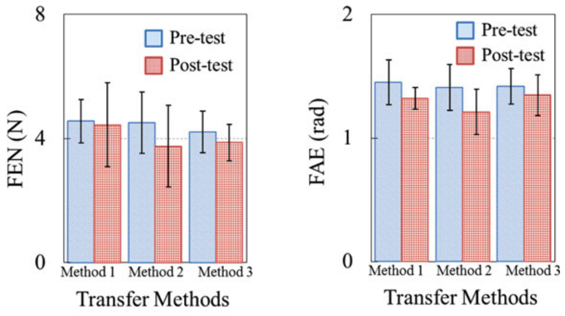
For FEN as shown in Fig. 10(a), we performed a two-way repeated measures ANOVA on FEN value, with the training effect and the training method. We found a significant effect of training ($F(1, 66) = 2.812$, $\eta^2 = 0.039$, $p = 0.098 < 0.1$). On the other hand, there was no significant effect for the training method ($F(2, 66) = 1.348$, $\eta^2 = 0.037$, $p = 0.267$) and there was no interaction between the training effect and the training method ($F(2, 66) = 0.603$, $\eta^2 = 0.017$, $p = 0.550$). Now a two-tailed paired t-test was carried out between pre-test and post-test for each transfer method. For Method 1, there was no significant difference between the



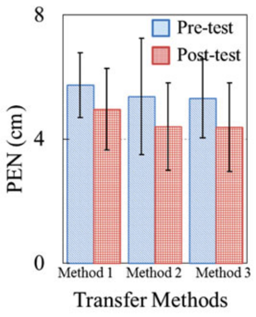
(a) The force trajectories of the trainer's index fingertip.

(b) The position trajectory of the trainer's index fingertip.

Fig. 9. (Colour online) The trajectories of the trainer's index fingertip in experiment 2. (a) The force trajectories of the trainer's index fingertip. (b) The position trajectory of the trainer's index fingertip.



(a) FENs. (b) FAEs.



(c) PENs.

Fig. 10. (Colour online) Experimental results in experiment 2. Error bars show ± SD. (a) FENs. (b) FAEs. (c) PENs.

pre-test (4.56) and the post-test (4.44) ($t = 0.31$, DOF = 11, $p = 0.763$), and for Method 3, there was no significant difference between the pre-test (4.21) and the post-test (3.75) ($t = 1.64$, DOF = 11, $p = 0.129$). On the other hand, there was a significant difference between the pre-test (4.51) and the post-test (3.75) in Method 2 ($t = 4.13$, DOF = 11, $p = 1.68 \times 10^{-3} < 0.01$). From these results, we found that Method 2 has a training effect and the force magnitude error of the fingertip decreases. In contrast, Methods 1 and 3 have no training effect.

Next, we considered FAE as shown in Fig. 10(b). According to a two-way repeated measures ANOVA with the training effect and training method, there was a significant effect of training ($F(1, 66) = 11.431$, $\eta^2 = 0.139$, $p = 1.22 \times 10^{-3} < 0.01$), but there was no significant effect for training method ($F(2, 66) = 0.594$, $\eta^2 = 0.010$, $p = 0.555$) and there was no interaction between the training effect and the training method ($F(2, 66) = 1.812$, $\eta^2 = 0.044$, $p = 0.171$). Further, according to the two-tailed paired t-test, there was no significant difference between the pre-test (1.41) and the post-test (1.32) in Method 1 ($t = 1.31$, DOF = 11, $p = 0.217$) or between the pre-test (1.42) and the post-test (1.21) in Method 3 ($t = 1.38$, DOF = 11, $p = 0.196$). In contrast, there was a significant difference between the pre-test (1.45) and the post-test (1.21) in Method 2 ($t = 5.60$, DOF = 11, $p = 1.597 \times 10^{-4} < 0.01$). Thus, for the force direction of the fingertip, it is thought that Method 2 has a training effect, and Methods 1 and 3 had no training effect, as the case of FEN.

Finally, for PEN, as shown in Fig. 10(c), we performed a two-way repeated measures ANOVA with the training effect and training method. We found a significant effect of training ($F(1, 66) = 6.591$, $\eta^2 = 0.089$, $p = 0.0125 < 0.05$). There was no significant effect for the training method ($F(2, 66) = 0.874$, $\eta^2 = 0.024$, $p = 0.422$) and there was no interaction between the training effect and the training method ($F(2, 66) = 0.030$, $\eta^2 = 0.001$, $p = 0.970$). Then we carried out a two-tailed paired t-test. In all methods, there was a significant difference. There was a significant difference between the pre-test (5.74) and the post-test (4.97) ($t = 2.21$, DOF = 11, $p = 0.049 < 0.05$) for Method 1, between the pre-test (5.38) and the post-test (4.40) ($t = 2.64$, DOF = 11, $p = 0.023 < 0.05$) for Method 2, and between the pre-test (5.31) and the post-test (4.39) ($t = 2.22$, DOF = 11, $p = 0.049 < 0.05$) for Method 3. Based on these results, we consider that all the methods had a training effect, and the position error decreased with all the methods.

Here, there is a possibility it does not make sense to perform comparisons between Method 1 and other methods because of the experimental sequences in Table IV. However, from the experimental results of the training effect (errors before and after the training), we can see the following findings: For position tracking, all methods had a training effect. In the proposed method (Method 2), the trainer's and trainee's hand motion images were used instead of the visual cues shown in Fig. 2(a), which shows the trainer's and trainee's fingertips (Method 1). However, we could confirm that the hand motion image did not negatively affect the position tracking. On the other hand, with regard to the force tracking, only the proposed method (Method 2) had a training effect. As mentioned in Section 5, the reason for the lack of training effect in Method 3 was that the trainee could not catch the exact force information by using only the images.

With regard to Method 1, we obtained the following comments from the participants: Method 1 did not transfer the force of multiple fingers well when the fingertip forces and positions changed by a large amount at a high speed. Here, note that a previous study[34] indicated that Method 1 has no training effect during a high-speed task, such as target hitting, which is not related to the transfer task of the fingertip force and position. Therefore, we consider Method 1 to have no training effect. However, note that Method 1 has a training effect for a low-speed task, as shown in Section 5 and Endo *et al.*[26]. In the proposed method (Method 2), for the position, force magnitude, and force direction of the fingertips, all error values after training were smaller than the error values before training. Therefore, when transmitting the trainer's fingertip force and position information to multiple fingers, we believe that the method that uses the hand motion image and transmits the posture of the trainer's fingers is effective.

7. Conclusion

We have described a newly developed finger skill transfer system. In particular, to accomplish the skill transfer in which a trainer's multiple fingertip forces, including the magnitude and the direction, as well as the finger positions in a three-dimensional space are transferred to a trainee, based on the record-and-replay strategy, we proposed a skill transfer method combining a multi-fingered haptic interface and the expert's recorded hand image. By using the multi-fingered haptic interface, an operator using the proposed method can present three-dimensional forces at multiple fingertips and can measure the three-dimensional forces and positions at multiple fingertips. Further, because the trainer's hand image is displayed to the trainee, the trainee can realize the difference between the operation of his or her own fingers and the operation of the trainer's fingers, and improved learning can be expected. The proposed method has high fingertip force and position transferability.

To investigate the effect of viewing the hand image on the force tracking, we carried out an assessment experiment. Displaying the trainer's hand motion image to the trainee can increase the information received by the trainee. The proposed method has a training effect, but we believe that the hand motion image does not have a wrong influence on the transferring of the fingertip force. Even when the fingertip forces and positions had to make large changes at a high speed, it was shown that the proposed method is effective in transferring of the fingertip force, including the magnitude and the direction, and the fingertip positions. These results show a high fingertip force and position transferability and the great potential of our proposed transfer system.

As part of breast palpation, we considered the task of moving a finger while applying force diagonally right from the center of breast. In addition to this task, the operator touched the surface while drawing a circle, which also occurs in breast palpation. In future experiments we will attempt to consider other tasks that are part of breast palpation. When using a method that includes displaying of a hand motion image, the size of the trainer's hand and the size of the trainee's hand may affect the results. For this reason, the next problem to be tackled is to clarify the influence of difference in hand size and to improve the system to overcome any errors caused by such a difference. Furthermore, the retention performance of training methods is also important to train medical students for breast palpation, and we will tackle to consider the retention performance.

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References

1. Ministry of Economy, Trade and Industry (METI), Ministry of Health, Labor and Welfare (MHLW), Ministry of Education, Culture, Sports, Science and Technology (MEXT), ed., *White Paper on Monozukuri 2007* (Gyousei, Tokyo, Japan, 2007) (in Japanese).
2. Cabinet Office and Government of Japan, ed., *White Paper on Aging Society* (Insatsu Tsuuhan, Japan, 2011) (in Japanese).
3. R. Haluck and T. Krummel, "Computers and virtual reality for surgical education in the 21st century," *Arch. Surg.* **135**, 786–792 (2000).
4. R. Reznick and H. MacRae, "Teaching surgical skills – change in the wind," *New England J. Med.* **355**, 2664–2669 (2006).
5. E. Foulke, "Transfer of a complex perceptual skill," *Percept. Mot. Skills* **18**, 733–740 (1964).
6. Y. Yokokohji, R. Hollis, T. Kanade, K. Henmi and T. Yoshikawa, "Toward Machine Mediated Training of Motor Skills – Skill Transfer From Human to Human Via Virtual Environment," **In**: *Proceedings of the IEEE International Workshop on Robot and Human Communication*, Ibaraki, Japan (1996) pp. 32–37.
7. D. Feygin, M. Keehner and F. Tendick, "Haptic Guidance: Experimental Evaluation of a Haptic Training Method for a Perceptual Motor Skill," **In**: *Proceedings of the 10th Symposia on Haptic Interfaces for Virtual Environmental and Teleoperator Systems (HAPTICS'02)*, Florida, USA (2002) pp. 40–47.
8. C. Teo, E. Burdet and H. Lim, "A Robotic Teacher of Chinese Handwriting," **In**: *Proceedings of the 10th Symposia on Haptic Interfaces for Virtual Environmental & Teleoperator Systems (HAPTICS'02)*, Florida, USA (2002) pp. 335–341.
9. J. Bluteau, S. Coquillart, Y. Payan and E. Gentaz, "Haptic guidance improves the visuo-manual tracking of trajectories," *PLoS ONE* **3**, e1775 (2008).
10. K. Henmi and T. Yoshikawa, "Virtual Lesson and Its Application to Virtual Calligraphy System," **In**: *Proceedings of 1998 IEEE International Conference on Robotics and Automation*, Leuven, Belgium (1998) pp. 1275–1280.
11. S. Saga, N. Kawakami and S. Tachi, "Haptic Teaching Using Opposite Force Presentation," *Poster Presentation in Proceedings of the 1st Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC '05)*, Pisa, Italy (2005).
12. K. Okuda, Y. Suzuki and K. Ohnishi, "Improvement in Motion Learning System Using Force Reverse Presentation Control with Variable Force and Time," **In**: *Proceedings of 2011 IEEE International Symposium on Industrial Electronics (ISIE)*, Gdansk, Poland (2011) pp. 2171–2176.
13. R. Williams II, M. Srivastava, R. Conatser, Jr. and J. Howell, "Implementation and evaluation of a haptic playback system," *Haptics-e* **3**, 1–6 (2004).
14. D. Morris, H. Tan, F. Barbagli, T. Chang and K. Salisbury, "Haptic Feedback Enhances Force Skill Learning," **In**: *Proceedings of the 2nd Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC '07)*, Tsukuba, Japan (2007) pp. 21–26.
15. K. Maclean and V. Hayward, "Do it yourself haptics, part II: Interaction design," *IEEE Robot. Autom. Mag.* **15**, 104–119 (2008).
16. L. Marchal-Crespo and D. Reinkensmeyer, "Review of control strategies for robotic movement training after neurologic injury," *J. Neuro. Eng. Rehabil.* **6**, 20 (2009).
17. E. Billodeau and I. Billodeau, "Motor-skills learning," *Annu. Rev. Psychol.* **12**, 243–280 (1961).
18. R. Schmidt and T. Lee, *Motor Control and Learning: A Behavioral Emphasis*, 5th ed. (Human Kinetics, Champaign, Illinois, 2011).
19. M. Dinsmore, N. Langrana, G. Burdea and J. Ladeji, "Virtual Reality Training Simulation for Palpation of Subsurface Tumors," **In**: *Proceedings of the Virtual Reality Annual International Symposium (VRAIS '97)*, New Mexico, USA (1997) pp. 54–60.
20. M. Alhalabi, V. Daniulaitis, H. Kawasaki and T. Hori, "Medical Training Simulation for Palpation of Subsurface Tumor Using HIRO," **In**: *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC '05)*, Pisa, Italy (2005) pp. 623–624.
21. M. Nakao, K. Minato, T. Kuroda, M. Komori, H. Oyama and T. Takahashi, "Transferring bioelasticity knowledge through haptic interaction," *IEEE Multimedia* **13**, 50–60 (2006).
22. Y. Kuroda, M. Hirai, M. Nakao, T. Sato, T. Kuroda, Y. Masuda and O. Oshiro, "Construction of training environment for surgical exclusion with a basic study of multi-finger haptic interaction," **In**: *Proceedings of the 2nd Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC '07)*, Tsukuba, Japan (2007) pp. 525–530.

23. J. Howell, R. Conatser, R. Williams II, J. Burns and D. Eland, “Palpatory diagnosis training on the virtual haptic back: Performance improvement and user evaluations,” *J. Am. Osteopath Assoc.* **108**, 29–36 (2008).
24. S. Ullrich and T. Kuhlen, “Haptic palpation for medical simulation in virtual environments,” *IEEE Trans. Vis. Comput. Graphics* **18**, 617–625 (2012).
25. T. Endo, H. Kawasaki, T. Mouri, Y. Ishigure, H. Shimomura, M. Matsumura and K. Koketsu, “Five-fingered haptic interface robot: HIRO III,” *IEEE Trans. Haptics* **4**, 458–463 (2011).
26. T. Endo, T. Kanno, M. Kobayashi and H. Kawasaki, “Human perception test of discontinuous force and a trial of skill transfer using a five-fingered haptic interface,” *J. Robot.* **2010**, Article ID 542360, 14 pp (2010) doi:10.1155/2010/542360.
27. CyberGlove Systems, “CyberGrasp,” (2013) [online]. Available at: http://www.cyberglovesystems.com/products/cybergrasp/overview.
28. A. Frisoli, F. Rocchi, S. Marcheschi, A. Dettori, F. Salsedo and M. Bergamasco, “A New Force-Feedback Arm Exoskeleton for Haptic Interaction in Virtual Environment,” **In**: *Proceedings of the First Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC ’05)*, Pisa, Italy (2005) pp. 191–201.
29. H. Maekawa and J. Hollerbach, “Haptic Display for Object Grasping and Manipulating in Virtual Environment,” **In**: *Procceedings of 1998 IEEE ICRA*, Leuven, Belgium (1998) pp. 2566–2573.
30. K. Sato, K. Minamizawa, N. Kawakami and S. Tachi, “Haptic Telexistence,” *Proceedings of 34th International Conference on Computer Graphics and Interactive Techniques*, ACM SIGGRAPH (2007).
31. Y. Yokokohji, R. L. Hollis and T. Kanade, “WYSIWYF display: A visual/haptic interface to virtual environment,” *Presence* **8**, 412–434 (1999).
32. H. Kawasaki, Y. Ohtuka, M. O. Alhalabi and T. Mouri, “Haptic Rendering and Perception of Frictional Moment,” **In**: *Proceedings of EuroHaptics Conference*, Paris, France (2006) pp. 201–206.
33. M. Rissanen, Y. Kuroda, M. Nakao, N. Kume, T. Kuroda and H. Yoshihara, “Toward Visualization of Skill in VR: Adaptive Real-Time Guidance for Learning Force Exertion Through the ‘Shaping’ Strategy,” **In**: *Proceedings of the 2nd Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC ’07)*, Tsukuba, Japan (2007) pp. 324–329.
34. D. Powell and M. O’Malley, “Co-Presentation of Force Cues for Skill Transfer via Shared-Control Systems,” **In**: *Proceedings of the 16th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, Massachusetts, USA (2010) pp. 453–456.