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# A fine motor skill training system using multi-fingered haptic interface robot ☆

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ABSTRACT

This paper focuses on a haptic training system for fine motor skills using multiple fingers. To transfer skills involving such fine motor tasks, instruction on how to move the fingers and use fingertip forces is essential. In this paper, we propose an optimal method for transmitting knowledge regarding fingertip forces from trainer to trainee; we then construct a haptic training system based on the proposed method. The resulting system conveys knowledge of fingertip forces and positions in three-dimensional space by combining an image display system with a five-fingered haptic interface robot capable of alternating force presentation. Finally, we describe several experiments carried out to optimize and evaluate the performance of the proposed method.



## 1. Introduction

Haptic interfaces allow us to communicate in virtual reality (VR) environments using the sense of touch. The user of a haptic interface feels a force sensation from the VR environment, and likewise, can provide force and position information to the VR environment. The haptic interface thus represents a bidirectional interaction between the user and the VR environment. It is a key input/output device for communication with highly realistic sensations, and has been used in many application areas (for example, see Hayward et al., 2004; Saddik, 2007; Ohnish et al., 2009; Seth et al., 2011; Katsura et al., 2012).

One important use of the haptic interface is in virtual training systems for expert skill transfer from a trainer to a trainee in medical fields, manufacturing industries, and others. For example, given the demographic changes in Japan, which include a falling birthrate and aging population, skilled engineers are retiring without successors to take their place. It is, however, vital that their valuable skills be transferred to the next generation (METI, MHLW, MEXT, 2007; Cabinet Office, Government of Japan, 2011). Furthermore, in the medical field, expert skills such as palpation and surgical techniques were traditionally obtained through long-term training and experience working with actual patients. Today, it is difficult to train directly with actual human bodies due to patient safety issues, and training with animals is also problematic because of ethical concerns (Haluck and Krummel, 2000; Reznick and MacRae, 2006). To transfer the skills required to perform the above fine motor tasks using multiple fingers, instruction on how to move the fingers and use fingertip forces is essential. However, trainees cannot gain the complex skills involving exact fingertip force and position simply by reading a description, or even watching and imitating a trainer's motions.

To address these problems, many researchers have been developing skill-transfer systems using VR and haptic interface technology (Yokokohji et al., 1996; Feygin et al., 2002; Bluteau et al., 2008; Marchal-Crespo et al., 2010; Klein et al., 2012; Basteris et al., 2012; Henmi and Yoshikawa, 1998; Saga et al., 2005; Kikuuwe and Yoshikawa, 2001; Okuda et al., 2011; Williams et al., 2004). These systems have several key advantages. Creating a training model in a VR environment allows a trainee to learn specific skills such as palpation through a haptic interface with realistic touch sensation; it might even eventually be possible to eliminate the need for human patients in training. In addition, the movement of trainer's hand and exact degree of the trainer's force can be recorded. Accurate information can thus be transmitted from the trainer to many trainees through the screen and haptic interface; this training method is known as a record-and-replay strategy (Yokokohji et al., 1996). Finally, training can be selected according to the trainee's skill level, and an appropriate level of training presented to the user. It is understood that real-time feedback on performance is important for skill acquisition (Billodeau and Billodeau, 1961; Schmidt and Lee, 2011; van der Linden et al., 2011). Thus, a skill-transfer system that uses VR and haptic interface technology could increase the efficiency of the skill transfer.

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This paper focuses on the transfer of skills involving the fingers. Several previous studies have examined how to convey force and position information for the human fingers (Henmi and Yoshikawa, 1998; Saga et al., 2005; Kikuuwe and Yoshikawa, 2001; Okuda et al., 2011; Williams et al., 2004). Henmi and Yoshikawa (1998) proposed a virtual calligraphy system using a brush-type haptic interface. The system was based on the record-and-replay strategy: the position and force trajectories of the teacher's writing brush were recorded, and then displayed to students using the haptic interface and visual display. Saga et al. (2005) also developed a haptic teaching system for a handwriting task. In their system, the recorded expert's exact degree of force using a brush was displayed to trainee in reverse. In other words, trainee had to use the correct amount of force to counteract or cancel the trainer's force. Note that these systems consider the transfer of one-dimensional force and two-dimensional position. Kikuuwe and Yoshikawa (2001) and Okuda et al. (2011) proposed a skill-transfer system designed for both one-dimensional finger position and finger force. Williams et al. (2004) developed a playback training system for palpation of the human back. In this system, the recorded expert's position trajectory is displayed on a monitor by a ball. If trainees can touch the exact same position as the expert, they can also learn the expert's fingertip force. Again, this system considered the transfer of one fingertip force and one fingertip position. Thus, in many studies the force display is limited to a single point, and is not aimed at teaching the force of multiple fingers as occurs in actions like palpation. Although there have been several studies on multiple-finger systems (Dinsmore et al., 1997; Nakao et al., 2006; Kuroda et al., 2007; Howell et al., 2008; Ullrich and Kuhlen, 2012; Kotranza et al., 2012), these systems were simulators, and did not include a methodology for the transfer of multiple fingertip forces and positions. Skill instruction using multiple fingers in three-dimensional (3D) virtual space has not yet been realized except for our previous research (Endo et al., 2013).

For this reason, we previously developed a skill-transfer system based on the record-and-replay strategy (Endo et al., 2013). In this system, the trainer's multiple fingertip positions and forces in 3D space were recorded and transferred to the trainee. The system consisted of a five-fingered haptic interface robot, called “HIRO” for Haptic Interface Robot (Endo et al., 2011), and an image-display system. HIRO can display 3D forces at five fingertips and can measure 3D forces and positions at five fingertips. The image-display system records an image of the trainer's hand and displays it to the trainee. In tracking fingertip forces, HIRO alternately presents the reaction force, $\boldsymbol{F}_r$, which the trainee feels from the virtual object, and the trainer's force, $\boldsymbol{F}_t$, to the trainee. In this case, the user feels a pulse force, which is the difference between $\boldsymbol{F}_r$ and $\boldsymbol{F}_t$. When users are able to regulate their fingertip forces so that the pulse forces become small, force transfer is achieved. In our previous research, we determined switching time between $\boldsymbol{F}_r$ and $\boldsymbol{F}_t$ based on human perception of fingertip force (Endo et al., 2010), but did not clarify the optimal switching time. Clarifying the optimal switching time is important as it could significantly improve the effect of skill transfer. Here, optimal is defined as the minimizing of the force error between a trainer's and a trainee's force.

To clarify optimal switching time, we propose an optimal method of transferring fingertip forces, i.e. a method of deriving optimal switching time based on subject data. Using the proposed method, we then improved the finger skill transfer method using multiple fingertips in 3D space. Furthermore, we describe results from an experiment carried out to investigate the performance of the proposed transfer method. To summarize, the purpose and novel contribution of this paper is that we propose a method for deriving optimal switching time, determine optimal switching time, improve our skill-transfer method using this switching time, and investigate the proposed method experimentally.

The paper is organized as follows. In the next section, we introduce the five-fingered haptic interface robot, HIRO, and our previously reported skill-transfer method. Section 3 presents a method for deriving the optimal switching time. The experimental evaluation of the newly developed skill transfer method and its results are described in Section 4. Finally, Section 5 presents our conclusions.

## 2. Five-fingered haptic interface and skill-transfer system

### 2.1. Five-fingered haptic interface robot

We developed the five-fingered haptic interface robot, named HIRO (Endo et al., 2011), shown in Fig. 1. HIRO can present three-directional forces at a user's five fingertips, and can also measure 3D forces and positions at the user's five fingertips. The specifications of HIRO are shown in Table 1. HIRO can be briefly described as follows.

HIRO consists of an interface arm and a five-fingered haptic hand. The interface arm has 6 joints allowing 6 degrees of freedom (DOF). The haptic hand is constructed of five haptic fingers, each with 3 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 haptic hand has 15 DOF. The total DOF of HIRO is 21, and its working space covers the manipulation of the space on a desktop. Furthermore, a 3-axis force sensor is installed at the top of each haptic finger. To manipulate HIRO, the user wears a finger holder, shown in Fig. 1(b), on each of his/her fingertips.

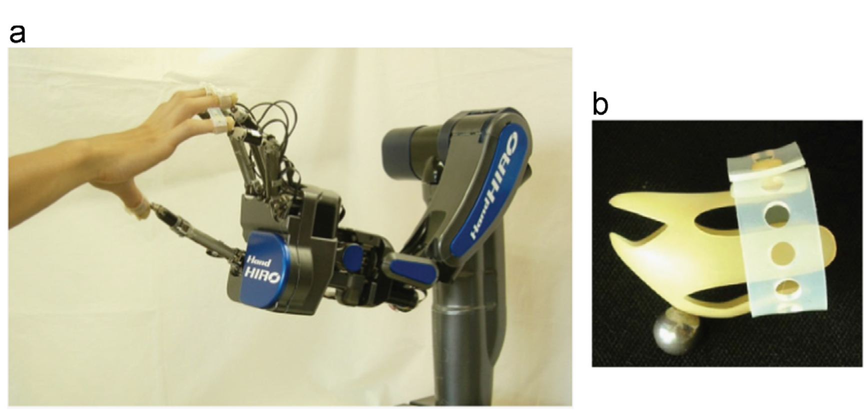

**Fig. 1.** Five-fingered haptic interface robot. (a) HIRO. (b) The finger holder.