Hand-Skill Learning Using Outer-Covering Haptic Display

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Abstract. During hand-skill learning, it is important for the learner to manipulate a tool with the appropriate amount of force. Haptic training systems in which a tool is directly actuated are therefore undesirable due to the fact that the force applied to the tool is assisted by an actuator. We report a method in which we have replaced guiding by a tool with an outer-covering haptic display in which a guidance sensation was imparted to the back of a learner's hand. To show the effectiveness of this approach for hand-skill learning, we conducted experiments with comparisons to two existing methods: a haptic guidance system in which the tool is directly actuated and a visual information guidance system.

Keywords: Hand-skill learning · OCHD · Haptic guidance · Back of hand

1 Introduction

Haptic devices are being actively studied for assisting in hand-skill training [1]. In most of these haptic devices, the tool is actuated and provides a haptic guiding sensation to the palm of a learner's hand. However, this approach is not desirable for teaching a learner the appropriate amount of force to apply to a tool, because the manipulation of the tool is assisted by the actuator.

As an alternative to actuation assistance, a learner may manipulate a tool with their own force by using visual information as a guide [2]. However, there is a lack of visual information for three-dimensional manipulation because of the limitations of the display monitor. Combining numerous two-dimensional images can provide detailed three-dimensional information, but it is difficult for a learner to pay attention to all of these images and interpret the guiding information.

To resolve these issues, we used an outer-covering haptic display (OCHD) (Fig. 1), by which a guiding force was imparted to the back of a learner's hand as if an instructor

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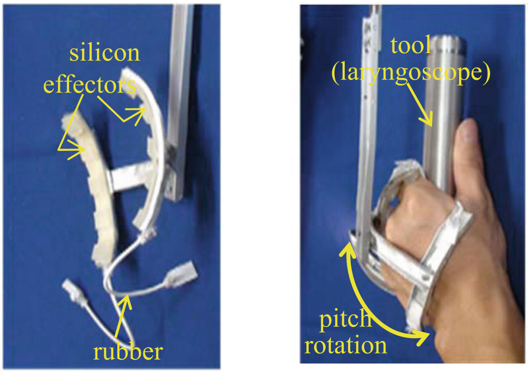

Fig. 1. An OCHD (left) and a left hand wearing OCHD (right)

were holding it and guiding the learner in the manipulation of the tool. The aim of this study was to show the effect of using an OCHD for skill learning by conducting a comparison experiment involving an OCHD and two existing methods.

2 Hand-Skill Learning

Haptic systems are being developed to support hand-skill learning. The most common method used in these systems is to operate a tool using an actuator so that the learner can directly sense the guiding force from the tool itself [1]. However, our previous study found that this method was not practical when applied to learning skills that require strength (i.e., when learners need to hold the tool tightly) because the guiding force inevitably increases, which typically increases the system's size and cost [3]. Moreover, it does not seem to be effective for skill learning, because the manipulation of the tool is mostly assisted by the actuator, which makes it difficult for the learner to perceive the amount of force required for manipulation.

Visual systems have also been studied in terms of their assistance in hand-skill learning. For example, Yoichi et al. developed a guitar-playing support system in which a learner can train by overlapping their hand on a visual guide [4]. Unfortunately, a visual system does not seem to be practical for learning a three-dimensional manipulation skill because of the lack of information provided by the visual display. Toru et al. used four monitors showing different images to provide detailed surgery training information (how to hold and insert the tool, etc.) [2]. However, the learner was not able to pay attention to all the images simultaneously.

To solve the above-mentioned issues, our previous work focused on the use of skin deformation for guidance [5, 6]. We developed an idea for using an OCHD to guide a learner by applying a haptic sensation on the back of a learner's hand and guiding their movements of a tool. An OCHD was designed to present skin deformation sensation in a large area of the back of the hand as shown in Fig. 1. Effectors with small contact surfaces were used to provide high shear stress on the skin.

For learning skills that require strength, such as laryngoscopy, preliminary evaluation showed that an OCHD has the potential to provide guiding sensations for pitch rotation (Fig. 1 (right)) with less actuator drive force compared to the case where the tool is directly actuated [3]. Laryngoscopy is a medical procedure in which a tool called a laryngoscope is used to open a patient's mouth to view the vocal folds and glottis.

The goal of this study is to demonstrate the effectiveness of using haptic guidance in a way that challenges a learner to manipulate a tool on their own initiative with the appropriate amount of force during learning. With our findings, we verified our understanding of the usefulness of providing guidance to the back of a leaner's hand for skill learning.

3 Experimental Setup

The purpose of this experiment was to investigate the effect of using an OCHD to assist in hand-skill learning. Our goal was to confirm that there was less error in the force used for the tool during recall if a learner was guided by an OCHD (OCHD case) compared to the cases where the learner was guided by the tool itself (tool case) or by visual information (visual case). Our hypothesis was that guiding a learner in moving the tool with the appropriate force during learning was an effective way for the learner to acquire the skill.

3.1 Apparatus

We used a six-axis force sensor (ATI Mini45 FT09486) and stereo labeling camera (CyVerse, SLC-C02) to measure the actual values of the force and angle of the tool (Fig. 2). A spring with a coefficient of 2.5 N/mm was attached between the six-axis force sensor and the tool to provide a resistance force sensation to the learner.

For the tool case, the tool was directly actuated by a manipulator with six degrees of freedom (Fig. 2 (left)). Proportional-integral (PI) feedback control was used to move the tool to a target. Subjects were asked to hold the tool and follow its movement.

For the OCHD case, the tool was not actuated by the actuator but was held by the subject. Subjects were asked to manipulate the tool by following the guidance of the OCHD, which was actuated by the manipulator (Fig. 2 (right)). As in the tool case, PI feedback control was used to move the OCHD.

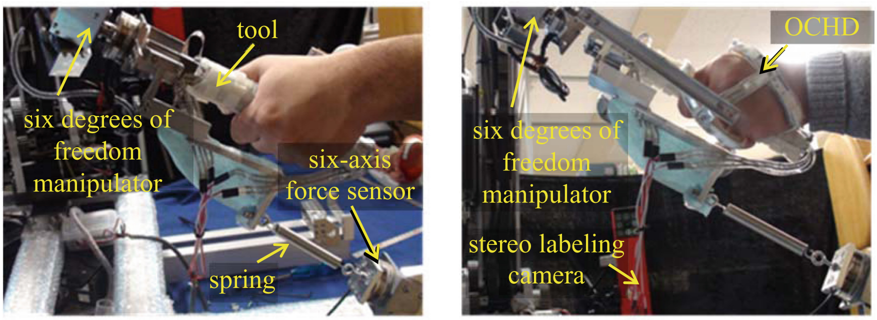

Fig. 2. Hand-skill learning with tool case (left) and OCHD case (right)

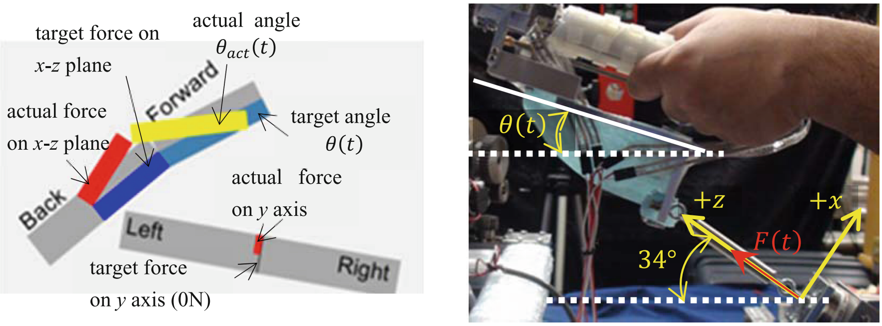

Fig. 3. Hand-skill learning with visual case (left) and experimental reference frame (right)

Figure 3 (left) shows a window containing the target information and actual values of the force and angle for the visual case. The three-dimensional information was divided into two parts: the information on the *x–z* plane and that on the *y*-axis. The angle information was shown on the *x–z* plane. Subjects were asked to manipulate the tool by tracking the target.

3.2 Task and Design

We chose the laryngoscopy procedure as a reference task for this evaluation. The mean time and maximum tool application forces for children and adult patients during laryngoscopy are 10 s, 21 N, and 38 N, respectively [7, 8]. The mean of the steady angle of the tool to the horizontal plane is 34°, and its rotation rate is approximately 44°/s [9]. Using these references, we set the target for the tool manipulation function as shown below:

$$F(t) = \begin{cases} f_n(1 - e^{-t}) & (0 \le t \le 10s) \\ 0 & (t > 10s) \end{cases}, \tag{1}$$

$$\omega(t) = \begin{cases} 34^\circ/s & (0 \le t \le 1s) \\ 0 & (t > 1s) \end{cases}, \tag{2}$$

$$\theta(t) = \begin{cases} \omega(t) \times t & (0 \le t \le 1s) \\ 34^\circ & (t > 1s) \end{cases}, \tag{3}$$

where $F(t)$ is the target of the force function and f_n is maximum force on the *z* axis (34° to the horizontal plane (Fig. 3 (right)), where the target forces on the *x* and *y* axes were zero, and $f_1 = 21\ N$, $f_2 = 29.5\ N$, and $f_3 = 38\ N$ for this experiment). $\omega(t)$ and $\theta(t)$ are the tool rotation rate and angle, respectively.

The error in the force is calculated using the functions below:

$$F_e = \frac{1}{\tau}\int_0^{\tau} \sqrt{F_x^2(t) + F_y^2(t) + F_{z1}^2(t) + F_{z2}^2(t)dt}\ , \tag{4}$$

$$\begin{cases} F_{z1}(t) = F(t) - F_z(t) \times cos(\theta_{act}(t) - \theta(t)) \\ F_{z2}(t) = F_z(t) \times \sin(\theta_{act}(t) - \theta(t)) \end{cases}. \quad (5)$$

Here, $F_x(t)$, $F_y(t)$, $F_z(t)$, and $\theta_{act}(t)$ are the actual values of the application force on the x, y, and z axes, and angle, respectively.

The error in the force was measured using a 3 × 3, two-way repeated design. The independent variables were the *guidance case* (OCHD case, tool case, visual case) and *maximum force* $\{f_1 = 21\ N, f_2 = 29.5\ N, \text{ and } f_3 = 38\ N\}$. The order of the guidance cases and maximum forces were counterbalanced across subjects.

3.3 Subjects and Procedure

The participants in this experiment included 24 right-handed subjects (6 female and 18 male) with ages in the range of 21–32 years. None of them had any experience in laryngoscopy training. The subjects were asked to stand in front of the experimental system and hold the tool with their left hand. They tested the experimental system twice with a maximum force $f_0 = 10\ N$ before each guidance case. After completing each learning task in approximately 2 min, they were asked to recall it without guidance. So that the subjects could see the tool and the movement of the OCHD, we did not ask the subjects to wear a headset or close their eyes during the experiment as is normally done during laryngoscopy training.

4 Results

Figure 4 (left) shows the average error in the force (F_e) during learning for each *guidance case*. A statistical Levene's test showed that the data do not possess a homogeneity of variance; therefore, we analyzed the data using a Freidman test. The results indicated a significant difference between the tool case and visual case for each *maximum force* (f_1: $p < 0.01$; f_2: $p < 0.05$; f_3: $p < 0.01$) and between the OCHD case and visual case for $f_1 = 21$ N and $f_3 = 38$ N ($p < 0.05$ for both maximum forces). No significant difference between the OCHD case and the tool case was found for any of the maximum forces.

Figure 4 (right) shows the average error in the force (F_e) during recall for each *guidance case*. A two-way analysis of variance (ANOVA) indicated the significant main effects for the *guidance case* and *maximum force* ($F(2, 72) = 15.87$, $p < 0.001$; $F(2, 72) = 25.15$, $p < 0.001$, respectively), but no significant interaction between the guidance case and the maximum force was found. A Bonferroni post hoc test showed the significant differences between the OCHD case and the visual case, the visual case and the tool case, and the OCHD case and the tool case ($p < 0.05$, $p < 0.01$, and $p < 0.01$, respectively).

5 Discussion

During learning, the smallest error in the force was found in the case where the learners were guided by the tool itself. It was not surprising that directly actuating the tool

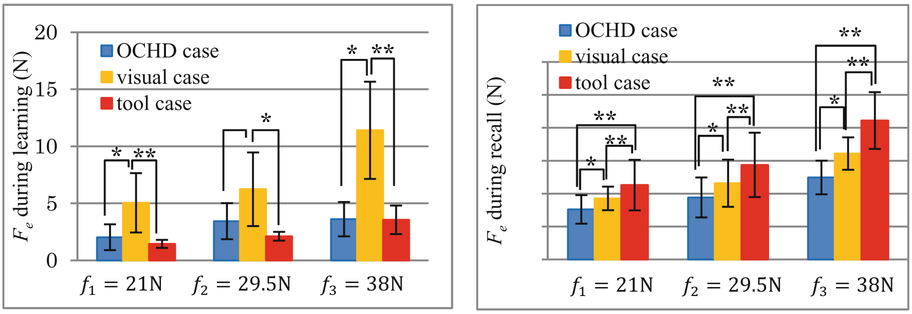

Fig. 4. Error in force (F_e) during learning (left) and recall (right) (* p < 0.05, ** p < 0.01)

would result in less error in the force. Interestingly, there was no significant difference found between the errors in the forces for the OCHD case and the tool case. The visual case had the largest error in the force. We believe that this was because learners found it difficult to interpret the combination of various images as three-dimensional information. Moreover, learners could not simultaneously concentrate on the multiple images and the movement of the tool.

In contrast to the above-mentioned results, during recall the largest error in the force was found in the case where the learner was guided by the tool. This showed the low effect of the method used in the tool case. Even though the tool was actuated with the most appropriate force during learning, and the learner could receive visual cues about the tool movement, they were unable to understand the manipulation force well because of the assistance of the actuator. The results showed that the OCHD case was the most effective for skill learning because it could challenge the learner to manipulate the tool with the appropriate force compared to the visual case.

Because the tool is not directly actuated, the OCHD approach has the added advantage that it can be applied to various types of hand-skill learning, e.g., endoscopy. A guiding system could also be implemented as a wearable computer, as it is able to guide a learner with less actuator force [3].

6 Conclusion and Future Work

To assist in hand-skill learning, our approach was to present a force sensation on the back of a learner's hand to guide them in manipulating a tool. In this study, we used an OCHD to evaluate the concept and found that there was less error in the force during recall, indicating effective skill learning.

Our future work will involve implementing an OCHD as a wearable computer that can be used for guiding hand motion in various activities. The next step is developing an approach in which an OCHD can use computing to automatically guide a learner.

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