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Haptic Display Device with Fingertip Presser for Motion/Force Teaching to Human

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Abstract

The purpose of this study is to establish a method of virtual-reality-mediated motion/force teaching from human teacher to human "teachee". For effective teaching, position and force information of the teacher's action have to be communicated to the teachee. Position information is easy to display, but force information is difficult to display by conventional haptic devices. In this paper, we propose a new type of haptic interface with fingertip presser which could make it possible to display both position and force information. The teacher's finger force of pushing a surface is displayed as a mechanical pressing force onto the teachee's fingertip, and position is displayed by active multijoint linkage. The results of basic experiments show that the proposed method is effective as a media of motion/force teaching, but reveal some limitations.

1 Introduction

Human motions are difficult to describe in words. In cases of training of motor skills or directing unskilled operators, verbal languages, gestures, or physical guidance by human instructors are traditionally used as media of communication.

Virtual reality (VR) technology has a potential to be a new kind of communication medium between teacher and "teachee", which could substitute a human instructors who physically guides the teachee's arms or fingers. VR-mediated motion teaching is advantageous over traditional methods for the following reasons: (i) Information is communicated correctly.

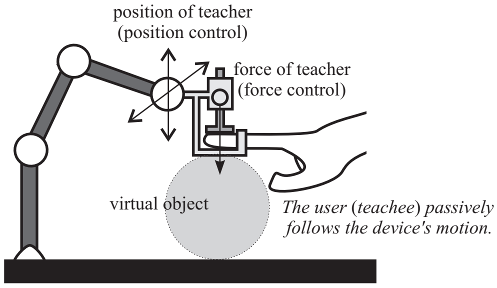

Figure 1: Proposed Mechanism — Haptic Device with Fingertip Presser

In cases of physical guidance such as tennis or golf coaching, the interference between the teacher's and the teachee's bodies obstructs the teacher's natural motion. This kind of problems can be solved by using haptic devices. (ii) Temporal or spatial distance do not affect. The teacher and the teachee do not have to be at the same place at the same time. Besides, instruction from one person to two or more persons is possible. (iii) Recorded data can be modified on demand. It is possible to emphasize specific aspects of the teacher's action.

For effective teaching, position and force information of teacher's action have to be communicated to teachee. Position information is easy to display, since it can be displayed by physical guidance using a haptic device (or generally, an active multijoint linkage). Force information, however, cannot be displayed by guidance. In this paper, we propose a new type of haptic interface, shown in Fig.1, composed of a multijoint arm and a fingertip presser attached on its end-effector. This mechanism makes it possible to display both position and force information. The results of basic experiments show that the proposed method is effective as a media of motion/force teaching, but reveal some limitations.

2 Previous Works on VR-Mediated Teaching

Various researches have been done for displaying virtual environment where an operator can experience a variety of physical behaviors[3]. Some of them are developed for skill training mainly in the area of medicine, and flight simulator is a typical example of VR-training that has been successful. However, those are simulators for mimic operations for learners and not meant to be media of teaching from expert(teacher) to novice(teachee).

Kuzuoka et al.'s GesureCam[4] and Mikawa et al.'s CTerm[5] could be mentioned as media of remote teaching. Each of them is a remote actuator on which a small camera and a laser pointer are mounted, and instructions are given by pointing objects by the laser pointer. Those kinds of systems could complement verbal direction by substituting finger pointing by human instructor in real-world collaborating task. However, since the signal is very simple, the teachee must have sufficient preliminary knowledge to accomplish a complicated task.

By using augmented reality (AR) technologies [6], more complicated graphic images can be drawn (or superimposed) on real environment surfaces, and a larger amount of information can be displayed to users. AR could make instructions easier to understand for teachee and could complement ambiguity of verbal direction. Suenaga et al.'s tele-instruction system for ultrasound tele-diagnosis[7] is a medium of teaching from a medical specialist to an ultrasound diagnostic device operator. Several graphic symbols are projected on the surface of patient's body at the request of the medical doctor, and the operator can know where to put and how to move the device.

As researches on teaching media involving haptics, Henmi and Yoshikawa's "virtual calligraphy system"[1] and Yokokohji et al.'s experiments using WYSIWIF display[2] could be mentioned. Henmi and Yoshikawa's idea was basically "record-and-replay" strategy, recording and replaying position and force information of teacher's action. Yokokohji et al. enhanced the previous Henmi's research, and investigated several control methods of haptic device. Since it is impossible to display both position and force information at one time through a haptic device, those systems depend heavily on visual cues.

3 Haptic Display Device with Fingertip Presser

The problem which surfaced in researches[1][2] is that it is impossible to display both position and force information at one time through a haptic device. A haptic device, generally an active multijoint linkage, could be used to communicate position information of teacher's action by physically guiding the teachee's arms or fingers. Force information, however, cannot be communicated in this method. It means that when the target task was to manipulate objects by hands, the teachee could understand how s/he should move his/her hands and fingers, but could not understand how strongly s/he should press the object.

To display force information, an additional channel is required. And, it has to generate a sensation which is equivalent to what the teacher feels when s/he is pushing a surface with his/her fingers. In this paper, we propose to use a fingertip pressing device as a medium of displaying force information. Mounting the fingertip presser on the end-effector of a multijoint linkage, as shown in Fig.1, both position and force information could be displayed to the teachee. Using this method, the teachee can understand how strongly the teacher is pushing the environment surface without preliminary knowledge about the impedance of the surface. The position and force information of the teacher's actions and information on environment are communicated through proprioception and haptic/tactile sensations, without help of vision. Besides, when the fingertip pressers are attached to more than one finger, internal force of grasping can be displayed.

The proposed method is expected to be useful for tasks of manipulating hard objects where delicate force control is required, such as planing or polishing, and tasks of manipulating soft objects, such as surgery or ceramic arts, and effective especially for visually impaired people since information is communicated without vision. Applicable usage of the proposed method is not limited to the field of virtual reality; training of delicate telerobotic operations, such as robotic surgery, will also be in the range of application.

4 Experiments

In order to evaluate the validity of the proposed method, we built an apparatus and conducted two experiments. Experiment I was conducted to test the availability of fingertip pressing function as a medium of teaching force. Experiment II was conducted to test the composite method of fingertip pressing and displaying position.

4.1 Apparatus

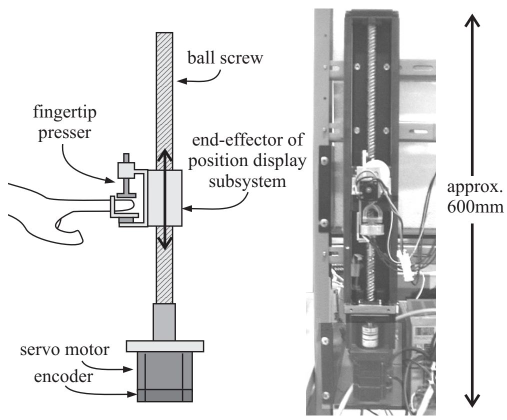

Figure 2: Apparatus

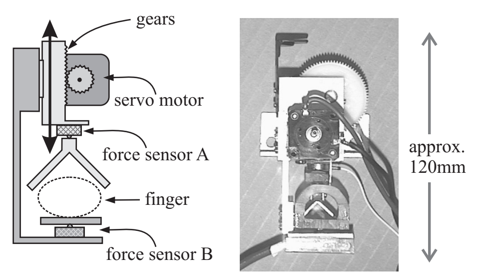

Figure 3: Apparatus's Fingertip Pressing Subsystem

Figure 4: Arrangement of Experiments

The apparatus is composed of a 1-DOF position display subsystem and a fingertip pressing subsystem, as shown in Fig.2 and Fig.3. These are connected to a control PC through D/A and A/D converters and digital I/O.

The fingertip pressing subsystem has a DC servo motor and 2 force sensors below and above the finger. The components which directly contact with the user's finger are aluminum roof-shaped (angle of 90°) part on the back of finger and a smooth acrylic board on the fingerpad. Force sensor A measures the user's voluntary generated pushing force f_U. Force sensor B measures mechanical pressing force F_D and allows feedback control of the force.

The position display subsystem is driven by AC servo motor and ball screw, and an encoder is attached to the motor. Position of its end-effector is controlled by processing velocity command to the dedicated amplifier of the AC servo motor.

4.2 Experiment I

The proposed method requires human user to make correspondence between the force F_D mechanically applied on his/her finger and the force f_U s/he voluntarily generates, though feeling of being pressed is quite different from that of pushing a surface. The purpose of Experiment I is to find out a relation between F_D and f_U.

4.2.1 Protocol

Each trial of this experiment was carried in the following procedure:

1. The subject placed his right-hand index finger on the apparatus as shown in Fig.4.
2. A randomly chosen force F_D was applied on the subject's finger for 5 seconds.
3. The mechanical force was removed for 2 seconds.
4. The subject pushed the apparatus "as strongly as" he was pressed before.
5. The subject's pushing force was recorded as f_U.

F_D was randomly chosen out of 5 ranks(2.5N, 3.5N, 5.1N, 7.4N and 11N), and 1 "set" of experiment consists of 25 trials (=[5 trials]× [5 ranks]). 6 male subjects, between 22 and 30 years of age, were recruited and are referred to as A, B, · · ·, F. For each subject, 4 sets were run at regular intervals of 3 to 6 days. Each set is named as A0, A1, · · ·, F2, F3.

4.2.2 Results

The results are shown in Fig.5, where geometric average and geometric standard deviation of voluntary pushing force f_U of every rank, every set are presented. Note that both axes of every figure are logarithmic. The estimated regression line of every set are drawn as a dotted line. We can see that F_D and f_U are not equal. Instead, they have a relation

$$f_U = C{F_D}^m. \quad (1)$$

In the following analysis, let us use an independent variable $X = \ln F_D - \ln \tilde{F}_D$ and a dependent variable $Y = \ln f_U$, where $\tilde{F}_D$ is the geometric mean of F_D used in this experiment ($\tilde{F}_D = 5.1$[N]). We obtained the following results: (i) Within subjects, there were no inter-set differences in regression slope ($F(18, 552) = 1.10$; $p = 0.349$). However, assuming intra-subject homogeneity of regression and removing the effect of X, significant inter-set differences were found in Y's averages ($F(18, 570) = 7.71$; $p < 1.0 \times 10^{-16}$). To put it shortly, a subject's regression line slides up and down without changing its inclination. (ii) Assuming intra-subject homogeneity of regression, there were significant inter-subject differences in regression ($F(5, 588) = 5.20$; $p = 0.0111$). (iii) Analyzing intercepts of regression lines (which correspond to f_U at the midpoint of the measurement range $F_D = 5.1$[N]), inter-subject variability was significantly greater than intra-subject one ($F(5, 18) = 17.0$; $p < 1.0 \times 10^{-5}$).

The statistic results above lead us to the conclusion that mechanical pressing force F_D and its correspondent voluntary pushing force f_U have a relation $f_U = C{F_D}^m$, where C and m values vary among individuals, and C value changes even in one person. Therefore, it would be desirable to calibrate C and m values every time prior to using the system.

4.3 Experiment II

Experiment II is conducted to evaluate the validity of the combined method of physical guidance and pressing fingertip, comparing a teaching effect of displaying both position and force to that of displaying position only. The target task chosen is very simple; that is to push an elastic object down to a specified position.

4.3.1 Protocol

The subject put his right-hand index finger on the apparatus as shown in Fig.4. Position was displayed by its movement and force by fingertip pressing force. The subject's hand were hidden by a board to prevent him from recognizing its movement visually. Therefore, the subject is supposed to perceive position by proprioception and force by sense of being pressed in his fingertip.

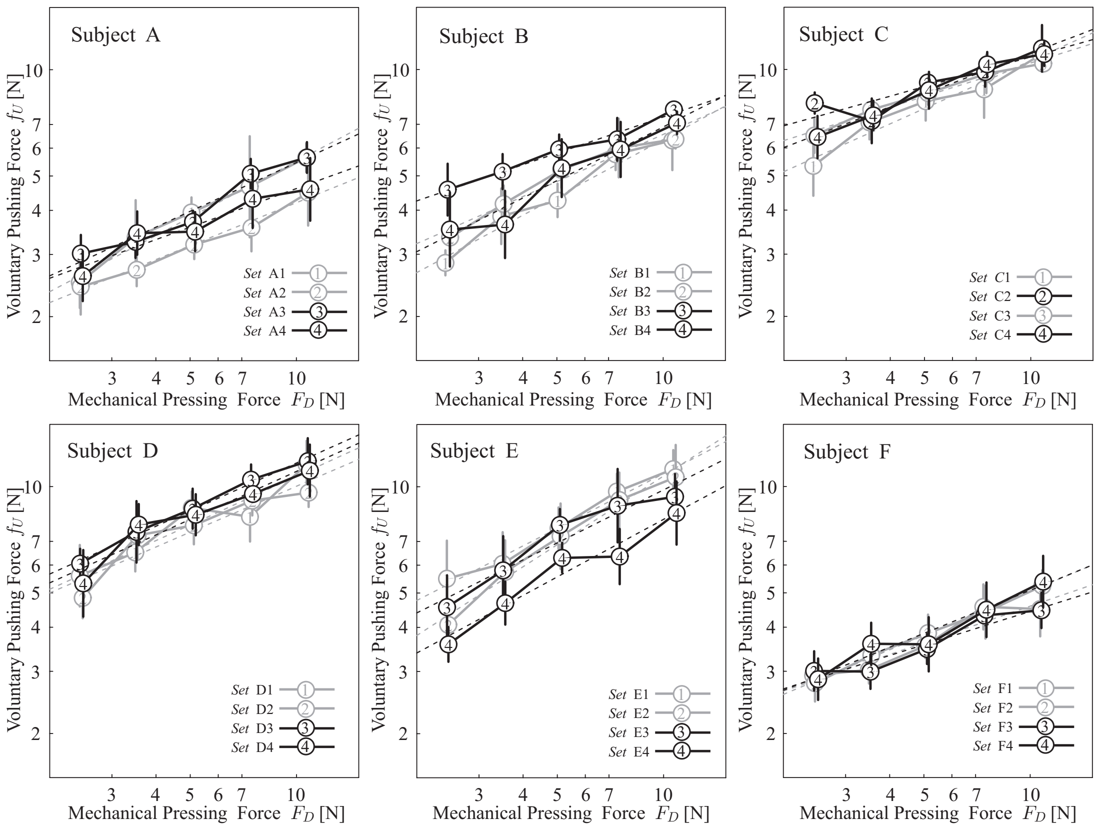

Figure 5: F_D versus f_U in Experiment I

The virtual object to push was a simple spring-mass-damper system shown in Fig.6(a), where $M_E = 0.04$[kg], $V_E = 0.01$[N·s/mm] and K_E varies by trials.

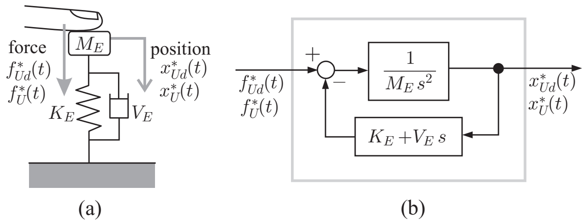

Figure 6: Virtual Environment

One trial in this experiment consists of a one-time teaching and a one-time execution. In teaching phase, an example trajectory of position, or trajectories of both position and force, was/were displayed to the subject by the apparatus. In the following executing phase, the subject pushed the apparatus as deeply and as strongly as he was instructed, and the subject's trajectories of position and force were recorded.

Time spans for each phase was 1.5 second, and an interval of 1 second was placed between the phases. Let us define several symbols as follows; $x^*_{Ud}(t)$ and $x^*_U(t)$ are the position trajectories in teaching and executing phases respectively, which are measured positive downward from the equilibrium of the virtual spring. $f^*_{Ud}(t)$ and $f^*_U(t)$ are the force trajectories in teaching and executing phases respectively. $f^*_{Ud}(t)$ is generated by the computer, while $f^*_U(t)$ is generated by human subjects. f_{Ud}, x_{Ud}, f_U and x_U are the peak values of $f^*_{Ud}(t)$, $x^*_{Ud}(t)$, $f^*_U(t)$ and $x^*_U(t)$ respectively. $\Psi(t)$ is a time function used to generate $f^*_{Ud}(t)$ which is shown in Fig.7 and described as;

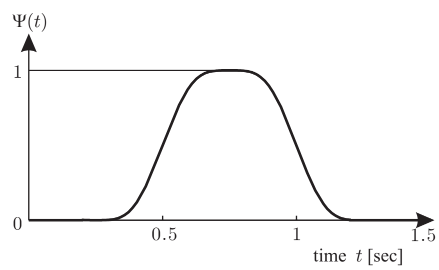

Figure 7: A Time Function $\Psi(t)$

$$\Psi(t) = \begin{cases} \dfrac{3}{2}\displaystyle\int_{0.25}^{t} \sin^3 2\pi(\tau - 0.25)d\tau & \\ \qquad\qquad : \text{ if } \ 0.25 \le t \le 1.25 & \\ 0 \qquad\qquad : \text{ otherwise} & \end{cases} \tag{2}$$

$F^*_D(t)$ is the trajectory of mechanical fingertip pressing force in teaching phase.

The simulator of the object is described as a block shown in Fig.6(b), which receives force input $f^*_{Ud}(t)$ or $f^*_U(t)$, and produces position output $x^*_{Ud}(t)$ or $x^*_U(t)$. Data flows in teaching and executing phase

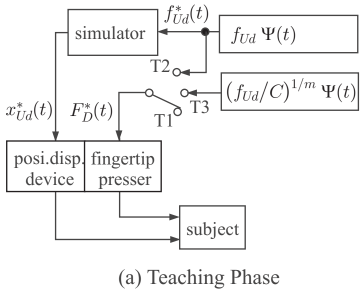

Figure 8: Data Flow

Table 1: V_n and E_n of each method.

method	imprecision	inaccuracy
T1a (T1 in Ua)	$V_{1a} = 2.78$	$E_{1a} = 0.0567$
T1b (T1 in Ub)	$V_{1b} = 2.43$	$E_{1b} = 0.127$
T2	$V_2 = 1.13$	$E_2 = 0.135$
T3	$V_3 = 0.745$	$E_3 = 0.107$

are shown in Fig.8(a) and Fig.8(b) respectively. The simulators used in both phases are identical to each other. The values of functions and variables are determined in the following procedure;

1. A pair of position and force (x_{Ud}, f_{Ud}) is randomly chosen. x_{Ud} is chosen out of 4 ranks; 1, 2, 4 and 8[mm], and f_{Ud} out of 4 ranks; 2.9, 4.4, 6.6 and 9.9[N]. Therefore the "task" (x_{Ud}, f_{Ud}) is chosen out of 16 candidates.
2. K_E is set to be $K_E = f_{Ud}/x_{Ud}$.
3. $f^*_{Ud}(t)$ is generated as $f^*_{Ud}(t) = f_{Ud}\Psi(t)$
4. In teaching phase, $f^*_{Ud}(t)$ is handed to the simulator and consequently $x^*_{Ud}(t)$ is produced. The position of the subject's finger is controlled to be $x^*_{Ud}(t)$. (The peak value of $x^*_{Ud}(t)$ necessarily becomes x_{Ud})
5. In executing phase, $f^*_U(t)$ is measured by force sensor B (see Fig.3). The simulator receives $f^*_U(t)$ and produces $x^*_U(t)$ in real-time. The position of the subject's finger is controlled to be $x^*_U(t)$.
6. After trial, x_U and f_U are set to be the maximum values of the recorded $x^*_U(t)$ and $f^*_U(t)$ (They necessarily satisfy $f_U = K_E x_U$).

Considering the results of Experiment I, three teaching methods were defined;

- method T1: displaying position only
- method T2: displaying both position and force *without* compensating for (1)'s relation; $F^*_D(t)$ is set to be $F^*_D(t) = f^*_{Ud}(t)$.
- method T3: displaying both position and force *with* compensating for (1)'s relation; $F^*_D(t)$ is set to be $F^*_D(t) = (f_{Ud}/C)^{1/m}\,\Psi(t)$.

When method T1 is used, the subject has no way to estimate the applied force from the displacement of the object, since he was not informed about K_E in advance. In contrary when method T2 or T3 is used, the subject can perceive f_{Ud} by mechanical pressing force in his fingertip.

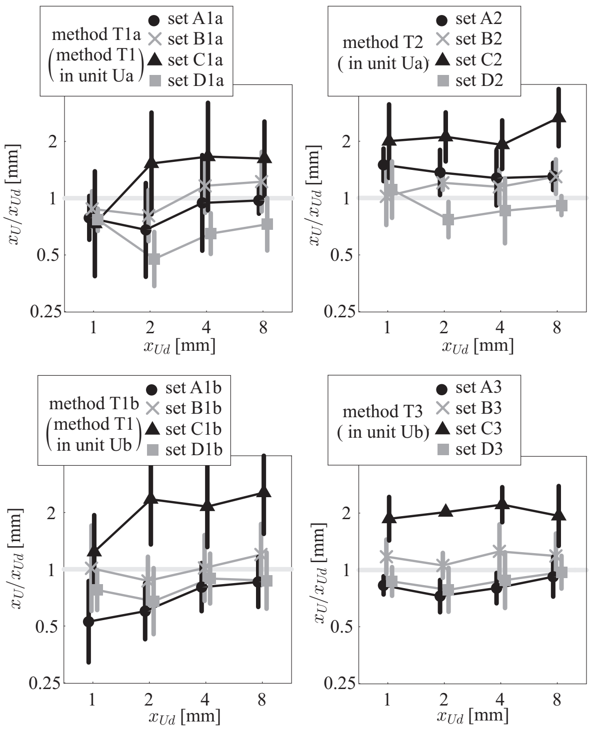

Figure 9: Result of Experiment II

C and m values of every subject was calibrated in advance by conducting 10 trials in the same procedure as Experiment I.

2 methods were tried in 1 "unit" of experiment, and 2 types of units were defined (unit Ua: T1 and T2 , unit Ub: T1 and T3). 1 unit is composed of 32 trials(=[1 trial]×[2 methods]×[16 tasks]). Within each unit, methods were switched after every 4 trials. The reason why the both of Ua and Ub include method T1 is to detect unexpected inter-unit factors. For brevity, we refer to data sets obtained out of method T1 in unit Ua and Ub as T1a and T1b respectively.

4 male subjects, between 22 and 30 years of age, were recruited and are referred to as A, B, C and D. For each subject, 2 units Ua and Ub were run at a interval of more than 1 days.

The result obtained out of method Tn (n={1a, 1b, 2, 3}) of subject X (X={A, B, C, D}) is referred to as "set" Xn. Out of 1 subject, 4 sets(=[1 set]×[2 methods]×[2 units]) were obtained, and 1 set is composed of 16 trials(=[1 trial]×[16 tasks]).

4.3.2 Results

We analized the result by using the error in logarithm of position; $\varepsilon = \ln(x_U) - \ln(x_{Ud}) = \ln(x_U/x_{Ud})$. In Fig.9, geometric average and geometric standard deviation of x_U/x_{Ud} of every rank of x_{Ud} of every set are presented. In Table 1, V_n and E_n are defined as $V_n = V_{An} + V_{Bn} + V_{Cn} + V_{Dn}$ and $E_n = \bar{\varepsilon}_{An}{}^2 + \bar{\varepsilon}_{Bn}{}^2 + \bar{\varepsilon}_{Cn}{}^2 + \bar{\varepsilon}_{Dn}{}^2$ respectively, where $\bar{\varepsilon}_{Xn}$ is the intra-set average of ε of set Xn, and V_{Xn} is intra-set sum of $(\varepsilon - \bar{\varepsilon}_{Xn})^2$ of set Xn.

Firstly, we made a comparison between T1a and

T1b and found no significant differences between V_{1a} and V_{1b} ($p = 0.301$), or between E_{1a} and E_{1b} ($p = 0.223$). Therefore we supposed that units Ua and Ub were homogeneous, and that the only factor which distinguishes T3 from T2 was compensation for F_D-f_U relation. The statistic analysis, assuming the homogeneity between Ua and Ub, revealed the following facts: (i) Fingertip pressing, with or without compensation for F_D-f_U relation, made V_n significantly smaller ($p < 0.001$). (ii) Compensation for F_D-f_U relation made V_n more smaller with a borderline significance ($p = 0.055$). However, excluding trials of $X_{Ud} > 8$[mm], V_n became significantly smaller ($p = 0.0195$). (iii) There were no significant changes among E_n's.

The statistic results above lead us to the following conclusions:

1. Fingertip pressing improves the precision of reproducing a target position. This effect is enhanced by compensation for (1)'s relation especially when the motion is small.
2. However, fingertip pressing does not improve the accuracy.

To put it simply, fingertip presser helps the teachee to perceive the teacher's action *clearly* but not *correctly*.

Solutions for improving the accuracy will have to be sought in future researches. Several past studies on kinesthesia have been revealed that every human subjects had a particular inaccuracy of matching or reproducing targe positions, and that the inaccuracy could vary over time and between subjects [9]. Therefore, it is inferred that the inaccuracy observed in this experiment is rooted in the methodology of displaying position, not in that of fingertip pressing.

4.3.3 Discussion

To take (1)'s relation into consideration rigorously, $F_D^*(t)$ should have been

$$F_D^*(t) = \left(\frac{f_{Ud}^*(t)}{C}\right)^{\frac{1}{m}} = \left(\frac{f_{Ud}\Psi(t)}{C}\right)^{\frac{1}{m}}. \quad (3)$$

However when (3) was tried, we received an apparently unnatural feeling because the pressing force raises behind the moment when the movement starts. Therefore, in this paper, we used the equation

$$F_D^*(t) = \left(\frac{f_{Ud}}{C}\right)^{\frac{1}{m}} \Psi(t), \quad (4)$$

knowing it greatly lacks generality.

Cutaneous mechanoreceptors respond to mechanical stimuli in two distinct manners; all kinds of receptors respond during the intensity of stimulus is changing, while some of them respond to static maintenance of the stimulation as well [8]. Because (1) is only the 'static' relation, a 'dynamic' relation have to be sought in future research. A better substitution for (4) would be described as

$$F_D^*(t) = \left(\frac{f_{Ud}^*(t)}{C}\right)^{\frac{1}{m}} + \Phi\left(\frac{d}{dt} f_{Ud}^*(t)\right), \quad (5)$$

using an unknown function $\Phi(\cdot)$.

5 Conclusion

A new mechanism of a haptic device as a medium of motion/force teaching from human to human has been proposed. This mechanism has a fingertip presser, and the teacher's finger force of pushing a surface is displayed as a mechanical pressing force onto the teachee's fingertip. It can complement conventional physical guidance which displays position information.

Experimental results led us to some conclusions. First, mechanically applied pressing force F_D and its correspondent voluntary pushing force f_U have a relation $f_U = CF_D{}^m$, and that C and m vary among individuals. Therefore, to compensate for the relation, C and m have to be calibrated every time prior to using the system. Second, fingertip presser helps the teachee to reproduce the teacher's action "precisely", but not "accurately".

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