

Development of a Training-Assist Robotic System Adapting to Individual Motor Abilities in Virtual Tennis Task

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Abstract—The present paper develops a training-assist robotic system that can adapt a reference hand motion for a virtual tennis task to individual motor abilities. The system first measures maximum hand force and velocity in reaching arm movements prior to the training, and designs a suitable reference trajectory for teaching motion smoothness and timing in the virtual tennis task based on the measured results. A quantitative index for evaluating task performance and motor functions are then defined with consideration of task dynamics. Finally, the effectiveness of the developed training system is validated through a set of preliminary training experiments with health subjects.

I. INTRODUCTION

Aging society in Japan has led to increase the number of patients with motor disorders, such as a stroke patient who does not perform a coordination of movements and a motor task requiring accurate timing [1][2], while the shortage of therapists and increasing burden to them has been grown as a serious problem in the rehabilitation field more than ever. For such a social problem, an advanced rehabilitation system using robotic devices has been expected as one of effective means to reduce the burden of therapists and to improve motor skills of the patients efficiently.

In this decade, many robot-assisted training systems have been developed especially for motor recovery of the upper limb [3]-[8]. For example, Krebs et al. [3][4] developed the training system using an impedance-controlled robot in which the trainee manipulates an end-effector by the hand to follow a target trajectory provided on the feedback display. Furusho et al. [8] developed the 3D rehabilitation system using ER actuators with highly safety and performance for practical use. Focusing on the regulation ability of human impedance properties [9][10], Tsuji and Tanaka et al. [11]-[14] developed a virtual sports training system and examined the relationship between trainee's skill-level and hand impedance properties estimated at the moment of static periods during dynamic contact tasks, such as virtual tennis, air-hockey and curling. These robotic systems enabled not only to accurately repeat standardized movements programmed in advance but also to provide the individual data measured during training tests and

the potential for developing a novel training method. However, they did not clearly discuss on how to assist and teach transient behaviors of the trainee's hand motion in training even for a simple task.

On the other hand, a healthy human involuntary or voluntary performs skillful motion according to target tasks. For example, a skilled tennis player strikes an approaching ball at a desired point in smooth arm movements. In other words, he has abilities to predict ball behavior and control his arm muscles and posture so that the racket can impact the ball in good timing. Such abilities requiring in a dynamic contact task are dominantly managed in the cerebellum. Thus, it is expected that cerebellar function of a trainee as well as physical ability will be trained through dynamic contact tasks when well-skilled motion depending on tasks can be provided as a reference motion in training.

Based on that consideration, we have developed the virtual tennis system and extracted a smooth motion of the skilled-subject as a reference motion in the virtual tennis task [15]. However, to realize active motion assist and teaching by the robot must deal with individual differences in trainee's motor abilities. In fact, the lack of flexibility for such individual differences has been one of major bottlenecks on utilizing a robotic training system in the rehabilitation field. Therefore, the present paper aims to develop a training-assist algorithm to design and teach a reference motion in the virtual tennis training with considerations of trainee's motor abilities.

This paper is organized as follows: Section II explains a virtual tennis training system and defines a standard reference motion from hand movements of a skilled healthy subject. Section III describes an algorithm of the proposed training-assist program for designing a reference motion according to individual motor abilities. Finally, in Section IV, basic training experiments with unskilled healthy volunteers are carried out to verify effectiveness of the proposed training-assist methodology.

II. VIRTUAL TENNIS SYSTEM

A. Structure

Fig. 1 shows an overview of the virtual tennis system using robotic devices developed for motor training of the upper extremity. The system is composed of an impedance-controlled robot [16] for providing virtual force loads to a trainee during movement tasks, a DSP system for robot control and signal processing, and a bio-feedback display for presenting a virtual tennis and a training result.

The robot has two linear motor tables with one degree of freedom (x axis: Nihon Thompson Coop., maximum force ± 10 [kgf], encoder resolution 2 [μm]; y axis: Nihon Seikou Coop., maximum force ± 40 [kgf], encoder resolution 1 [μm]) that are placed orthogonally in order to realize hand motion exercise on the horizontal plane. Hand force generated by the trainee is measured by a six-axis force/torque sensor (BL Autotec Co. Ltd., resolution: force x and y axes, 0.05 [N]; z axes, 0.15 [N]; torque, 0.003 [Nm]) attached on the handle of robot, and hand position is measured by an encoder built in the linear motor tables.

B. Virtual Tennis Model

Fig. 1(b) illustrates a virtual tennis model installed into the training system. A trainee is asked to manipulate the robot handle to move a virtual racket to strike a virtual ball toward the center of a target on the wall.

Dynamics of the impedance-controlled robot in the virtual tennis task is given by

$$F_e = M_r \ddot{X}_e + B_r \dot{X}_e \quad (1)$$

where $F_e \in \mathfrak{R}^2$ is the hand force, $X_e \in \mathfrak{R}^2$ is the hand position, $M_r = \text{diag.}(m_r, m_r) \in \mathfrak{R}^{2 \times 2}$ and $B_r = \text{diag.}(b_r, b_r) \in \mathfrak{R}^{2 \times 2}$ are robot inertia and viscosity, respectively.

Hand motion along the x -direction, x_e , is converted into rotation of the racket around the point S in the virtual tennis space, in which the racket angle θ is given by

$$\theta = \frac{\pi}{2} - \frac{5}{4}\pi x_e. \quad (2)$$

The ball is thrown from a specified initial position with a certain velocity in the virtual time scale v , and its motion before contact with the racket is calculated by

$$M_b \left(\frac{d^2 X_b}{dv^2} + g \right) + B_{air} \frac{dX_b}{dv} = 0 \quad (3)$$

where $X_b \in \mathfrak{R}^2$ is the ball position, g is the gravitational acceleration, $M_b = \text{diag.}(m_b, m_b) \in \mathfrak{R}^{2 \times 2}$ and $B_{air} = \text{diag.}(b_a, b_a) \in \mathfrak{R}^{2 \times 2}$ are the ball inertia and the air resistance, respectively. The virtual time v is given by

$$v = ct \quad (4)$$

where t is actual time and c (≥ 1) is a time scale parameter [17]. The moving speed of ball becomes slower in proportional to the value of c . Ball behavior after contact with the racket

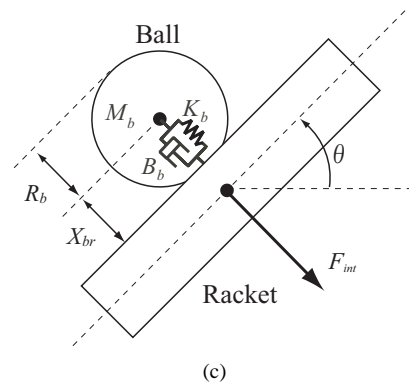
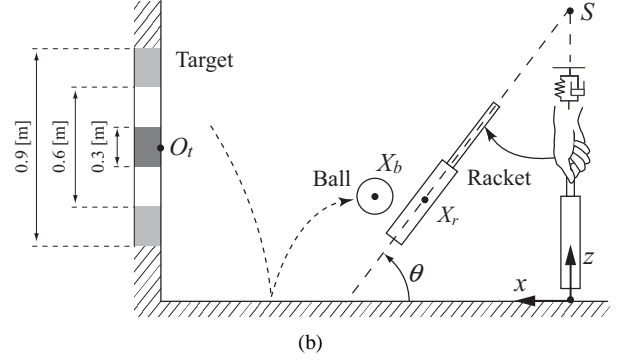
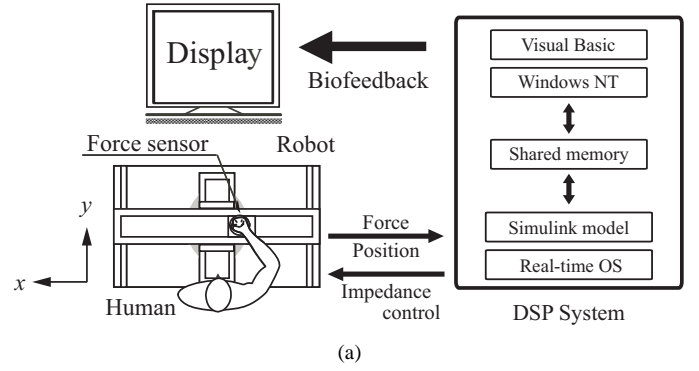


Fig. 1. An overview of the virtual tennis training system.

is then calculated by setting the following initial velocity into Eq. (3) as

$$\left. \frac{dX_{b0}}{dv} \right|_{v=t_c} = \frac{5\pi cl}{4} \dot{x}_e(t_c) \quad (5)$$

where l is the distance between S and the contact point of racket with ball, and t_c is the contact time. Consequently, ball motion stroked by the racket is uniquely determined with hand velocity and racket angle at hitting a ball.

Mechanical properties of a virtual ball including racket strings are expressed with a viscoelastic model (Fig. 1(c)). The interaction force $F_{int} \in \mathfrak{R}^2$ between ball and racket is given by

$$F_{int} = R(\theta)^T B_{br} R(\theta) \dot{X}_{br} + R(\theta)^T K_{br} R(\theta) dX_{br} \quad (6)$$

where $X_{br} \in \mathfrak{R}^2$ is the vector normal to the racket surface, $R(\theta) \in \mathfrak{R}^{2 \times 2}$ is the rotational matrix transforming from the

basic coordinate system to the local coordinate system at the racket, $dX_{br} \in \mathcal{R}^2$ is the deformation of the ball

$$dX_{br} = R_b \frac{X_{br}}{|X_{br}|} - X_{br}. \quad (7)$$

The robot can provide F_{int} to a trainee under $0 \leq |X_{br}| \leq R_b$.

In this paper, the ball was thrown from the initial position $X_b(0) = (4.0, 1.0)^T$ [m] with the initial velocity $\dot{X}_b(0) = (-3.0, 2.0)^T$ [m/s], and the initial angle of racket was set at $\theta(0) = \pi/2$ [rad]. The center of the target circle was at $O_t = (5.0, 1.0)^T$ [m]. The task performance was scored according to the distance between target center and ball position on the wall: 30-point within 0.15 [m]; 20-point within 0.3 [m]; 10-point within 0.45 [m]; and no-point over 0.45[m] (See Fig. 1(b)). No-point recorded when the ball contacts with the ground before the wall. The other parameters were set as $(m_b, b_{br}, k_{br}) = (0.05$ [kg], 2.0 [Ns/m], 500 [N/m]), $R_b = 0.05$ [m], $b_a = 0.01$ [Ns/m], $m_r = 5.0$ [kg], $b_r = 5.0$ [Ns/m].

C. Reference Motion in the Virtual Tennis Task

Figs. 2(a) and (b) show the time histories of hand position and velocity along the x -direction in the case where the task performance was the 30-point for a well-skilled subject. The initial time is the ball-throwing time, a solid line is the mean profile of hand trajectory and velocity for three trials, a dotted line is the profile of standard deviations, and the shade zone represents the contact time between ball and racket. It can be seen that the skilled subject produced the almost unique hand velocity profile and hit the ball at the peak velocity time. Such the well-trained hand motion is regarded as a training reference for the virtual tennis task [15].

Fig. 2(c) shows the relationship between racket angle and hand velocity at the ball-impact, where the shade zone indicates simulated conditions for getting 30-point, the double circles are representative results for the skilled subject. It can be seen that the skilled subject controlled hand velocity according to racket angle in the case when he had 30-point.

Based on these results, the mean of three hand velocities scored 30-point (the double circle in Fig. 2(b)) were extracted as a reference motion of the virtual tennis task in this paper.

III. TRAINING-ASSIST SYSTEM

The proposed training-assist system for individual differences of motor skill consists of a diagnosis part of trainee's motor ability, a teaching part of reference motion, a training part of the virtual tennis task, and an evaluation part of training results.

A. Diagnosis part

Maximum hand velocity and force during reaching arm movements produced by a trainee are measured for diagnosis of trainee's motor ability (Fig. 3(a)). Based on the diagnosis result, the time scale parameter c is regulated to set suitable reference motion for a trainee, where the maximum velocity and force in the reference motion do not exceed the measured ones by the trainee. This part also investigates whether a trainee should carry out the virtual tennis training; a trainee can

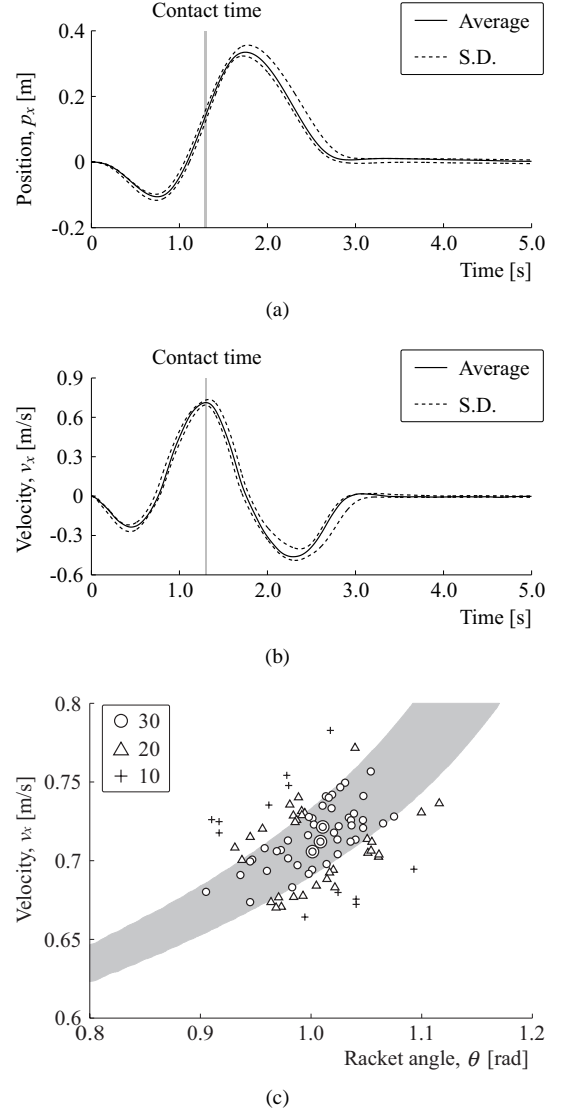


Fig. 2. Motor skills for a skilled subject in the virtual tennis task.

be perform the virtual tennis training, if he/she would generate a hand velocity profile with a maximum value enough large to move the robot handle.

B. Teaching part

The teaching part aims to assist the trainee in acquiring suitable hand motion for the virtual tennis task. (Fig. 3(b)). The trainee holds the handle of robot automatically following his/her reference motion with the parameter c designed in the diagnosis part or the evaluation part so as to know how to move his/her hand in training. The display shows a time profile of reference motion at the same time. An auditory guidance can be also provided to the trainee, where the sound volume changes in proportional to hand velocity. It is expected that the fusion of somatosensory, auditory and visual feedbacks will promote a trainee to learn the motor image of suitable hand motion for getting higher points. This part is terminated when

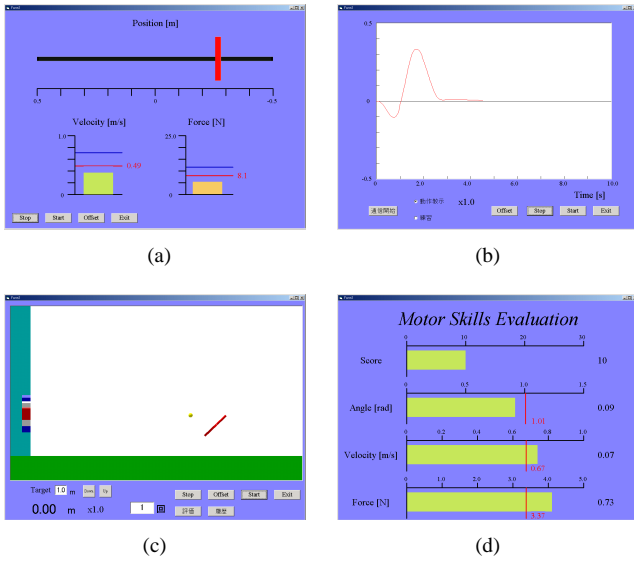


Fig. 3. Examples of GUIs.

the trainee gets the feel of producing the reference motion without any guides from the robotic system.

C. Training part

The training is performed in the virtual time scale utilized in the teaching part (Fig. 3(c)). A trainee performs the virtual tennis task in which he/she strikes a virtual ball toward the center of a target on the wall. To guide motion timing indirectly, the magnitude of hand velocity is auditory fed back during movements, and the interaction force is provided to trainee's hand at the ball-impact.

D. Evaluation part

After each trail of the training, the racket angle, hand velocity and force at the ball-impact as well as the score obtained are displayed to check his motor abilities quantitatively (Fig. 3(d)). If a trainee's motor skill is not improved, the parameter c is increased to make the trainee get higher scores and the system switches to the teaching part. Otherwise, the virtual tennis training is continued.

Currently, the time scale parameter c is regulated by a system operator based on his/her experience. We plan to add a function for automatically regulating the time scale parameter.

IV. TRAINING EXPERIMENTS

A. Method

Training experiments were carried out with three healthy volunteers (male university students) who were unskilled in the virtual tennis and did not suffer from any known neuromuscular disorders. After brief explanations on the training task, a subject was asked to stand in front of the system and strike the ball to hit the center of a target circle on the wall directly as possible.

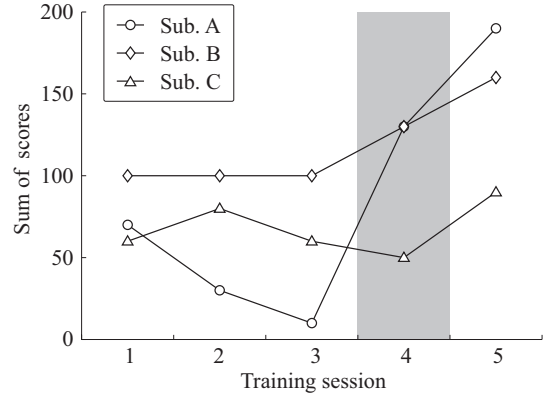


Fig. 4. Changes of the task performance for the session number.

Subjects carried out a set of five sessions in which ten trials were set for each teaching and training modes: they learned how to move their own hand ten times in the teaching mode (except the first session), and carried out ten trials of the virtual tennis task in the training mode. The time scale parameter was set as $c = 1$ because they did not have any motor disorders, but $c = 1.3$ only in the fourth session where the ball motion became slower than the other session.

B. Results

Fig. 4 shows the trial history of summed scores obtained in each session for all subjects, where the shade zone represents the session with $c = 1.3$. The unskilled subjects did not improve task performances by the first three sessions, whereas they showed higher performances after the fourth session.

Figs. 5(a), (b), and (c) show the hand velocity profiles for Sub. A measured in the first, fourth and fifth sessions, respectively, where a solid line is an average velocity profile of ten trials and a dotted line is a reference velocity. The large difference between subject's hand and reference motions exists in the first session, whereas the subject almost generated the reference velocity profile in the fourth and last session. The dispersion of ball-hitting times in the last session is obviously narrower compared than the first session. Fig. 5(d) shows the relationships between racket angle and hand velocity at ball-impact. It can be seen that the subject controls his hand motion to get higher points while involuntarily reproducing the reference velocity profile in the training. Similar results were confirmed in the results for Subs. B and C (See Table I).

These results indicate that an adjustment of the virtual time scale according to trainee's motor skills is helpful for the trainee to understand how to move his/her hand during the virtual tennis tasks.

C. Skill Evaluation

Based on the behavioral results, the quantitative evaluation index I was designed as

$$I = w_1 \frac{p}{30} + w_2 \left(1 - \frac{e}{e_{max}} \right) + w_3 r^2 + w_4 \left(\frac{1}{1+L} \right)^2, \quad (8)$$

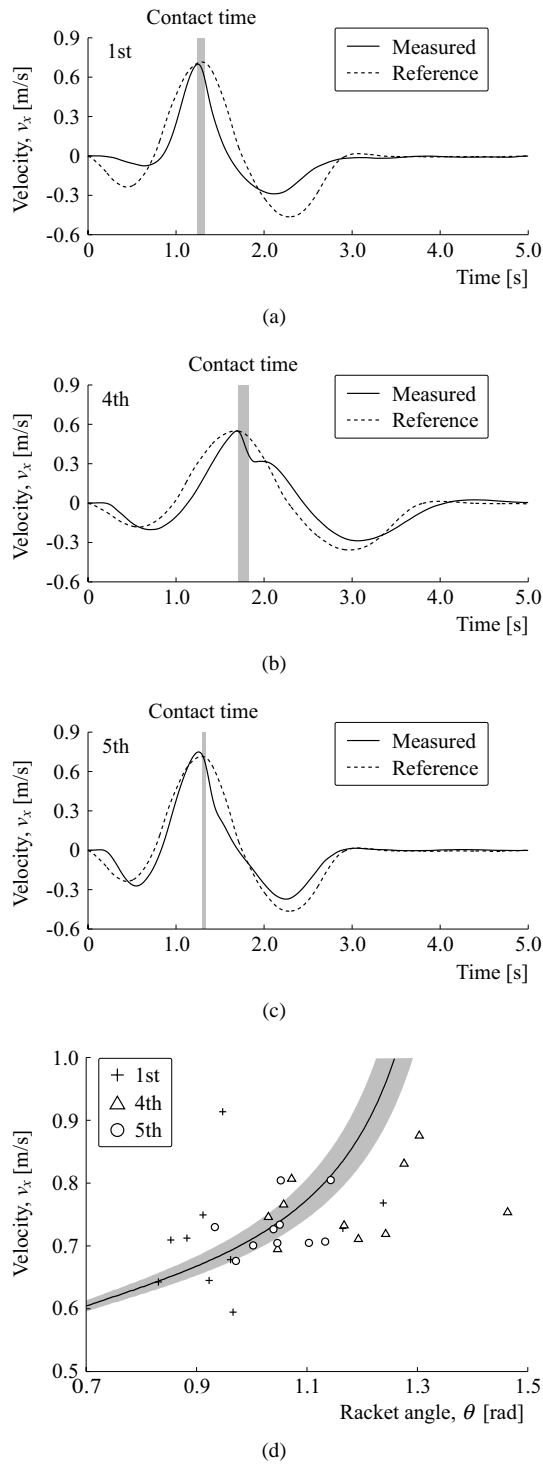


Fig. 5. Change of motor skills during training experiments for Subject A.

where p is the point obtained, e and r^2 are the difference between reference and measured velocity profiles and the coefficient of determination, respectively, e_{max} is the summing integral value of the reference velocity profile, L is the minimum distance between the position of racket-angle and hand-velocity and the simulated line to hit the target center

TABLE I
CHANGES OF THE CONTACT TIME IN TRAINING.

Subject	1st session [s]	4th session [s]	5th session [s]
A	1.289 ± 0.041	1.765 ± 0.062	1.313 ± 0.020
B	1.318 ± 0.052	1.732 ± 0.051	1.345 ± 0.024
C	1.405 ± 0.083	1.674 ± 0.100	1.320 ± 0.052

(See Fig. 5(d)). The first term (I_1) is for the evaluation of task performance, the second and third terms (I_2, I_3) are of motor skills such as motion smoothness and timing, and the last term (I_4) is of task-dependent skills in the virtual tennis. These evaluation elements can be weighted by the coefficient $0 \leq w_i \leq 1$ ($i = 1, \dots, 4$) by a trainer.

Fig. 6(a) shows the mean value of each term with $w_i = 1$ in the first and fifth sessions for all subjects. The quadrangles of the fifth session are obviously larger than those of the first session. Finally, Fig. 6(b) shows the total evaluation results with $w_i = 0.25$, in which the highest evaluation is at $I = 1$. It can be found that the subjects significantly improved their motor skills although there exist some individual differences. These quantitatively evaluations demonstrate that the designed index will be useful to reveal which motor abilities as well as task-dependent skills are improved though the virtual tennis training.

V. CONCLUSIONS

This paper discussed a methodology for managing individual differences in trainee's motor abilities and developed the training-assist system for the virtual tennis task in which the trainee has to control his/her motion smoothness and timing. The system designs an appropriate reference motion for individuals based on the diagnosis results of trainee's motor abilities in reaching arm movement by using a time scale transformation method, and evaluates trainee's motor skills using the quantitative index. Effectiveness of the proposed system was then validated through a set of training experiments with the unskilled subjects. However, there still exist insufficiencies in the developed system, i.e.; how to automatically adjust the time scale parameter during training. The future research will be directed to perform a training test with corporation of stroke patients after refining on the system functions.

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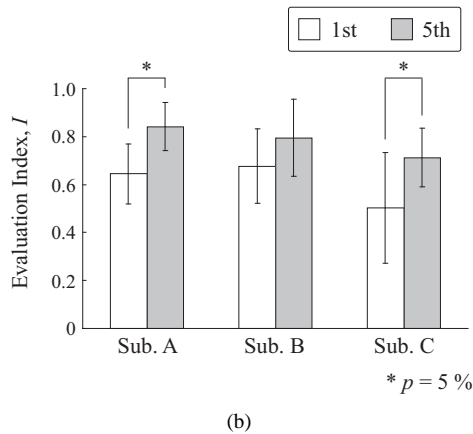
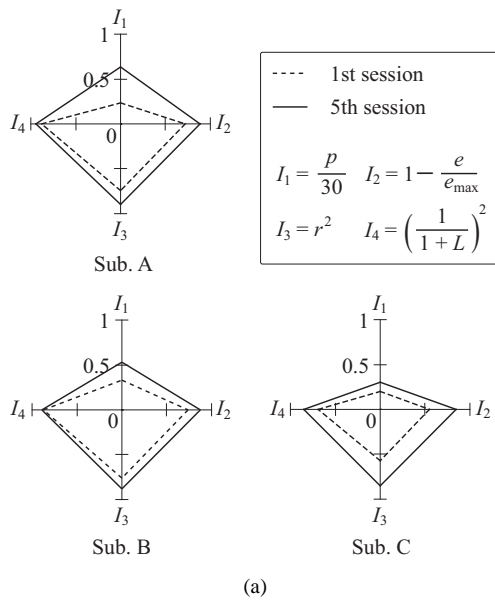


Fig. 6. Evaluation results of training-effect

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