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A Motor-Control Training Method for Smoothness and Timing of Voluntary Arm Movements in a Virtual Tennis Task

Yoshiyuki Tanaka, *Member, IEEE*, Haruhito Inoue, Toshio Tsuji, *Member, IEEE*, and Nobuaki Imamura, *Member, IEEE*

Abstract— **This paper discusses the training method for motion smoothness and timing of arm movements with consideration in individual differences in trainee's motor abilities. The virtual tennis operation is designed as a target task in which a trainee will be required to control his hand motion to hit an approaching ball in good timing. The skilled subject's hand motion is regarded as one of a reference motion in the virtual tennis task, and was expressed in the framework of the minimum jerk model with task-related constraints. A regulation algorithm of the reference motion is then presented for the training of upper limbs in individuals. Effectiveness of the proposed method is validated through training experiments with the unskilled subjects and quantitative evaluation of their motor abilities.**

I. INTRODUCTION

An advanced training system using robotic devices has been expected as one of new means to improve motor functions of the patients efficiently but also to reduce the burden of therapists. Therefore, many robotic neuro-rehabilitation systems have been developed in recent years, especially for motor recovery of the upper limb [1]-[6].

For example, Krebs et al. [1] developed a training system using an impedance-controlled robot in which the trainee manipulates an end-effector to follow a target trajectory provided on a feedback display. Furusho et al. [2] developed the 3D rehabilitation system using ER actuators with highly safety and performance. Tanaka and Tsuji et al. [5], [6] developed the virtual sports system for the training of motion timing and smoothness, which are required abilities in dynamic tasks and are dominantly managed in the cerebellum [7]. They also reported that well-trained subjects make a hand velocity pattern depending on dynamics of the virtual environments. On the other hand, Mussa-Ivaldi et al. [4] proposed the training-assist approach using force field for teaching point-to-point hand movements to a trainee, in which the desired trajectory is not required in training.

These robotic systems enabled not only to present standardized motions for a training task programmed in advance but also to evaluate trainee's motions measured during training tests for developing a novel training method. However, robotic training systems must deal with individual differences in trainee's motor abilities in teaching and/or training an adequate reference motion to a trainee. In fact, the lack of flexibility for such individual differences has been one of major bottlenecks on utilizing such a system in the rehabilitation field. For that, this paper presents a method to regulate a reference motion for the virtual tennis task according to the training history on trainee's motion.

This paper is organized as follows: Section II explains the virtual tennis system and defines the reference motion considering motion timing and smoothness through experiments with skilled healthy volunteers. The training assistance method adaptable to individual motor abilities is proposed in Section III. Finally, Section IV reports on training experiments carried out with unskilled healthy volunteers to verify the effectiveness of the proposed training assistance method.

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Y. Tanaka, H. Inoue, and T. Tsuji are with Graduate School of Engineering, Hiroshima University, Higashi-hiroshima, Japan {ytanaka, inoue, tsuji}@bsys.hiroshima-u.ac.jp

N. Imamura is with Department of Engineering, Hiroshima Kokusai University, Higashi-hiroshima, Japan n-imamur@it.hirokoku-u.ac.jp

II. VIRTUAL TENNIS TASK

Fig. 1 (a) shows an overview of the virtual tennis system, which is composed of an impedance-controlled robot [8] to provide force loads to a trainee's hand, two computers for robot control and signal processing, and a biofeedback display to present the virtual tennis space and training results. The hand force generated by the trainee is measured using a six-axis force/torque sensor attached on the handle of robot, and hand position is measured by encoders built in the linear motor tables. Real-Time Linux software installed on a Linux PC enables precise robot motion control in real time.

Fig. 1 (b) illustrates the virtual tennis model installed on the training system. The trainee manipulates the handle to move a virtual racket to strike a virtual ball toward the center of a target $\boldsymbol{O}_t$ on the wall. The dynamics of the impedance-controlled robot in this virtual tennis is given by

$$F_e = M_r \ddot{X}_e + B_r \dot{X}_e \tag{1}$$

where F_e is the hand force, X_e is the hand position in the x-direction, M_r and B_r are robot inertia and viscosity, respectively. Hand motion is converted into racket rotation around the point S in the virtual tennis space, in which the racket angle is given by $\theta = \frac{5\pi}{4} X_e$. The ball is thrown from a specified initial position with a certain velocity and its motion is given by

$$\begin{cases} M_b \ddot{X}_{bx} = 0 \\ M_b \ddot{X}_{bz} = -\frac{1}{2} M_b g \end{cases} \tag{2}$$

where $\boldsymbol{X}_b = (X_{bx}, X_{bz})$ is the ball's position, M_b is its inertia, and g is the gravitational acceleration. The ball's

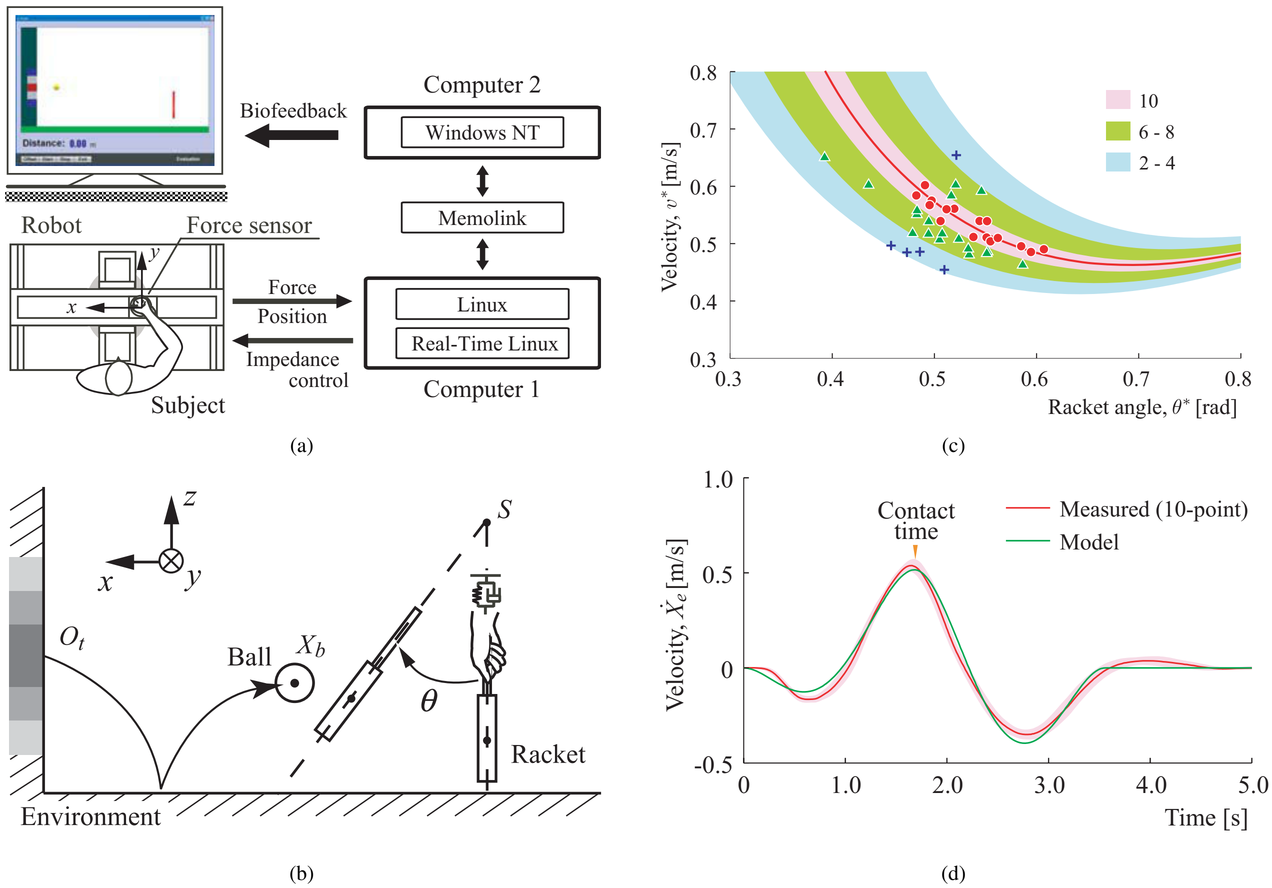

Fig. 1. Experimental apparatus and skilled movements in the virtual Tennis Task.

behavior after contact with the racket is then calculated by setting the following ball velocity just after ball impact $\dot{\boldsymbol{X}}_b^*$ into Eq. (2)

$$^o\dot{\boldsymbol{X}}_b^* = {}^o\boldsymbol{R}_c(\theta^*)^c\dot{\boldsymbol{X}}_b^* \tag{3}$$

where $^o\boldsymbol{R}_c(\theta) \in \Re^{2\times2}$ is the rotation matrix transformed from the basic coordinate system to the local coordinate system at the impact point.

In this study, the handle inertia and viscosity are set at (M_r, B_r) = (5.0 [kg], 5.0 [Ns/m]). The ball is thrown from the initial position $\boldsymbol{X}_b(0) = (3.0, 1.0)$ [m] with the initial velocity $\dot{\boldsymbol{X}}_b(0) = (-1.5, 1.5)$ [m/s], and its inertia and radius are set at $M_b = 0.25$ [kg], $R_b = 0.075$ [m]. The center position and radius of the target circle are at $\boldsymbol{O}_t = (3.5, 1.0)$ [m] and $R_t = 0.5$ [m]. The task performance is scored according to the distance E_p: 10 points for within 0.1 [m], 8 points for within 0.2 [m], 6 points for within 0.3 [m], 4 points for within 0.4 [m], and 2 points for within 0.5 [m]. No points are recordedif the ball hits with the ground before hitting the wall.

Fig. 1(c) shows the simulated results of the combinations of the racket angle θ^* and hand velocity v^* upon ball impact, and the solid line is the hand velocity required to hit the ball on to the target center. The trainee needs to properly control hand velocity according to the racket angle to get more points. Therefore, in this paper, the combination of racket angle and hand velocity (θ^*, v^*) are defined as the task skill for the virtual tennis task. The task skills for a skilled-subject are also plotted with markers according to the scored points. The skilled subject properly controlled hand velocity depending on the racket angle to score more points.

On the other hand, Fig. 1(d) shows the time histories of hand velocity and the contact time between the ball and the racket in the case where the task performance was 10 points. It can be seen that he produced almost-unique hand velocity profiles and hit the ball at the peak velocity time. These properties were observed in the results with other four skilled subjects. Based on these results, a minimum jerk model [9] is utilized to provide a reference motion for the virtual tennis in this study. The model generates hand trajectories $X_e(t)$ for reaching movements with minimization of the evaluation function J given by

$$J = \frac{1}{2}\int_0^{t_f}\left(\frac{d^3X_e}{dt^3}\right)^2 dt \tag{4}$$

with the task-related constraints at the time t_1 $(0 \leq t_1 \leq t_f)$

$$X_e(t_1) = \tfrac{4}{5\pi}\Theta^* \quad \dot{X}_e(t_1) = V^* \quad \ddot{X}_e(t_1) = 0 \tag{5}$$

where t_f is the terminal time of hand motion, Θ^* is the racket angle upon ball impact, t_1 is the contact time calculated from racket angle Θ^*, and V^* is the hand velocity required to hit the ball onto the target center according to Θ^*. The

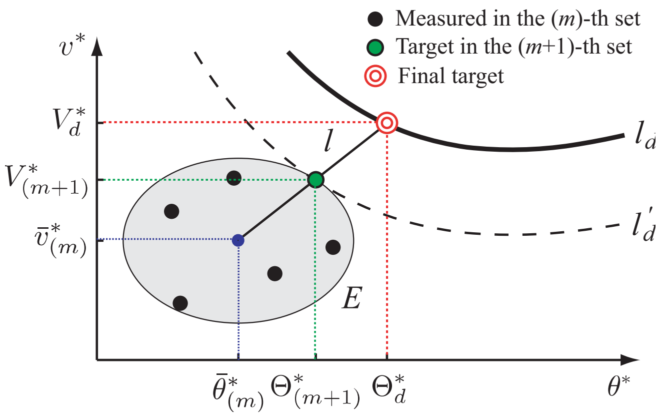

Fig. 2. An overview of the Regulation method of target task skill.

reference velocity simulated using the constraints is plotted as the green line in Fig. 1(d). It is found that the simulated motion almost reproduces the measured motion. However, such skilled motions of the healthy subject may not be always appropriate as a reference motion for trainees whose motor abilities are inferior.

III. Regulation of the Reference Motion

Fig. 2 shows an overview of the regulating method for reference motion. First, the following ellipse E is determined from the trainee's n-trials of task skill $({}^i\theta^*_{(m)}, {}^i v^*_{(m)})$ $(i = 1, 2, \cdots, n)$ measured in the (m)-th set of training.

$$\frac{(\theta^* - \bar{\theta}^*_{(m)})^2}{r_\theta^2} + \frac{(v^* - \bar{v}^*_{(m)})^2}{r_v^2} = 1 \tag{6}$$

where the center of ellipse $(\bar{\theta}^*_{(m)}, \bar{v}^*_{(m)})$ are the mean values of ${}^i\theta^*_{(m)}$ and ${}^i v^*_{(m)}$, r_θ and r_v, are the standard deviations. The area of ellipse E can be regarded as the range of task skills that the trainee can generate easily.

The target skill for the next $(m+1)$-th set of training, $(\Theta^*_{(m+1)}, V^*_{(m+1)})$, is given by the crossing point of the ellipse E and the line l between the center of E and the final target on the line l_d (See Fig. 2). Since the target velocity $V^*_{(m+1)}$ is different from the hand velocity required to hit the ball onto the target center, the curve line l_d is shifted to l_d' passing the position of $(\Theta^*_{(m+1)}, V^*_{(m+1)})$. Namely, the ball speed in the virtual tennis space is regulated so that the ball will be hit on the target center by $V^*_{(m+1)}$. This time operation is realized by using time scale transformation [10], in which the relationship between the actual time t and the virtual time ν is given by $c = d\nu/dt$ (> 0). Note that the moving speed of ball decreases when the value of time scale constant c is less than 1.

Transforming the time scale of the virtual tennis space from the actual time t to the virtual time ν, the ball velocity just after ball impact is given by

$$\frac{d\,{}^o\boldsymbol{X}_b^*}{d\nu} = {}^o\boldsymbol{R}_c(\theta)\frac{d\,{}^c\boldsymbol{X}_b^*}{d\nu}, \tag{7}$$

and the task-related constraints to generate the reference motion for $(\Theta^*_{(m+1)}, V^*_{(m+1)})$ are converted to the following equations as

$$X_e(\nu_1) = \tfrac{4}{5\pi}\Theta^*_{(m+1)} \quad \dot{X}_e(\nu_1) = V^*_{(m+1)} \quad \ddot{X}_e(\nu_1) = 0 \tag{8}$$

where $\nu_1 = t_1/c$. By updating the target task skill $(\Theta^*_{(m+1)}, V^*_{(m+1)})$ in the direction of the final target task skill (Θ^*_d, V^*_d) according to trainee's task performance, it is expected that the trainee will be able to recover motor functions requiring for motion timing and smoothness without excessive loads.

IV. Training Experiments

Training experiments were carried out with 8 healthy volunteers who were unskilled in the virtual tennis. In the experiment, the subjects were divided into two groups (Group I: Subs. A-D, Group II: Subs. E-H). The subjects in Group I carried out a 6 sets of training made by 10 trails in which the system assisted the trainee's motion at the first five trials by providing the regulated reference motion with auditory feedback and displaying their task skills (θ^*, v^*). While the subjects in Group II carried out the same numbers but with no training assistance and the time scale constant was fixed at $c = 1.0$.

Fig. 3 (a) shows the changes of task skill (θ^*, v^*) for Sub. A (Group I) and Sub. E (Group II). In the first set, the task skills of Subs. A and E are far from the final target skill with large dispersions. As progressing the training set number, Sub. A gradually generated task skills close to the final target skill in the earlier set number, whereas the measured task skills by Sub. E were still far from the final values in the last set.

Fig. 3 (b) show the time histories of hand velocity and the contact time between the ball and the racket in the first and last set. The color and solid lines indicate the mean profile of hand velocities in each set, the black line represents the reference velocity profile at the final target. It can be seen that Sub. A almost generated the reference velocity profile in the last set, whereas Sub. E generated the individual velocity profiles that are different from the reference one. Similar characteristics were almost observed for the other subjects in each group.

Finally, the training achievement was quantitatively evaluated by the distance between the center of ellipse E and the final target skill with the following evaluation index I as

$$I = ||(\Theta^*_d, V^*_d) - (\bar{\theta}^*_{(m)}, \bar{v}^*_{(m)})|| \tag{9}$$

The smaller values of index mean the higher training achievement. The changes of evaluation results for each group are shown in Fig. 4. The index values of the last set are smaller than those of the first set in both groups, and the subjects in Group I significantly improved their motor skills than the subjects in Group II. These evaluation results demonstrate that the training effects though the virtual tennis training could be improved effectively by providing the regulated reference motion depending on individual motor abilities.

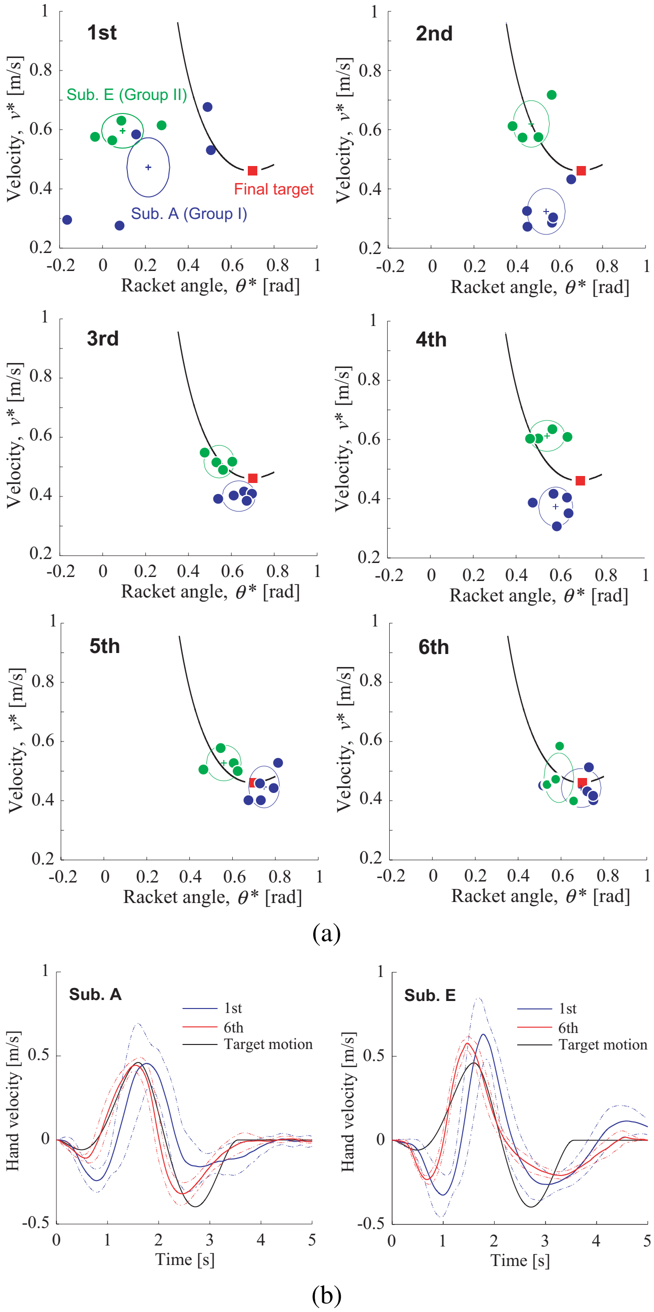

Fig. 3. Changes of task skills and hand velocity profiles for Sub. A (Group I) and Sub. E (Group II).

V. Conclusions

This paper presented a robotic rehabilitation system for upper limbs focusing on motion smoothness and timing in the virtual tennis task, and proposed an assistive methodology in order to adapt to individual differences in trainee's motor abilities. The proposed method designs and teaches an appropriate reference motion that is regulated based on the trainee's task skills measured in training. The skilled subject's hand motion was regarded as one of a reference motion in the virtual tennis task, and was expressed in the framework of the minimum jerk model with constraints. Then, effectiveness of the proposed training-assistance method was validated through training experiments with the unskilled subjects and quantitative evaluation of their motor abilities using the evaluation index.

The future research will refine the regulation method of the reference motion to improve the learning speed, and be directed to perform a training test with stroke patients.

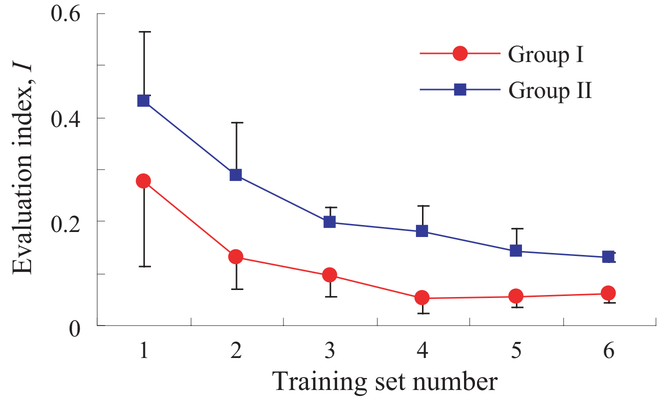

Fig. 4. Comparisons of the evaluation index for Group I and Group II.

References

[1] H. I. Krebs, N. Hogan, M. L. Aisen and B. T. Volpe, "Robot-aided neurorehabilitation," *IEEE Transactions on Rehabilitation Engineering*, Vol.6, No.1, pp. 75–87, 1998.

[2] J. Furusho, K. Koyanagi, K. Nakanishi, U. Ryu, S. Takenaka, A. Inoue, K. Domen and K. Miyakoshi, "Development of a 3-D rehabilitation system for upper limbs using ER actuators in NEDO project," *International Journal of Modern Physics B*, Vol.19, No.7-9, pp. 1591–1597, 2005.

[3] P. S. Lum, S. L. Lehman and D. J. Reinkensmeyer, "The bimanual lifting rehabilitator: An adaptive machine for therapy of stroke patients," *IEEE Transactions on Rehabilitation Engineering*, Vol.3, No.2, pp. 166–173, 1995.

[4] F. A. Mussa-Ivaldi, J. L. Patton, "Robots can teach people how to move their arm," In proceedings of *the 2000 IEEE International Conference on Robotics and Automation*, pp. 300–305, 2000.

[5] Y. Tanaka, K. Matsushita and T. Tsuji, "Sensorimotor characteristics in human arm movements during a virtual curling task," *Transactions of the Society of Instrument and Control Engineers*, Vol.42, No.12, pp. 1288–1294, 2006 (in Japanese).

[6] Y. Tanaka, M. Ishii, T. Tsuji, and N. Imamura, "Modeling and evaluation of human motor skills in a virtual tennis task," In proceedings of *the 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 4190–4193, 2008.

[7] H. Topka, J. Konczak and J. Dichgans, "Coordination of multi-joint arm movements in cerebellar ataxia: Analysis of hand and angular kinematics," *Experimental Brain Research*, Vol.119, No.4, pp. 483–492, 1998.

[8] N. Hogan, "Impedance control: An approach to manipulation, Parts I, II, III," *ASME Journal of Dynamic Systems, Measurement, and Control*, Vol.107, No.1, pp. 1–24, 1985.

[9] T. Flash and N. Hogan, "The coordination of arm movements: An experimentally confirmed mathematical model," *The Journal of Neuroscience*, Vol.5, No.7, pp. 1688–1703, 1985.

[10] M. Sampei, K. Furuta, "On time scaling for nonlinear systems: Application to linearization," *IEEE Transactions on Automatic Control*, Vol.AC-31, No.5, pp. 459–462, 1986.