Paper:

A Virtual Sports System for Skill Training

Toshio Tsuji[*], Yasuteru Sumida[*], Makoto Kaneko[*] and Sadao Kawamura[**]

[*] Graduate School of Engineering, Hiroshima University
4-1 Kagamiyama 1-chome, Higashi Hiroshima, Hiroshima, Japan
[**] Faculty of Science and Engineering, Ritsumeikan University,
1-1 Noji Higashi 1-chome, Kusatsu, Shiga, Japan
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Dynamic characteristics of human upper extremities are usually modeled with mechanical impedance. Although many studies have been reported on the human impedance characteristics, there is no such a report in which the human impedance is utilized for skill training and rehabilitation. As the first step to develop a training method based on human impedance characteristics, this paper proposes a virtual sports training system using a virtual reality technique in order to measure human movements during sports. From experiments, differences of movements between skilled and unskilled subjects are analyzed.

Keywords: Impedance, Human movements, Virtual sports system, Skill training

1. Introduction

Muscle training[1] widely conducted nowadays is a typical training for sports and rehabilitation, in which isometric, isotonic, and isokinetic motions are frequently practiced. Also, studies on practical training for developing skill through actual sports or motions have been pursued extensively in parallel with the study on muscle training. In many cases, however, these two types of training are conducted separately, so it is difficult to analyze or evaluate basic muscle motions in practical skill-level training.

We properly control the kinetic properties of our arms and legs when we move or take part in sports. A professional tennis player can serve an extremely fast ball compared to the average person because they excel in muscle power and make their arms supple like a rod by controlling the compliance of their bodies properly when they move. The motion of human as described above can generally be expressed by using mechanical impedance such as stiffness, viscosity, and inertia.

Many reports about measurement of the mechanical impedance of the arms have been published. Mussa-Ivaldi et al.[2] clarified after measuring hand stiffness during maintenance of posture that it largely depends on arm posture and that the magnitude but not the direction of stiffness can be changed. Dolan et al.[3] and Tsuji et al. [4] [5] clarified a qualitative analogy between stiffness and viscosity after estimating hand impedance for stiffness, viscosity and inertia. Tsuji et al. [6] clarified that hand viscoelasticity changes in proportion to muscle contractions. Gomi et al.[7] clarified that hand stiffness in motion changes more than that during maintenance of a specified arm posture after measuring hand impedance in reaching movements. They also calculated the virtual trajectory of human hand based on measured impedance.

In kinesitherapy for rehabilitation, the above impedance is used as a keyword in several research reports [8)-14)]. Tsuji et al.[15] pointed out the importance of human impedance regulation itself and proposed an impedance training method to test impedance regulation ability of trainees by measuring their hand impedance. They found that use of impedance training effectively improves hand impedance regulation ability, and that correlations between stiffness and muscle contraction, viscosity and motion direction and inertia and arm posture are essential for impedance regulation. The impedance training, however, can be applied only to static motions during maintenance of posture, not to skill training in dynamic motion.

Training in dynamic motion is easily conducted in actual sport, but use of impedance training involves difficulties in measuring forces and positions. When impedance is to be measured in impedance training, it is necessary to externally apply disturbance to a hand but such an action cannot be taken in the midst of a sport event. Some reports have tried to estimate impedance in motion based on EMG signals. [6,16,17] As hand impedance is influenced significantly by the intensity of contraction and arrangement of position of various muscles and also by the sensitivity of spinal reflex, it is difficult to accurately estimate it in training.

In the first step to realize impedance training in motion, we propose a virtual sports system to set up motions in virtual reality using an impedance-controlled robot. The technique of virtual reality makes it possible to apply external disturbance to a person in motion or to change environmental characteristics. The measurement of the motion of a person participating in a virtual sport allows us to analyze the muscular motion that takes an important role in acquiring skill and to collect basic data that will be used for sports training or rehabilitation. In this paper, a virtual sports training system is proposed in Section 2, and human movements in the developed virtual sports system are analyzed in Section 3.

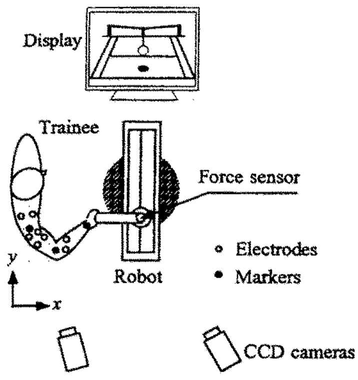

Fig. 1. Virtual sports training

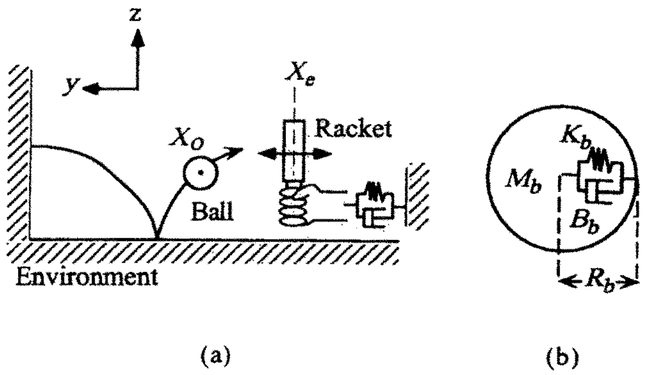

Fig. 2. Model of the virtual tennis

2. Virtual Sports Training System

2.1. Experimental Equipment

Figure 1 shows the system developed in this paper. Tennis is used as an example of virtual sports. A trainee is required to hit a computer-assisted virtual ball by grasping the handle attached to a robot instead of hitting an actual tennis ball. This system is provided with a one-link linear motor table (Nippon Thompson Co., Ltd.; maximum driving force: 10 [kgf]; encoder resolution: 2[μm]) to display information for the trainee. The driving force of the linear motor table is controlled by a computer, so that the force transmitted from the virtually computed ball to the racket can be displayed to the trainee. The movable part of the linear table is equipped with a handle and a 6-axis force sensor (B.L. Autotech Co., Ltd.; resolution: translational force on x- and y-axes: $5\mathrm{x}10^{-3}$[N], on z-axis: 15×10^{-2}[N]; forque: $3\mathrm{x}10^{-3}$[Nm]) to measure force applied by the trainee to the handle. The trainee can perform a virtual sport based on the visual information provided on the display. The hand impedance is changed by adjusting the intensity of muscle contraction and arm posture[6]. In training, surface EMG signals are measured from flexor in a wrist joint (flexor carpi radialis: FCR) and an extensor (extensor ulnaris: ECU); a flexor in an elbow joint (biceps brachii: BB) and an extensor (triceps brachii: TB); and flexors in a shoulder joint (pectoralis major: PM, deltoideus anterior: DA) and extensors (teres major: TM, deltoideus posterior: DP). Two CCD cameras (Quick MAG: Oh-yoh Keisoku Kenkyusho) are used to detect markers on the trainee, so arm postures can be determined.

2.2. Model of Virtual Tennis

Figure 2(a) shows the model of a virtual tennis. A ball hit by a racket bounces off a wall as shown in the figure, where it is assumed that mass of the ball is concentrated on the center of the ball. As shown in **Fig.2(b)**, the ball is approximated with a viscoelastic model. The viscoelasticity of the string of the racket is described together with that of the ball. The racket, a flat board parallel to the x-z plane having an infinite length both in the x and z axes, moves one degree of freedom only on the y axis. The ball moves two degrees of freedom on the y-z plane.

The motion equation of the racket (one degree of freedom on the y axis) is given as follows using F_y, interaction force on the y axis applied from the ball to the racket when the ball is hit, and F_e, the force applied by the trainee to the racket:

$$M_r \ddot{X}_{ey} + B_r \dot{X}_{ey} = F_y + F_e \quad \cdots\cdots\cdots\cdots (1)$$

where X_{ey} is the position of the racket on the y axis; M_r and B_r are the target inertia and target viscosity of the racket.

Thus the trainee can enjoy a realistic feel of a handle characterized by the inertia of M_r and viscosity of B_r, hitting the ball virtually with the racket.

If the position of the center of the ball is indicated as $X_o = (0, X_{oy}, X_{oz})$, the dynamic behavior of the ball satisfies the following motion equations:

$$M_b \ddot{X}_{oy} = -F_y + F_{wy} \quad \cdots\cdots\cdots\cdots (2)$$

$$M_b \ddot{X}_{oz} = -F_z + F_{wz} - M_b g \quad \cdots\cdots\cdots\cdots (3)$$

provided M_b is the mass of the ball, F_y and F_z are interaction forces in the y and z axis when the ball collides with the racket, and F_{wy} and F_{wz} are the reaction forces when the ball collides with the wall or with the floor, and g is the gravitational acceleration, where F_y and F_z are calculated as

$$F_y = \begin{cases} B_b(dX_{by})\, d\dot{X}_{by} + K_b(dX_{by})\, dX_{by} & (|X_{ry}| \le R_b) \\ 0 & (|X_{ry}| > R_b) \end{cases} \quad \cdots\cdots (4)$$

$$F_z = F_y \tan\theta \quad \cdots\cdots\cdots\cdots (5)$$

$$dX_{by} = X_{ry} - R_b \quad \cdots\cdots\cdots\cdots (6)$$

where $X_{ry} = X_{oy} - X_{ey}$ represents the relative position of the ball and racket; and dX_{by} is the displacement of the ball due to the collision. Note that the reaction force of the ball is produced in the z and y directions. $K_b(dX_{by})$ and $B_b(dX_{by})$ are

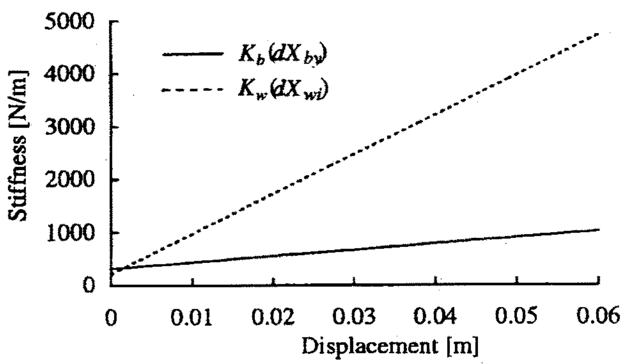

Fig. 3. Resultant stiffness of the ball-and-strings system (K_b) and the ball-and-environment system (K_w)

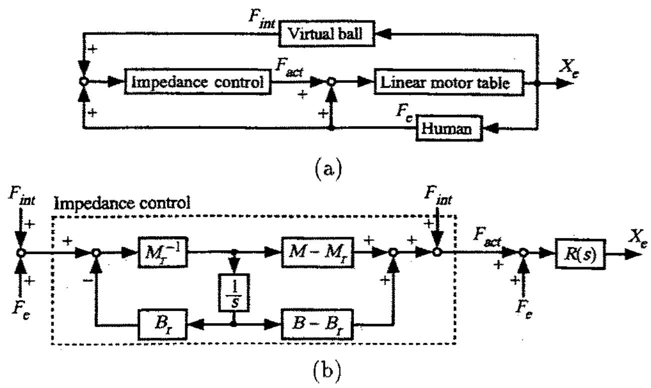

Fig. 4. Impedance control system for virtual tennis

stiffness and viscosity of the ball-and-strings system, established as

$$K_b(dX_{by}) = 318.5 + 11452.8\,|dX_{by}| \quad \ldots\ldots \quad (7)$$

$$B_b(dX_{by}) = 2\zeta_b\sqrt{M_b K_b(dX_{by})} \quad \ldots\ldots \quad (8)$$

ζ_b is the damping coefficient. Each parameter is determined based on trial and error by referring to the reference [18].

F_{wy} and F_{wz} included in Eqs.(2) and (3) are calculated using a viscoelastic model as in Eq.(9)

$$F_{wi} = \begin{cases} B_w(dX_{wi})\,d\dot{X}_{wi} + K_w(dX_{wi})\,dX_{wi} & (|X_{si}| \le R_b) \\ 0 & (|X_{si}| > R_b) \end{cases} \quad (9)$$

$$dX_{wi} = X_{si} - R_b n_i \quad \ldots\ldots \quad (10)$$

$$n_i = \begin{cases} \dfrac{X_{Si}}{|X_{Si}|} & (X_{Si} \neq 0) \\ 0 & (X_{Si} = 0) \end{cases} \quad \ldots\ldots \quad (11)$$

provided the index $i \in \{y,z\}$, $X_{si} = X_{oi} - X_{wi}$ is the relative position of the ball and environment, where X_{wy} and X_{wz} are the positions of the wall and the floor. $K_w(dX_{wi})$ and $B_w(dX_{wi})$ are the stiffness and viscosity of the ball when it collides with the environment, which are expressed as

$$K_w(dX_{wi}) = 214.6 + 75068\,|dX_{wi}| \quad \ldots\ldots \quad (12)$$

$$B_w(dX_{wi}) = 2\zeta_w\sqrt{M_b K_w(dX_{wi})} \quad \ldots\ldots \quad (13)$$

ζ_w is the damping coefficient.

Figure 3 shows the relationship between the displacement of the ball and stiffness, provided the solid line represents $K_b(dX_{by})$; the broken line, $K_w(dX_{wi})$. The stiffness established as above generates a nonlinear interaction, which makes it possible for the trainee to perceive the feel of a virtual ball as the feel of a real ball. The behavior of the ball can also be changed after collision by changing ζ_b and ζ_w.

2.3. Impedance Control

Figure 4(a) shows the configuration of a human-robot system used for training. F_{act} stands for control input to the table, under impedance control [19], while the behavior of the racket conforms to Eq.(1). **Figure 4(b)** shows impedance control when the dynamics of the table $R(S)$ are modeled based on Eq. (14).

$$R(s) = \frac{1}{Ms^2 + Bs} \quad \ldots\ldots \quad (14)$$

where M and B are inertia and viscous friction of the table. For impedance control in this paper, M = 4.7 [kg], B = 47.0[Ns/m] are used, and target impedance are set at M_r=0.9[kg], B_r= 0[Ns/m] and K_r = 0[N/s].

3. Analysis of Human Motions in Virtual Tennis

3.1. Experiments

Motion in training was measured for two well-trained subjects (A and B) who had received skill-acquisition training for virtual tennis and three untrained subjects (C, D, E and F) who had not received such training. Based on a series of experiments, we set the distance between the racket and wall at 2[m], the initial position of the racket represents the origin of the x and y axes, and floor in virtual space is chosen as the x-y plane (z = 0). The initial position of a ball is $X_o(0)$ = (0.0, 1.0, 0.5)[m], the initial speed of the ball is $\dot{X}_o(0)$ = 0.0, -2.0, 3.0)[m/s], the mass of the ball is M_b = 0.1[kg], and radius of the ball is R_b = 0.06[m]. The damping coefficient of the ball in a virtual space ζ_b and ζ_w are set to be ζ_b = 0.06 and ζ_w = 0.15 based on behavior measured when a real ball is caused to fall freely from the height of 1[m].

Under the above experimental conditions, each subject was required to hit the ball thrown from forward just one

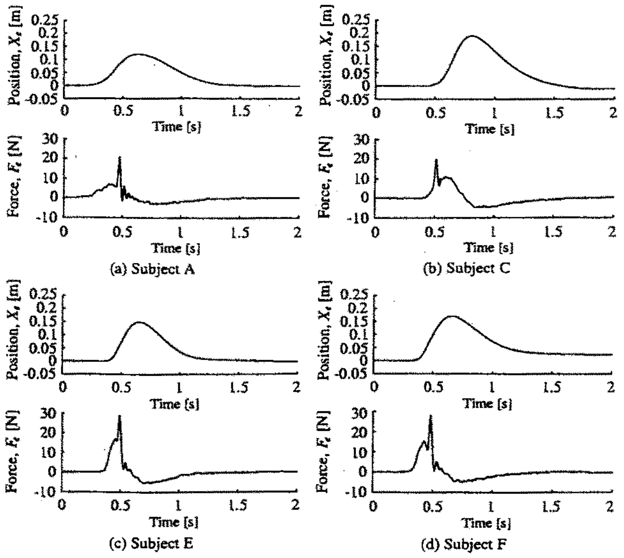

Fig. 5. Examples of experimental results

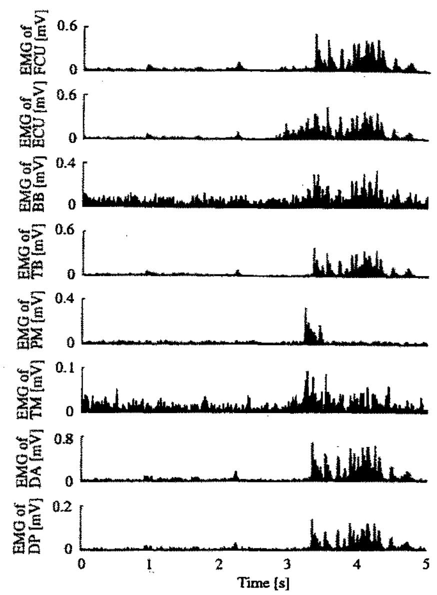

Fig. 6. An example of the measured EMG signals (Subject A).

time aiming at a round target (a radius of 0.1[m]) at the wall. Skill acquisition of subject was evaluated based on an index based on the ratio between the number of trials and hits. The precise moment when the ball is supposed to be thrown can be seen in advance, since the indicator is switched on the display 3 seconds before the ball is actually thrown.

3.2. Experimental results

Figure 5 shows changes in the hand position and hand force of subject with time. **Figure 5(a)** shows an example of the result when a well-trained subject hit the target with a ball. **Figures 5(b)**, **(c)**, and **(d)** show examples of the results when untrained subjects missed the target with a ball. The on-target impact rate of each subject is as follows: subject A, 91.2%; B, 85.7%; C, 56.5%; D, 59.6%; E, 28.8%; and F, 30.0%. The number of trials is as follows: A, 107 times; B, 121 times; C, 105 times; D, 118 times; E, 96 times; and F, 109 times.

Changes in hand position with time (**Fig.5**) show that each subject seems to hit the ball by thrusting the racket forward instead of taking it backward. This is because subject tries to swing the racket compactly in the hope of hitting the ball in good timing.

With regard to changes in hand force with time, well-trained subjects control themselves properly to apply the hand force to the fullest extent when they hit the ball. Changes in hand force with time in untrained subjects missing the target are classified into three patterns (**Fig.5(b)**, **(c)**, and **(d)**). **Figure 5(b)** shows untrained subjects applied hand force in a flurry after interaction was generated, so they were too slow to hit the ball. **Figure 5(c)** shows untrained subjects were good in timing to apply the hand force to the fullest extent at the moment of impact, but the force they had applied was too large compared to the that of well-trained subjects. Unlike **Fig.5(b)**, **Fig.5(d)** shows untrained subjects were too quick in timing to hit the ball, so they were obliged to hit it after applying hand force to the ball. To hit the target

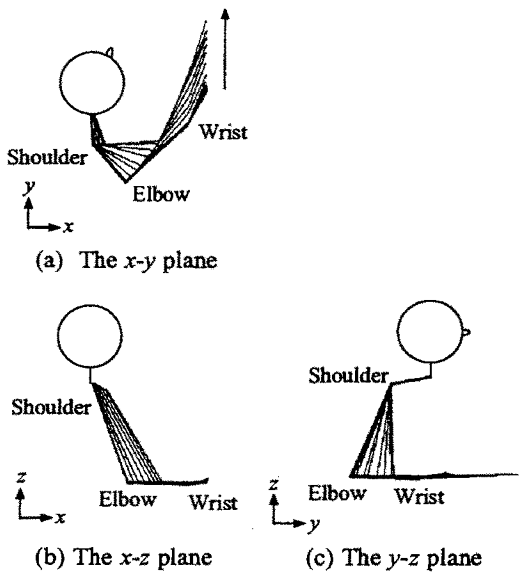

Fig. 7. An Example of arm postures while playing virtual tennis (Subuject B).

effectively, it is necessary to control amplitude and timing of force F_e, based on ball movement.

Figure 6 shows an example of the EMG signals obtained by measurement after full-wave rectification while subject A was continuing motion. The EMG was measured for 5 seconds from 3 seconds before the ball was thrown.

Figure 6 shows that the subject was ready for motion to begin by contracting each muscle before hitting the ball. Hand impedance related to holding the racket shows changes due to cocontraction of flexor and extensor[6,20]. **Figure 7** shows changes in the arm postures of subject with time, measured with a CCD camera. Subject was trying to hit the virtual ball using elbow and shoulder

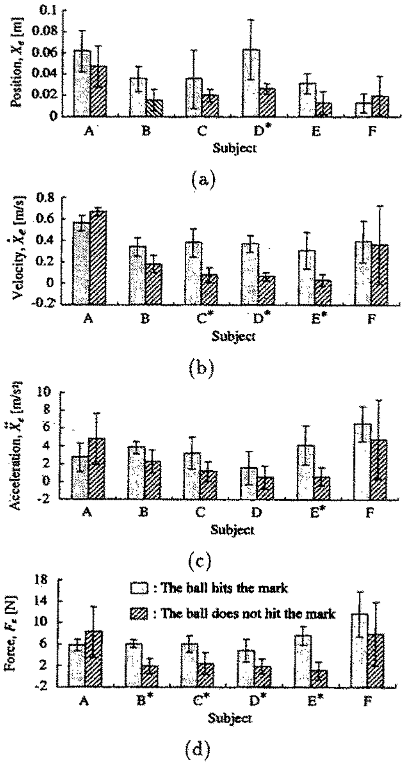

Fig. 8. Hand motion of the subjects at the time of impact.

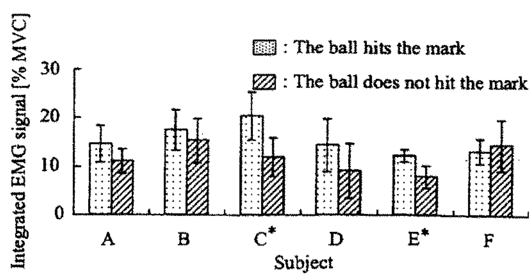

Fig. 9. Integrated EMG signals.

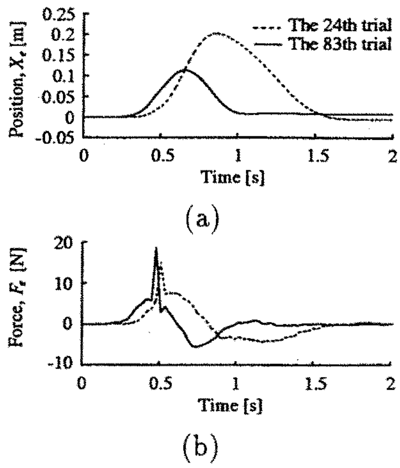

Fig. 10. Examples of experimental results before and after skill acquisition (Subject C).

joints. Thus virtual sports training can be effectively used for measuring the motions of subjects who are playing virtual sports.

In the next step, an attempt was made to discern the motion of each subject hitting the target from the same motion as when missing the target. **Figure 8** shows averages and standard deviations of hand position, hand velocity, hand acceleration, and hand force for each subject when the racket hit the ball (at impact). Each left bar graph stands for the result when the racket hit the target and each right bar graph the result when the racket missed the target.

At this stage, the difference between the average obtained when the racket hit the target and average obtained when the racket missed the target was examined (t test, one-sided test). In Fig.8, an asterisk indicates the parameter judged as having a significant difference due to the presence of 1% risk. Based on the figure, subject A missed the target when hand velocity and force at impact were too large; subjects B through E missed the target when their hand velocity and hand force at impact were too small. Subject F missed the target by being too quick in timing nearly equal in number to cases where missing the target by being too slow in timing. When the target was missed, therefore, the average and standard deviation for subject F are larger compared to those for other subjects.

Rectified integral EMGs were obtained for 0.5[s] before impact. By rectified EMG at maximum voluntary contraction, the rectified EMG from each muscle was normalized and integrated to obtain the total sum of rectified integral EMGs from 8 muscles. **Figure 9** shows the averages and standard deviations of the total sum of integral EMGs from the 8 muscles. Each left bar graph stands for the average obtained when the ball hit the target and each right bar graph the average obtained when the ball missed the target. For each of all subjects except F, the integral EMG obtained when the ball hit the target was large. The viscoelasticity of the arm varies with the muscle contraction level. Accordingly, a subject may stiffen the arm before impact when the ball hits the target This is the question to be closely analyzed in the future by measuring impedance in motion from a practical point of view.

3.3. Process of Skill Acquisition

Based on experimental results obtained with untrained persons (subjects C, D, E, and F), it has become clear that they can be classified into 2 groups after conducting a number of trials: subjects C and D who have finally succeeded in hitting the target skillfully with a ball and subjects E and F who have not. We have examined changes in the motions of subjects who have made improvements in skill during a series of experiments.

Figure 10 shows examples of experimental results before (the 24th trial) and after (the 84th trial) the skill acquisition on subject C for changes in the hand position and hand force with time. The broken line represents changes before skill acquisition and the solid line after skill acquisition. After skill acquisition, subjects decreased changes in hand position to apply a larger force to the racket from the beginning of motion. This resulted

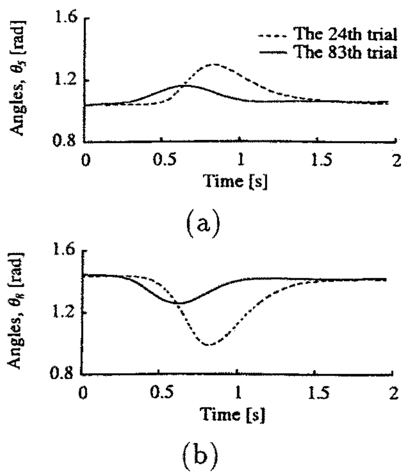

Fig. 11. Examples of the measured joint angles before and after skill acquisition (Subject C).

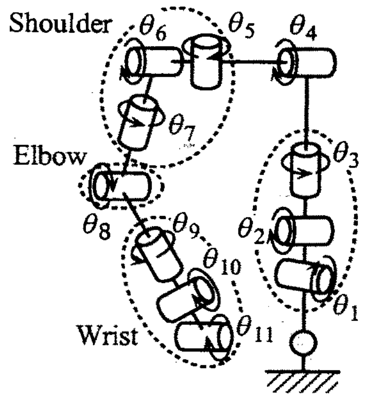

Fig. 12. A link model of a subject.

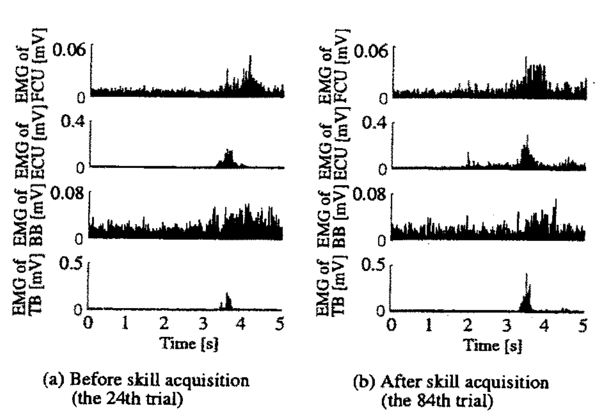

Fig. 13. An example of the measured EMG signals before and after skill acqusition.

in compact swings. This is common with joint motions. **Figure 11** shows the horizontally bending-stretching angle of the shoulder joint θ_5 and angle of the elbow joint θ_8 at trials as shown in **Fig.10**. The broken line represents the changes before skill acquisition and the solid line after skill acquisition. For the description of the joint angle, refer to **Fig.12**. During the process after skill acquisition, subjects decreased changes in each joint angle to make compact motion. Changes in EMG signals can also be seen before and after skill acquisition. **Figure 13** shows full-wave rectified EMGs before and after skill acquisition. After skill acquisition, the subject was ready for motion to begin before actually starting motion since discharge of EMG already occurred. The contraction of both the flexor (FCU) and extensor (ECU) around the wrist joint in motion increased after skill acquisition. This makes us perceive that the impedance of the wrist joint would be increased using the muscle contraction. Thus, well-trained persons acquire skill to adjust motion, force, and impedance of the arm properly by repetition of training.

4. Conclusion

This paper proposed virtual sports training to realize impedance training during dynamic motions. Tennis was chosen as the target sports and a virtual sports system was established to conduct motion in virtual reality using an impedance-controlled robot. Thus, we proved it possible to efficiently measure motion of a subject playing virtual sports and succeeded in analyzing the motion and muscle activity of subjects in training.

Through experiments, we found subjects (E and F) who cannot improve skill to hit the target even after 100 trials. For such subjects, it may be possible to let them take further improved training, provided their defects are pointed out and suitable measures for improvement are given to them during training. We intend to improve virtual sports so it can be used effectively for analyzing problems in training common to all untrained persons.

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Name:
Toshio Tsuji

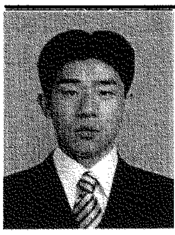
Affiliation:
Department of Artificial Complex Systems Engineering,
Hiroshima University

Address:
- 1-4-1 Kagamiyama, Higashi-Hiroshima 739-8527, Japan

Brief Biographical History:
- 1985- Research Associate at Hiroshima University
- 1995- Associate Professor at Hiroshima Univarsity

Main Works:
- Motor control in robot and human movements, EMG-controlled prostheses, Computational neural sciences, Biological motor control

Membership in Learned Societies:
- IEEE
- The Japan Society of Mechanical Engineers
- The Robotics Society of Japan
- The Japanese Society of Instrumentation and Control Engineers



Name:
Yasuteru Sumida

Affiliation:
Graduate School of Engineering,
Hiroshima University

Address:
4-1 Kagamiyama 1-Chome, Higashi-Hiroshima 739-8527, Japan

Brief Biographical History:
1996-Faculty of Engineering, Hiroshima University.
2000-Graduate School of Engineering, Hiroshima University.

Main Works:
- Analysis of Human arm impedance.

Membership in Learned Societies:

Name:
Makoto Kaneko

Affiliation:
Professor of Department of Artificial Complex Systems Engineering at Hiroshima University

Address:
4-1 Kagamiyama 1-Chome, Higashi-Hiroshima 739-8527, Japan

Brief Biographical History:

1989-Mechanical Engineering Laboratory (MEL), Ministry of International Trade and Industry (MITI),
1990-Associate Professor at Kyushu Institute of Technology,
1993-Full Professor at Hiroshima University.

Main Works:

- Tactile-based active sensing, Grasping strategy, Sensor apprications, Experimental robotics.

Membership in Learned Societies:

- The Japan Society of Mechanical Engineers
- The Robotics Society of Japan
- The Japanese Society of Instrumentation and Control Engineers

Name:
Sadao Kawamura

Affiliation:
Department of Robotics, Ritsumeikan University

Address:
1-1, Nojihigashi 1-Chome, Kusatsu, Shiga, 525-8577, Japan

Brief Biographical History:

1986-Assistant Professor in Osaka University
1987-Assosiate Professor in Ritsumeikan University
!995-Full Professor in Ritsumeikan University

Main Works:

- Learning control, Pneumatic Drive System, Under water robot, Biomechanics.

Membership in Learned Societies:

- The Japan Society of Mechanical Engineering
- The Robotics Society of Japan
- The Japanese Society of International and Control Engineering