Proceedings of the 2003 IEEE/ASME
International Conference on
Advanced Intelligent Mechatronics (AIM 2003)

A Virtual Training Sports System for Measuring Human Hand Impedance

Yusaku Takeda
Department of Artificial Complex Systems Engineering
Hiroshima University
Higashi-Hiroshima, Hiroshima, Japan
Email: takeda@bsys.hiroshima-u.ac.jp

Yoshiyuki Tanaka
Department of Artificial Complex Systems Engineering
Hiroshima University
Higashi-Hiroshima, Hiroshima, Japan
Email: ytanaka@bsys.hiroshima-u.ac.jp

Toshio Tsuji
Department of Artificial Complex Systems Engineering
Hiroshima University
Higashi-Hiroshima, Hiroshima, Japan
Email: tsuji@bsys.hiroshima-u.ac.jp

Abstract

The dynamic characteristics of human upper extremities are usually expressed by mechanical impedance. Although many studies have discussed human impedance characteristics, there are no reports on the practical application of human impedance to rehabilitation.

This paper proposes a new virtual training system which can measure task-related impedance of a trainee. The proposed system utilizes the robot consisting of direct drive type slider table to evaluate trainee's hand impedance quantitatively. Experimental results show that human hand impedance is possible to be estimated in the preliminary phase of motion during virtual sports.

Keywords

Impedance, Human movements, Virtual sports system

INTRODUCTION

A human performs a variety of skillful movements by adjusting dynamic characteristics of his/her musculoskeletal system in motion. For example, a professional tennis player can serve an extraordinarily fast ball through an arc-shaped movement of his arm. The player has not only strong muscle power but also the ability to freely control his arm dynamics. Such human movements have been often described with mechanical impedance parameters; i.e. stiffness, viscosity, and inertia.

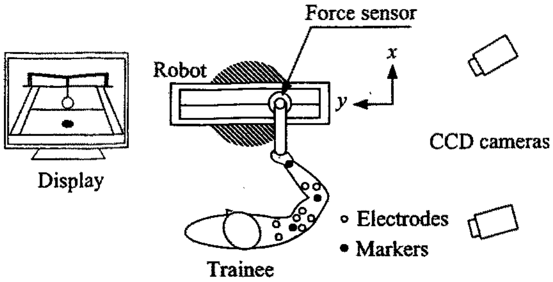
Many experimental studies on human arm impedance have been reported. For example, Mussa-Ivaldi et al. [1] pioneered the measurement of human hand impedance, and examined hand stiffness in a stable arm posture. It was reported that hand stiffness depends greatly on the arm posture and that a human can change the magnitude of stiffness at will but not its direction. Also, Dolan et al. [2] and Tsuji et al. [3],[4] investigated not only hand stiffness but also viscosity and inertia, and verified a qualitative analogy between hand stiffness and viscosity. Tsuji et al. [5] found that the hand viscoelastic characteristics change in proportion to the muscle contraction level. Gomi et al. [6] then examined hand impedance in reaching movements and demonstrated that hand stiffness in motion changes activity more than one in a stable arm posture.

Human impedance also has been utilizing for kinesitherapy in rehabilitation [7]–[9]. Hogan et al. and Krebs et al. [7],[8], for example, developed a new training system using the impedance-controlled robot with parallel mechanism. However, they did not consider training trainee's control ability of impedance itself. Tsuji et al. [9] proposed a concept of impedance training to improve trainee's ability for voluntary impedance regulation. The trainee is asked to adjust his or her hand impedance in a way that the hand impedance, which can be measured during the training in on-line, agrees with the target one. They verified that the impedance regulation ability can be improved effectively by the developed prototype training system based on the impedance training method. They also described the primary factors for the regulation of impedance parameter effectively; i.e. muscle contraction level for the stiffness, motion direction for the viscosity, and arm posture for the inertia. However, the developed training system can be applied only to static motions with the maintained posture, not to skill training associated with dynamic motion.

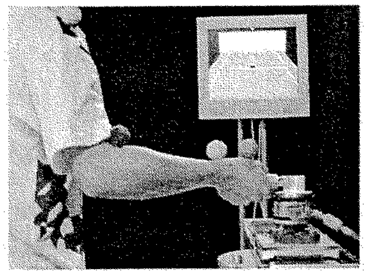
Sports exercises could be good examples of the impedance training for dynamic movements. There are difficulties, however, in measuring force and positional information in human motion. Also, in the impedance training method, it is necessary to apply an external disturbance to the trainee's hand movements during dynamic movements in order to estimate the human hand impedance. Such operations may be extremely difficult to conduct in the midst of the sports exercises. Although some reports attempted to estimate human impedance parameters in dynamic motion from the EMG signals [5],[10],[11], it may not be expected to estimate hand impedance in motion accurately because human impedance is influenced significantly by the conditions of musculoskeletal system depending on the contraction intensity, the arrangement of various muscles, and the sensitivity of the spinal reflex.

The present paper develops a virtual sports system as a first step to realizing impedance training in dynamic motion by utilizing a virtual reality technique and an impedance-controlled robot. The technique of virtual reality makes it possible to apply an external disturbance to trainee's motion. The measurement of human hand impedance in a virtual sport allows us to analyze the muscular activities playing an important role in acquiring task-related hand impedance characteristics that should be useful for sports training and rehabilitation.

0-7803-7759-1/03/$17.00 © 2003 IEEE



(a) The system configuration



(b) A trainee playing virtual tennis

Figure 1. Virtual tennis system

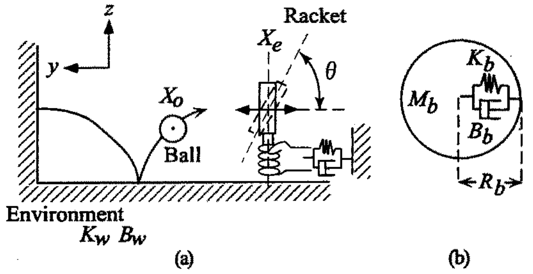


Figure 2. Model of the virtual tennis

VIRTUAL TENNIS SYSTEM

Experimental Equipment

Figure 1 depicts the overview of the developed prototype system for virtual sports training, in which a trainee can play virtual tennis. The trainee is required to hit a computer-controlled virtual ball instead of hitting an actual tennis ball by operating handle attached to a robot, while the robot displays interaction force to the trainee in hitting the ball. The robot in the training system is constructed with a linear motor table (Nippon Thompson Co., Ltd.; maximum driving force 10 [kgf]; stroke length 400 [mm]; encoder resolution 2 [μm]), which is impedance-controlled so that the virtual interaction force between the virtual ball and the racket handle can be displayed to the trainee. A six-axis force sensor (B.L. Autotech Co., Ltd.; resolution: translational force on x- and y-axes 5×10^{-3} [N], on z-axis 15×10^{-2} [N], torque 3×10^{-3} [Nm]) is attached at the base of the handle to measure the operating hand force of the trainee. The trainee can play virtual tennis on the basis of the visual information provided on the display. A human can change his hand impedance by adjusting the muscle contraction level as well as his arm posture [5]. To investigate a mechanism of human impedance regulation, surface EMG signals in the training are measured from the flexor (flexor carpi radialis, FCR) and the extensor (extensor ulnaris, ECU) in the wrist joint, the flexor (biceps brachii, BB) and extensor (triceps brachii, TB) in the elbow joint, and the flexors (pectoralis major, PM, deltoideus anterior, DA) and extensors (teres major, TM, deltoideus posterior, DP) in the shoulder joint. The sampling rate for hand movements and EMG signals was set at 1 [kHz] in the experiments. Also, the stereo video camera system with two CCD cameras (Quick MAG: Oh-yoh Keisoku Kenkyusho, sampling rate: 60 [Hz]) is utilized to observe the arm posture of a trainee by detecting color markers attached to the trainee.

Model of Virtual Tennis

Figure 2 (a) shows a model of virtual tennis, in which a trainee hits a virtual ball so as to make the ball bounce off a wall. The virtual ball is represented by a viscoelastic model under the assumption that the mass is concentrated at the center of the ball as shown in Fig. 2 (b), where the model parameters are determined with consideration of the racket strings. The racket is regarded as a flat board parallel to the x-z plane with an infinite length both in the x and z axes, and has only one degree of freedom along y axis. Also, the racket has inclination θ from the y axis in the virtual tennis space. The virtual ball moves with two degrees of freedom on the y-z plane.

Then, the motion equation of the racket can be written as follows:

$$M_r \ddot{X}_{ey} + B_r \dot{X}_{ey} = F_y + F_e, \tag{1}$$

where F_y denotes the interaction force applied from the virtual ball to the racket along the y axis; F_e is the operating hand force; X_{ey} is the racket position on the y axis; M_r and B_r are the target inertia and the target viscosity of the robot respectively. The trainee can enjoy a realistic feel of the racket handle characterized by M_r and B_r, and can perceive a virtual interaction force at hitting the virtual ball.

Dynamic behaviors of the virtual ball can be given by the following equations:

$$M_b \ddot{X}_{oy} = -F_y + F_{wy}, \tag{2}$$

$$M_b \ddot{X}_{oz} = -F_z + F_{wz} - M_b g, \tag{3}$$

where X_o ($= (0, X_{oy}, X_{oz})^T$) denotes the center position of the ball; M_b is the mass of the ball; F_y and F_z are interaction forces in the y and the z axis at impact, respectively; F_{wy} and F_{wz} are the reaction forces as the ball rebounds off the wall and the floor, respectively; and g represents the gravitational acceleration. F_y and F_z are calculated as follows:

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

$$F_z = F_y \tan\theta, \tag{5}$$

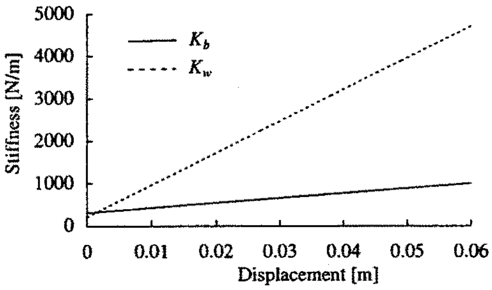


Figure 3. Resultant stiffness of the ball-and-strings system (K_b) and the ball-and-environment system (K_w)

$$dX_{by} = X_{ry} - R_b, \tag{6}$$

where X_{ry} ($= X_{oy} - X_{ey}$) represents the relative position of the ball and the racket; θ is the inclination of the racket from the y axis; and dX_{by} is the displacement of the ball due to the impact. Note that the reaction force of the ball can be generated in the z direction as well as the y direction. The viscoelastic properties of the ball, $K_b(dX_{by})$ and $B_b(dX_{by})$, are defined together with the ones of a racket string by

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

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

where ζ_b denotes the damping coefficient. Each parameter was designed by trial-and-error on the basis of the reference study [12]. F_{wy} and F_{wz} in Eqs. (2) and (3) are expressed with a viscoelastic model as

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

$$dX_{wi} = X_{si} - R_b n_i, \tag{10}$$

$$n_i = \begin{cases} \dfrac{X_{si}}{|X_{si}|} & (X_{si} \neq 0) \\ 0 & (X_{si} = 0), \end{cases} \tag{11}$$

where $i \in \{y,z\}$; and X_{si} ($= X_{oi} - X_{wi}$) represents the relative position of the ball and the environment; 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 the viscosity of the ball upon impact with the environment expressed by

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

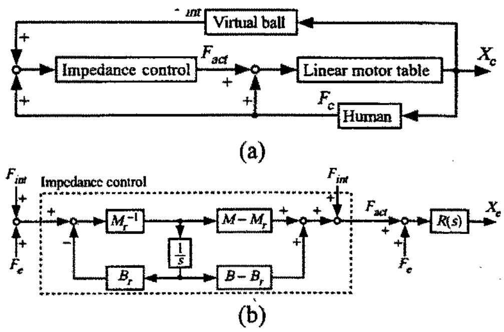


Figure 4. Impedance control system for virtual tennis

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

where ζ_w is the damping coefficient.

Figure 3 illustrates the relation between the stiffness and the displacement of the virtual ball, in which the solid line represents for $K_b(dX_{by})$ and the broken line for $K_w(dX_{wi})$. The non-constant stiffness of Eqs. (12) and (13) enable us to generate a nonlinear interaction force, so that the trainee can have a realistic feeling of hitting a real ball. Note that the damping characteristics of the ball can be regulated by ζ_b and ζ_w.

Impedance Control

Figure 4 (a) represents a block diagram of the developed human-robot system for virtual tennis training, and Fig. 4 (b) explains the impedance control part. The robot is impedance-controlled by a control input F_{act} [13], while the dynamic behavior of the racket handle follows Eq. (1).

The dynamics of the robot under the impedance control can be expressed by

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

where M and B denote the desired inertia and the desired viscous friction of the robot. These parameters on the robot motion control are set as $M = 4.7$ [kg], $B = 47.0$ [Ns/m], and the target impedance as $M_r = 0.9$ [kg], $B_r = 0$ [Ns/m] and $K_r = 0$ [N/s] in this paper.

MEASURING HAND IMPEDANCE DURING THE VIRTUAL SPORTS

A set of experimental results of the EMG signals suggests that a human regulates his/her hand impedance not suddenly but gradually in preparation for motion [14]. It is supposed that the impedance regulation is performed successfully in the motion of a well-trained subject. This section, then, investigates human hand impedance in the preparation phase to reveal how a human regulates his/her hand impedance according to the experimental conditions.

Impedance Measurement

Let us consider a situation wherein a trainee is playing virtual tennis by operating the racket handle attached to the robot. When the subject's hand is displaced in the y direction from its equilibrium by a small disturbance with short duration as shown in Fig.

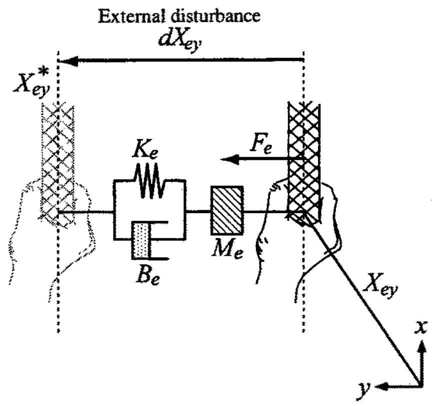


Figure 5. Schematic description of hand impedance

5, the dynamic properties of the hand can be approximated with mechanical impedance parameters as

$$M_e d\ddot{X}_{ey}(t) + B_e d\dot{X}_{ey}(t) + K_e dX_{ey}(t) = -F_e(t), \quad (15)$$

where M_e, B_e, and K_e represent the hand inertia, viscosity, and stiffness; and dX_{ey} $(= X^*_{ey}(t) - X_{ey}(t))$ denotes the distance between the hand position $X_{ey}(t)$ and the virtual trajectory $X^*_{ey}(t)$. $F_e(t)$ is the hand force corresponding to the external disturbance to the handle. The impedance parameters might be estimated by means of the least squares method with the measured hand motion; $X_{ey}(t)$, $X^*_{ey}(t)$ and $F_e(t)$ [3], [4]. However, the virtual trajectory $X^*_{ey}(t)$ in dynamic motion is not measurable and may vary with respect to trainee's hand movements.
The unknown parameters M_e, B_e, K_e, and $X^*_{ey}(t)$ cannot be uniquely determined since the measurable parameters are only $X_{ey}(t)$, $\dot{X}_{ey}(t)$, $\ddot{X}_{ey}(t)$, and $F_e(t)$. Moreover, hand impedance should be regarded as a time-varying element because impedance parameters vary according to the arm posture and the muscle contraction level [15]. Consequently, it is very difficult to estimate the hand impedance in dynamic motion.
On the other hand, a human seems to regulate his impedance properties before motion [14]. A player of virtual tennis should adjust his hand impedance just before hitting the ball according to the velocity and physical properties of the ball; otherwise, it would be too late to prepare for the hitting action. Thus, this paper focuses on hand impedance in the preparation phase, experimentally investigating *task readiness impedance* in virtual tennis. The virtual trajectory $X^*_{ey}(t)$ can be regarded as invariable in the preparation phase, so the task readiness impedance parameters in Eq. (15), M_e, B_e, and K_e, can be estimated. Some aspects of human impedance mechanisms, such as functions of regulation and adaptation according to circumstances, can be exploited in terms of task readiness impedance, although task readiness impedance differs from the human impedance in dynamic motion.

Accuracy of Estimated Impedance

Figure 6 illustrates the results of the accuracy testing of estimated impedance parameters in the developed virtual tennis system. A weight was attached to the racket handle of the robot while a spring was set between the handle and the fixed environment.

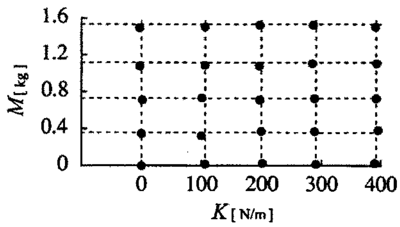


Figure 6. Accuracy of estimated impedance parameters in the developed virtual tennis system

Table 1. The onset time of the disturbance for impedance measurements

Subjects	Experimental conditions I	II	III	IV
A	2.60	2.65	2.65	2.75
B	2.65	2.65	2.75	2.65
C	2.65	2.60	2.65	2.65
D	2.60	2.65	2.75	2.60

(sec)

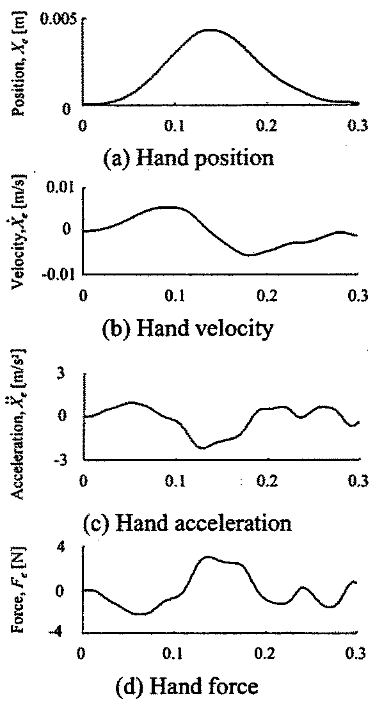


Figure 7. An example of measured signals for measurement of task readiness impedance (Subject A)

The intersections of the dotted lines in the figure represent the true values of the attached impedance to the robot handle. It can be seen that both stiffness and inertia were estimated correctly, in which the standard deviations for the stiffness and the inertia are less than 4.53 [N/m] and 0.01 [kg], respectively.

Experiments

Task readiness impedance was investigated on four well-trained subjects, who had received skill-acquisition training of virtual tennis and showed high success rates. To change the impact

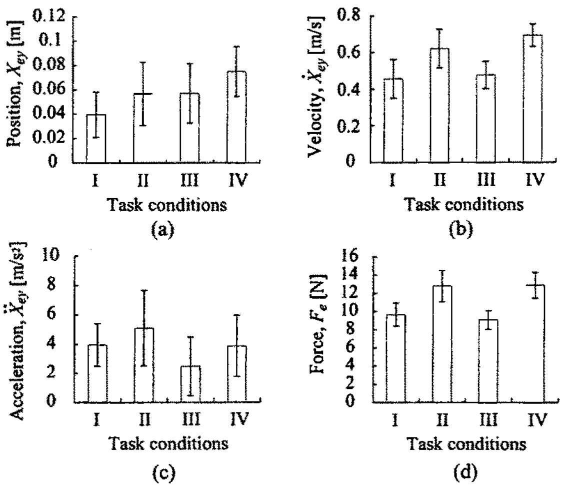


Figure 8. Hand motion at the time of impact (Subject A)

force between the racket and the ball, two different ball masses $M_b = 0.1, 0.5$ [kg] are used, and two different handle viscosities are prepared to change the dynamic properties of the racket handle (K_r, B_r, M_r) = (0.0, 5.0, 1.0), (0.0, 20.0, 1.0) [N/m, Ns/m, kg]. The experiments were carried out under the following four conditions:

I. $M_b = 0.1$ [kg], $B_r = 5.0$ [Ns/m]

II. $M_b = 0.5$ [kg], $B_r = 5.0$ [Ns/m]

III. $M_b = 0.1$ [kg], $B_r = 20.0$ [Ns/m]

IV. $M_b = 0.5$ [kg], $B_r = 20.0$ [Ns/m]

Hand impedance along the y axis was estimated by applying a disturbance at two different timing. The first disturbance was added at 2.5 [s] before the ball was thrown (before motion), and the second was at 0.7 [s] before the subject started moving the handle (task readiness). Table 1 shows the onset time of the disturbances in each condition for all subjects. The hand impedance was then estimated with 300 data points from the beginning of the onset time of the disturbance, assuming that the virtual trajectory was constant. Fig. 7 shows an example of the measured signals for impedance measurements, where the time histories of hand position $X_{ey}(t)$, hand velocity $\dot{X}_{ey}(t)$, hand acceleration $\ddot{X}_{ey}(t)$, and hand force $F_e(t)$ are given in the order from the top. The hand impedance parameters, K_e, B_e and M_e, were estimated by using Eq. (15) with these time series.

Analysis of Human Impedance

We analyzed how the well-trained subjects (Subjects A $\sim$ D) adjusted their motions according to the experimental conditions. Figure 8 shows the experimental result by Subject A, which gives the mean values and standard deviations of hand movements at the moment of impact with the ball.

As shown in Fig. 8, the well-trained subjects increased their hand force for hitting the large mass of the ball to counteract the interaction force (II and IV). On the contrary, it is difficult for a player to move a hand with rapid acceleration under highly viscous conditions (III and IV). Thus, the subjects took the larger back-swing of the racket in order to hit the ball with sufficient velocity than the one under less viscous conditions. These experimental evidences suggests that the well-trained subjects could adapt their dynamic motion according to circumstances.

Table 2. Measured hand impedance during virtual tennis (Subjects A).

(i) Task condition I

	K_e [N/m]	B_e [Ns/m]	M_e [kg]	ρ
During maintenance of the stable posture	110.3±63.4	25.8±1.3	1.6±0.1	0.97±0.01
Before motion	125.0±40.0	26.4±1.4	1.6±0.1	0.97±0.01
Task readiness	124.1±59.0	26.4±0.9	1.5±0.1	0.97±0.01

(ii) Task condition II

	K_e [N/m]	B_e [Ns/m]	M_e [kg]	ρ
During maintenance of the stable posture	110.2±63.4	25.8±1.9	1.6±0.1	0.97±0.01
Before motion	128.1±34.3	26.2±1.8	1.6±0.1	0.97±0.01
Task readiness	147.3±47.3	26.3±1.1	1.6±0.1	0.97±0.01

(iii) Task condition III

	K_e [N/m]	B_e [Ns/m]	M_e [kg]	ρ
During maintenance of the stable posture	134.9±43.0	22.4±1.1	1.9±0.1	0.99±0.01
Before motion	151.1±42.3	22.5±1.2	1.8±0.1	0.97±0.01
Task readiness	164.9±78.0	22.8±3.5	1.9±0.2	0.97±0.02

(iv) Task condition IV

	K_e [N/m]	B_e [Ns/m]	M_e [kg]	ρ
During maintenance of the stable posture	134.9±43.0	22.4±1.1	1.9±0.1	0.99±0.01
Before motion	164.3±33.2	22.5±2.4	1.8±0.1	0.95±0.01
Task readiness	199.1±76.0	23.6±2.9	1.8±0.1	0.95±0.01

Next discusses human hand impedance characteristics during virtual tennis, and evaluates the acquired-skill of the subjects in view of their hand impedance. Tables 2 shows an example of the mean values and standard deviations of the estimated impedance parameters in each task condition. Figures 9 and 10 show the changes of the hand stiffness and viscosity, respectively, depending on the task conditions.

It can be found from Fig. 9 that the subjects increased their hand stiffness to prepare for the impact under all experimental conditions. The well-trained subjects stiffen their arm to respond to the impact force depending on the weight of the ball.

Comparing the experimental results of four subjects with different viscous environments under the same weight of ball (I and III, II and IV), it can be seen from Fig. 10 that the hand viscosity of Subjects A, B, and C in a less viscous environment becomes greater than in a more viscous environment. This suggests that well-trained subject increases his hand viscosity to maintain stability under a less viscous environment.

Meanwhile, the hand viscosity of Subject D in a more viscous environment becomes greater than one in a less viscous environment. Although Subject D was regarded as a well-trained subject from the rate of successful trials, he was the only player who increased his hand viscosity unnecessarily in more viscous environments. From the impedance point of view, Subject D is a less skilled player comparing to other well-trained players and needs to polish his skills. Impedance analysis in human movements reveals such subtle differences between players, which cannot be found through the analysis of the success rates.

CONCLUSION

This paper developed a virtual tennis system using an impedance-controlled robot as a first step to realizing impedance training in dynamic motion. The task readiness impedance of

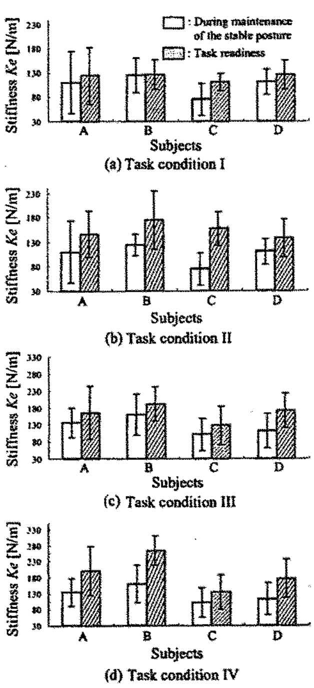


Figure 9. Hand Stiffness during maintenance of the stable posture and at the task readiness

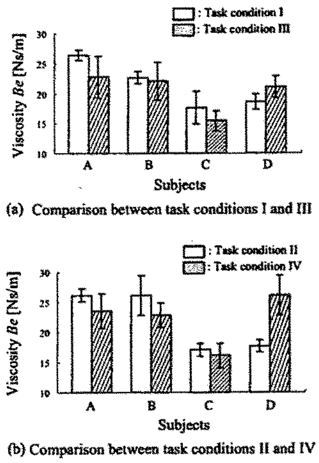


Figure 10. Hand viscosity at the task readiness

the well-trained subjects was then investigated, and the following primary characteristics were clarified;

1. Subjects prepare for a motion by increasing hand stiffness.
2. Subjects change their hand stiffness according to the mass of the ball to control the interaction force.
3. Skilled subjects increase their hand viscosity in less viscous environments to maintain stability.

We can thus conclude that a human skillfully regulates his/her hand impedance according to given tasks.

Future research will be directed to measure and analyze hand impedance in two-dimensional movements. We also intend to collect the task-related impedance data of human movements for the application to sports training and rehabilitation.

REFERENCES

[1] F. A. Mussa-Ivaldi, N. Hogan, and E. Bizzi : Neural, Mechanical and Geometric Factors Subserving Arm in Humans, Journal of Neuroscience, Vol. 5, No. 10, 2732/2743 (1985).

[2] J. M. Dolan, M. B. Friendman, and M. L. Nagarka : Dynamics and Loaded Impedance of Human Arm Posture, IEEE Transaction on Systems, Man, and Cybernetics, Vol.23, No. 3, 698/709 (1993).

[3] T. Tsuji, K. Goto, K. Ito and M. Nagamachi : Estimation of Human Hand Impedance During Maintenance of Posture, Transactions of the Society of Instrument and Control Engineers, Vol. 30, No. 3, 319/328, (1994) (in Japanese).

[4] T. Tsuji, P. G. Morasso, K. Goto, K. Ito : Human Hand Impedance Characteristics during Maintained Posture, Biological Cybernetics, 72, 457/485 (1995).

[5] T. Tsuji, M. Moritani, M. Kaneko and K. Ito : An Analysis of Human Hand Impedance Characteristics during Isometric Muscle Contractions, Transactions of the Society of Instrument and Control Engineers, Vol. 32, No. 2, 271/289, (1996) (in Japanese).

[6] H. Gomi and M. kawato : Human arm Stiffness and Equilibrium-point Trajectory during Multi-joint Movement, Biological Cybernetics, 76, 163/171 (1997).

[7] N. Hogan, H. I. Krebs, J. Charnnarong, P. Srikrishna and A. Sharon : MIT - MANUS : a Workstation for Manual Therapy and Training II, Proc. of Telemanipulator Technology - SPIE - The International Society of Optical Engineering, Vol. 18, No. 33, 28/34 (1993).

[8] H. I. Krebs, N. Hogan, M. L. Asen and B. T. Volpe : Application of Robotics and Automation Technology in Neurorehabilitation, Proc. of Japan/USA Symposium on Flexible Automation, Vol. 1, 269/275 (1996).

[9] T. Tsuji, H. Kanji, T. Kato, M. Kaneko and S. Kawamura : Impedance Training : Can We Regulate Our Hand Impedance Through Training, Transactions of the Society of Instrument and Control Engineers, Vol. 35, No. 10, 1300/1306, (1999) (in Japanese).

[10] T. Tsuji and M. Kaneko : Estimation and Modeling of Human Hand Impedance during Isometric Muscle Contraction, Proceedings of the ASME Dynamic Systems and Control Division, DSC-Vol. 58, 575/582 (1996).

[11] R. Osu, and H. Gomi : Multijoint Muscle Regulation Mechanisms Examined by Measured Human Arm Stiffness and EMG signals, Journal of Neurophysiology, Vol. 81, No. 4, 1458/1468 (1999).

[12] Y. Kawazoe : CAE of Tennis Rackets with Impact Phenomena, Transactions of the Japan Society of Mechanical Engineers, Vol. 58, No. 552, 2467/2474, (1992) (in Japanese).

[13] N. Hogan : Impedance Control : An Approach to Manipulation, Parts I, II, III, ASME Journal of Dynamic Systems, Measurement, and Control, Vol. 107, No. 1, 1/24 (1985).

[14] T.Tsuji, Y.Sumida, M.Kaneko and S.Kawamura : A Virtual Sports System for Skill Training, Journal of Robotics and Mechatronics, Vol.13, No.2, 168/175 (2001).

[15] H. Gomi and M. Kawato : Equilibrium-Point Control Hypothesis Examined by Measured Arm Stiffness During Multijoint Movement, SCIENCE, Vol. 272, 117/120 (1996).