Proceedings of the 2004 IEEE
Conference on Cybernetics and Intelligent Systems
Singapore, 1-3 December, 2004

Analysis of Human Hand Impedance Regulation Ability

Yoshiyuki Tanaka
Graduate School of Engineering, Hiroshima University,
Higashi-hiroshima, 739-8527, JAPAN
Email: ytanaka@bsys.hiroshima-u.ac.jp

Toshio Tsuji
Graduate School of Engineering, Hiroshima University,
Higashi-hiroshima, 739-8527, JAPAN
Email: tsuji@bsys.hiroshima-u.ac.jp

***Abstract*— This paper investigates human impedance regulation ability for the purpose of developing a skill-level training method for sports and rehabilitation. The training system to experiment on human impedance regulation was constructed using impedance-controlled robot. In the experiments, a subject is instructed to regulate his/her hand impedance to the desired impedance as closely as possible according to the visual biofeedback information including EMG signals from muscles, joint angles of the upper limb, and estimated hand impedance. Experimental results demonstrate that a human can greatly improve his/her regulation ability of hand impedance by repetitive training.**

I. INTRODUCTION

In playing sports and exercising, a human regulates characteristics of the musculoskeletal system dexterously. As in the act of catching a ball, we might fail to catch a ball if muscles of the arm are overly stiff since the contact force from the ball is too large to damp with the rigid arm. In contrast, if the muscle is too soft, we might also fail since the requisite hand force cannot be generated to suppress the ball movement. Thus, in catching the ball, a human should regulate the mechanical characteristics of his/her arm according to the task conditions, such as ball speed, weight and size. Such arm properties can be expressed with mechanical impedance parameters (i.e., stiffness, viscosity, and inertia).

Many experimental studies on human hand impedance in multi-joint arm movements have been reported. For example, Mussa-Ivaldi et al. [2] pioneered the measurement of hand impedance and examining hand stiffness in a stable arm posture. They found that hand stiffness strongly depends on arm posture, and that a human can change the size of a stiffness ellipse, although he/she can neither change its orientation nor its shape. Dolan et al. [3] and Tsuji et al. [4][5] investigated hand stiffness, viscosity and inertia, and verified a qualitative parallel between stiffness and viscosity. Tsuji et al. [6] also showed that human hand viscoelasticity is widely affected by muscle activation level during isometric contraction in the upper limb. Gomi and Kawato [7] have documented hand stiffness during a reaching movement. They reported that hand stiffness changes considerably during reaching movements, compared to the one maintaining arm posture. These experimental studies reveal that a human can control his/her hand impedance by regulating the arm posture and/or the muscle contraction level. Thus, if a training methodology for the regulation of human impedance is established, it is expected to affect the skill-level training for sports and rehabilitation.

On the other hand, several studies focusing on mechanical impedance have been reported in kinesitherapy rehabilitation. Kinesitherapy aims to recover motor control, such as muscle strength and joint motion range, by repeating simple physical exercises at a slow pace. For example, Weltman et al. [8] proposed a training method for muscle strength by using water resistance, which can provide comparatively safe muscle training. Nonaka et al. [9] developed a system for muscle strength training in which mechanical impedance properties of a training load can be changed. A study on a Continuous-Passive-Motion (CPM) device, which reflexively moves joints, was performed to support joint motion exercise to prevent and improve joint contraction and muscle atrophy. Specifically, Sakaki and Okajima et al. [10] developed the impedance-controlled CPM device that can actualize passive motion exercise.

Some robot-aided training approaches using kinetic properties of human movements have been proposed [11][12]. For example, Krebs et al. [11] developed a training system using the impedance-controlled robot for the improvement of sensorimotor function in multi-joint arm movements. In this system, a subject operates the end-effector of the robot according to a target pattern, such as a circle, shown on the computer display. However, these studies do not deal with the training for human impedance regulation ability.

This paper investigates human hand impedance regulation ability, and discusses a new training methodology for the human impedance regulation function. In the experiments, a subject is instructed to match his/her hand impedance parameters with the desired values by regulating the characteristics of his/her own musculoskeletal system. This paper is organized as follows: Section II explains a measuring method of human hand impedance properties, and Section III describes an experimental method for the analysis of human impedance regulation. Finally, Section IV demonstrates the regulation capacity of human hand impedance through a set of experiments with healthy subjects.

II. MEASUREMENT OF HUMAN HAND IMPEDANCE

Let us consider multi-joint movements by the human upper extremity in the l-dimensional task space. When the subject's

0-7803-8643-4/04/$20.00 © 2004 IEEE

end-point is displaced from its equilibrium by a small disturbance with a short duration as shown in Fig. 1, dynamic characteristics of the hand can be expressed with an impedance model [4] as

$$M_e\ddot{x}(t) + B_e\dot{x}(t) + K_e(x(t) - x_v(t)) = F(t), \quad (1)$$

where $F(t)$ is the hand force; $x(t)$ the hand position; $x_v(t)$ a virtual trajectory; and M_e, B_e and K_e represent hand inertia, viscosity and stiffness, respectively. Assuming that the disturbance is applied at time t_0, dynamic characteristics of the human hand at time t can be described from (1) as follows:

$$M_e d\ddot{x}(t) + B_e d\dot{x}(t) + K_e dx(t) = dF(t), \quad (2)$$

where $dx(t) = x(t) - x(t_0)$; $dF(t) = F(t) - F(t_0)$; and t_0 denotes the time when the disturbance is applied to the hand. In this model, the hand impedance matrices can be estimated from the measured hand position $x(t)$ and the hand force $F(t)$, induced by the external disturbance, with the least squares method [13].

III. A TRAINING SYSTEM FOR HUMAN IMPEDANCE REGULATION

A. Experimental Apparatus

Fig. 2 depicts the developed training system for investigating human impedance regulation in multi-joint arm movements. It is composed of a robot that stimulates the subject's hand with external disturbances, a computer for robot motion control as well as signal processing, and a display of training information to the subject. The linear motor table with one degree of freedom (Nihon tomson coop., maximum force ±10 [kgf]) is used as the robot in the developed system. Hand force generated by the subject is measured by a six-axis force/torque sensor (BL Autotec Co'Ltd., resolution ability: force x axis, y axis: 0.05 [N], z axis: 0.15 [N], torque: 0.003 [Nm]) attached to a handle of the linear motor table. The handle position is also measured by an encoder built in the table (encoder resolution: 2 [μm]). In order to train the subject's motion ability in several directions, the operational direction of the robot ϕ is changed by a rotary motor (Nihon Denyu Co'Ltd.), set under the table.

The surface EMG signals were measured from the flexor (flexor carpi radialis (FCR)) and the extensor (extensor carpi 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 to 1 [kHz]. Also, a stereo video camera system with two CCD cameras (Quick MAG: Oh-yoh Keisoku Kenkyusho, sampling rate: 60 [Hz]) was utilized to observe the subject's arm posture from color marker positions attached to the subject's body.

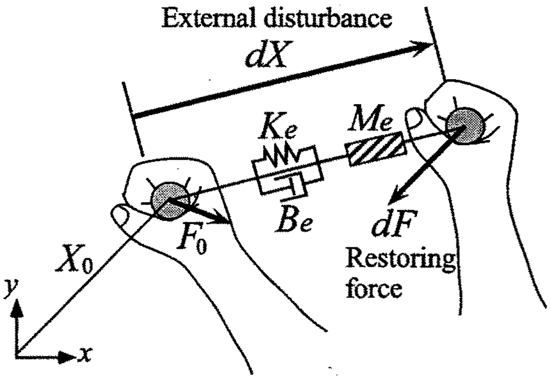


Fig. 1. Schematic description of hand impedance.

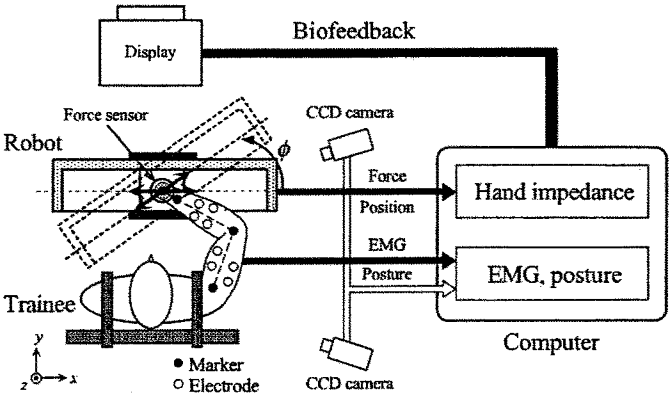


Fig. 2. Experimental Apparatus.

B. Biofeedback

In the experiment, a subject regulates his hand impedance based on the training information such as the measured hand impedance from past trials, the EMG level of the muscles, the arm posture, and the force profiles. It is important to provide precise training information to the subject.

Fig. 3 illustrates examples of the biofeedback information during the experiments of impedance regulation ability. The muscle contraction level during experiments is represented by the bar-graph as shown in Fig. 3. Each bar graph indicates the mean value of the muscle contraction level in the flex-extension motion of the corresponding joint, so that the subject can easily understand his muscle activation pattern in the experiment.

C. Regulation Training of Hand Impedance

In the training experiment, a subject is asked to match his/her hand impedance with the desired impedance properties while not exerting operational hand force on the robot handle voluntarily. The subject's hand is displaced by the external disturbance, and hand impedance is estimated from the measured hand position and force. The subject regulates muscle contraction level and arm posture based on the biofeedback information.

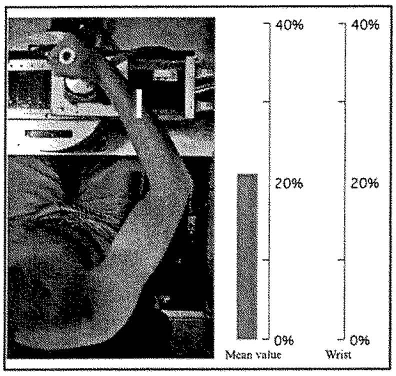


Fig. 3. Examples of the biofeedback display.

The desired hand force $F^*(t)$ is calculated with the measured hand movements and the desired impedance by

$$F^*(t) = M_r d\ddot{x}(t) + B_r d\dot{x}(t) + K_r dx(t), \qquad (3)$$

where M_r, B_r and K_r are the desired inertia, viscosity, and stiffness, respectively. The subject tries to match his hand impedance with the desired one; the subject's hand force is then depicted in the biofeedback display.

In the regulation training only for hand stiffness, the desired hand force $F_k{}^*(t)$ is given by

$$F_k{}^*(t) = K_r dx(t), \qquad (4)$$

and the subject's efforts to match his hand force $F_k(t) (= K_e dx(t))$ with $F_k{}^*(t)$. Similarly, the desired hand force in the training for hand viscosity and inertia, $F_b{}^*(t)$ and $F_m{}^*(t)$, are computed with the following equations:

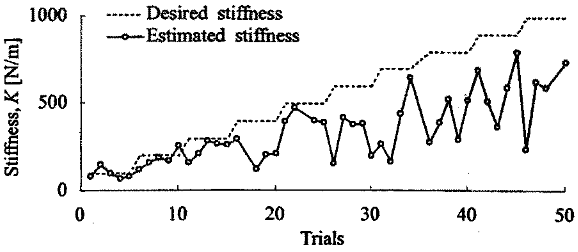
$$\begin{aligned} F_b{}^*(t) &= B_r d\dot{x}(t), & (5) \\ F_m{}^*(t) &= M_r d\ddot{x}(t). & (6) \end{aligned}$$

IV. EXPERIMENTS

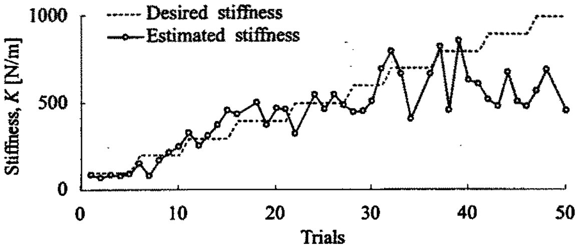
A set of training experiments with three healthy male volunteers, aged 21 ~ 25, was carried out to analyze human impedance regulation ability.

A. Training Effect of Impedance Regulation

Fig. 4 presents typical experimental results for hand-stiffness regulation. This figure illustrates the training records in the first and sixth trial; a dotted line represents the desired stiffness, and a solid line with dots is the estimated one. The operational direction ϕ was set to 0 [deg.], and the desired stiffness was changed from 100 to 1000 [N/m] by 100 [N/m] increments. In the experiment, the subject was instructed to maintain his arm posture so as to hold the shoulder, elbow and wrist joint on the same horizontal plane with 0.4 [m] distance between his hand and body, and to contract his elbow and shoulder muscles isometrically without generating hand force to move the handle. Fig. 4 shows that the subject cannot match the desired stiffness over 400 [N/m] in the initial session, but can subsequently achieve higher desired values in the sixth session.

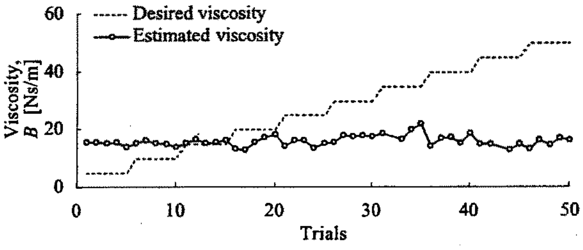


(a) The first training

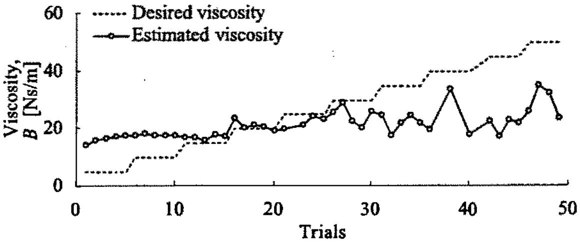


(b) The sixth training

Fig. 4. Typical training results for hand stiffness regulation (Subject A).



(a) The first training



(b) The sixth training

Fig. 5. Typical training results for hand viscosity regulation (Subject A).

On the other hand, Fig. 5 shows the typical experimental result of the hand viscosity regulation ability. The desired viscosity was changed from 5 to 50 [Ns/m] by 5 [Ns/m] increments. The subject realized the desired viscosity from 10 [Ns/m] to 25 [Ns/m] in sixth session, but the training effects cannot be clearly found on the training results of hand viscosity regulation by comparing with one of hand stiffness regulation as shown in Fig. 4.

These training results suggest that a human can improve his/her regulation ability of hand impedance properties through

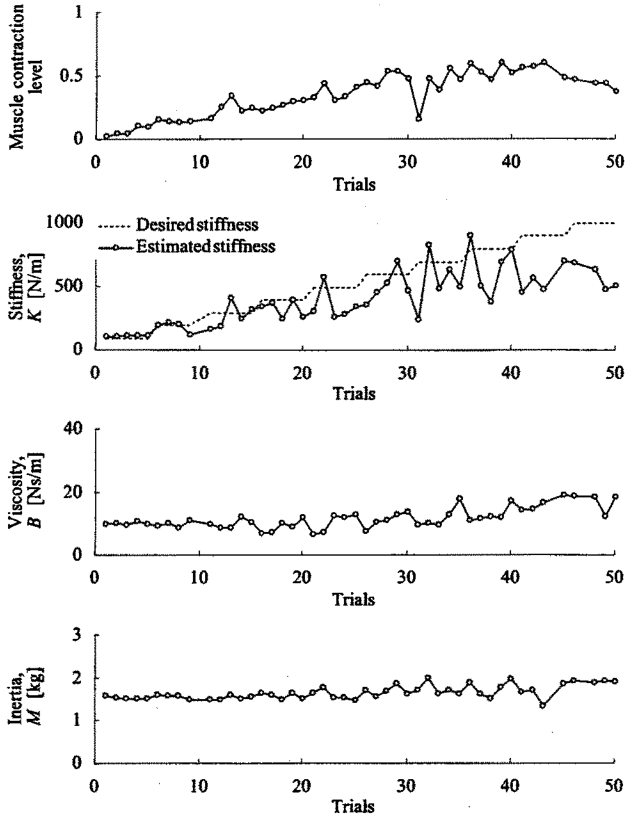


Fig. 6. Example of the training histories during training of stiffness regulation ability (Subject A).

the repetition of such exercises. In the following part of this paper, the impedance regulation ability of well-trained subjects is discussed in detail.

B. Hand Stiffness Regulation

Fig. 6 illustrates typical experimental results of hand stiffness regulation, in which the training histories of muscle contraction level, hand stiffness, viscosity and inertia are presented in descending order. The training experiments were conducted under the same conditions as the preliminary experiments depicted in Fig. 4. The figure reveals that the muscle contraction level is in proportional to the desired stiffness value, supporting that hand stiffness regulation is greatly affected by the level of muscle contraction. Thus, a human can regulate his/her hand responsiveness by changing hand stiffness via controlling the muscle activity in the upper extremity.

Fig. 7 illustrates the mean values of the square errors between desired and estimated hand stiffness with the standard deviations for 30 trials. It should be noted that the standard deviations for the desired stiffness over 400 [N/m] increase accordingly, although there exist some individual differences. This result indicates that the regulation of hand stiffness becomes to be difficult as the desired stiffness increases.

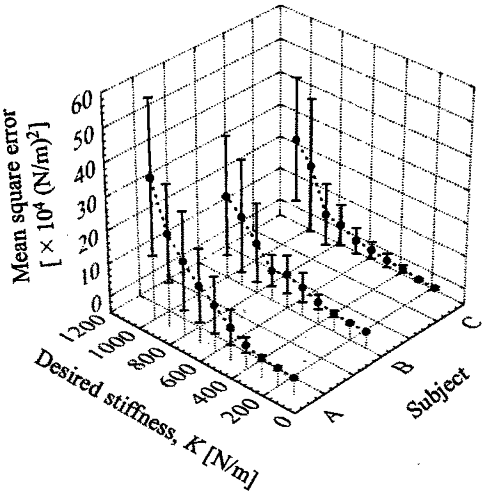


Fig. 7. Mean square errors and standard deviations between desired and estimated stiffness for 30 trials.

C. Hand Viscosity Regulation

The desired viscosity was varied from 5 to 50 [Ns/m] in 5 [Ns/m] increments, and the subject was instructed to maintain his arm posture under the same condition in the training experiments of stiffness regulation .

Fig. 8 shows the typical experimental results according to the hand operational directions with $\phi = 0, 45, 90, 135$ [deg.]. The subject can closely match his hand viscosity with the small desired values under $\phi = 45$ [deg.], and can also effectively regulate the large desired values under $\phi = 90$, 135 [deg.]. Fig. 9 illustrates the relationship between muscle contraction level and desired hand viscosity according to the operational direction. It was found that this relationship is greatly affected by the hand operational direction.

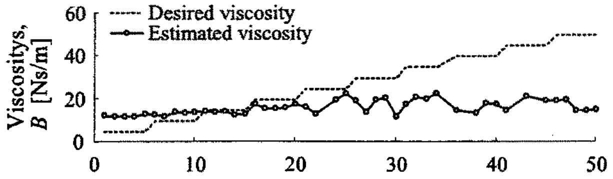
These results show that a human can regulate his/her hand viscosity by changing not only the muscle activation in the upper extremity but also through the arm posture and the body positioning.

D. Hand Inertia Regulation

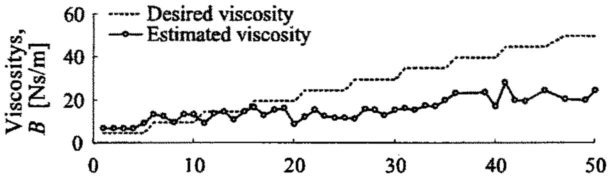
Fig. 10 shows the typical experimental results for hand inertia regulation. The arm posture in Fig. (a) was restricted to the horizontal plane with 0.4 [m] distance between his hand and body while the arm posture in Fig. (b) was unrestricted. The subject has little ability to regulate his hand inertia by the restricted arm, while he can closely approach the desired value under the free arm posture.

Fig. 11 expresses the relationship between the hand-damping coefficient and inertia under the free arm posture. It can be observed that the damping coefficient of the subject's hand decreases as hand inertia increases.

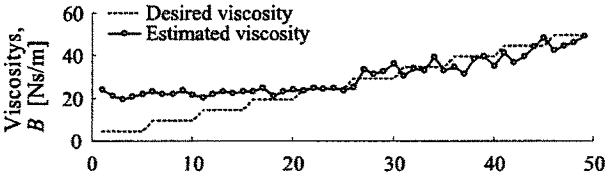
These results demonstrate that a human changes the damping coefficient of his/her hand by controlling the arm posture in order to regulate hand inertia property.



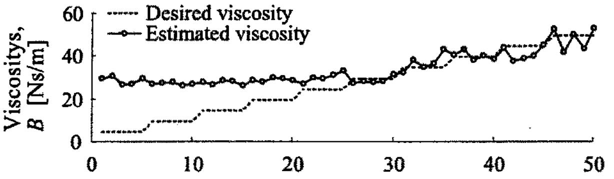
(a) Motion direction : $\phi = 0$ [deg.]



(b) Motion direction : $\phi = 45$ [deg.]

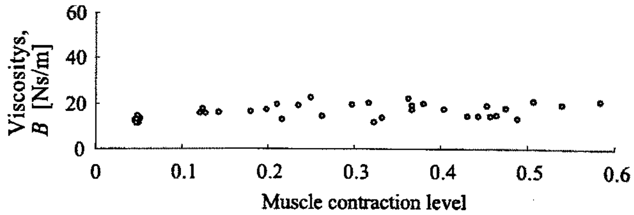


(c) Motion direction : $\phi = 90$ [deg.]

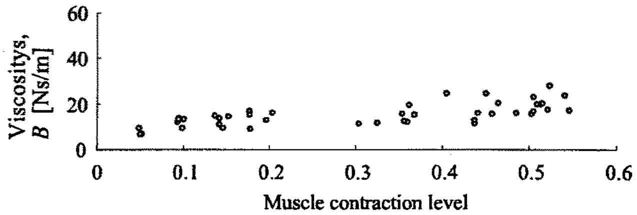


(d) Motion direction : $\phi = 135$ [deg.]

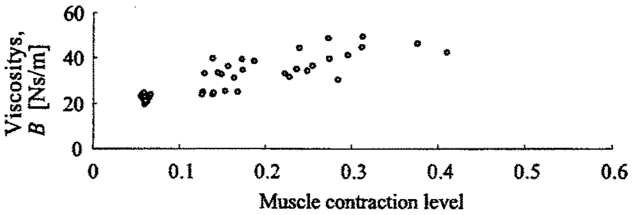
Fig. 8. Changes of human hand viscosity regulation ability according to the operational direction (Subject A).



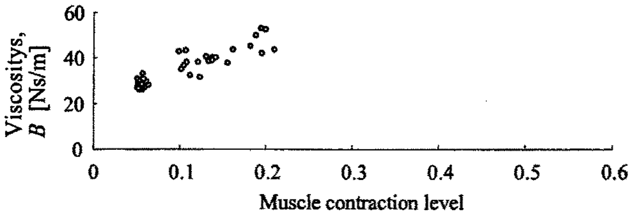
(a) Motion direction : $\phi = 0$ [deg.]



(b) Motion direction : $\phi = 45$ [deg.]



(c) Motion direction : $\phi = 90$ [deg.]



(d) Motion direction : $\phi = 135$ [deg.]

Fig. 9. Relations between the human hand viscosity and the muscle contraction level (Subject A).

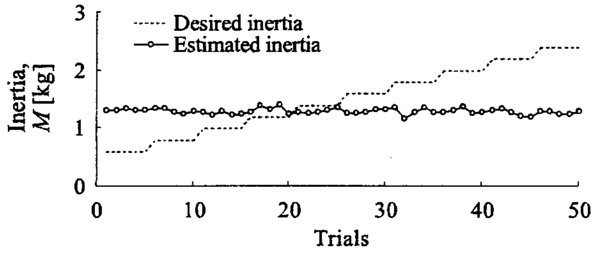
V. CONCLUSION

The present paper analyzed human hand impedance regulation ability for the purpose of developing a new training approach inspired by human impedance. The training experiments were carried out with the developed training system, in which the training information was fed back to a subject after each of experimental trials. The main results obtained from the preliminary experiments with the normal volunteers are summarized below:

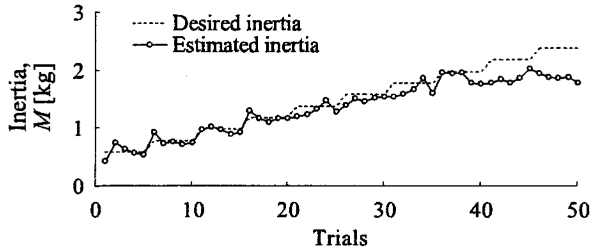
1) Impedance regulation ability can be trained.
2) Regulation of hand stiffness is strongly related to the muscle activation level so that a human can regulate his/her hand responsiveness by changing the level of muscle contraction.
3) Hand viscosity is difficult to regulate by muscle co-contraction while arm posture is restricted.
4) The ability to regulate hand viscosity depends on the operational direction.
5) The arm posture is the important factor for regulating hand inertia and the damping characteristics of hand movements.

Future research will be directed to develop a training system based on human impedance regulation ability with the aim of practical application to rehabilitation training, and to investigate training program as well as training effect for the handicapped in detail.

Acknowlegement. The authors would like to thank Prof. M.Kaneko of Hiroshima University, Prof. S.Kawamura of Ritsumeikan University. This research work was supported in part by a Grant-in-Aid for Scientific Research from the Japanese Ministry of Education, Science and Culture (15360226 and 14750188).

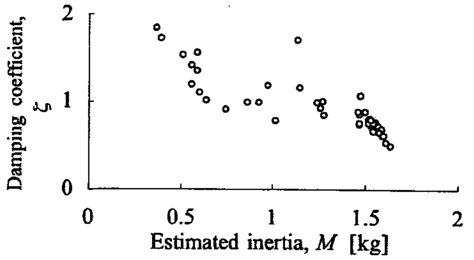


(a) A case of horizontal arm posture

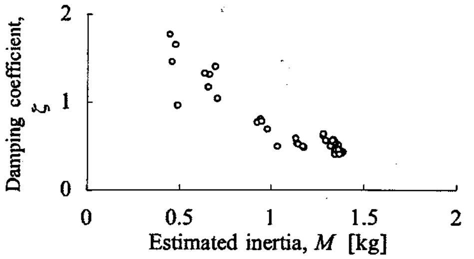


(b) A case of free arm posture

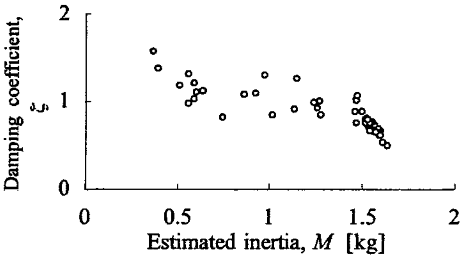
Fig. 10. Changes of human hand inertia during training of inertia regulation ability (Subject A).



(a) Subject A



(b) Subject B



(c) Subject C

Fig. 11. Relations between the damping coefficient and the hand inertia by the subjects during training of inertia regulation.

REFERENCES

[1] S. Kanehisa: "Science of muscle training", Koubundou Published Company, 1989. (in Japanese)

[2] 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, pp. 2732–2743, 1985.

[3] J. M. Dolan, M. B. Friendman and M. L. Nagarka: "Dynamics and loaded impedance components in the maintenance of human arm posture," *IEEE Transactions on Systems, Man and Cybernetics*, vol. 23, no. 3, pp. 698–709, 1993.

[4] T. Tsuji: "Human arm impedance in multi-joint movements," in Self-Organization, Computational Maps and Motor Control, P. G. Morasso and V. Sanguineti, Ed., Advances in Psychogy, 119, pp. 357–382, Elsevier, North-Holland, Amsterdam, 1997.

[5] T. Tsuji, P. G. Morasso, K. Goto and K. Ito: "Human hand impedance characteristics during maintained posture," *Biological Cybernetics*, vol. 72, pp. 457–485, 1995.

[6] T. Tsuji and M. Kaneko: "Estimation and modeling of human hand impedance during isometric muscle contraction," in *Proceedings of the ASME dynamic systems and control division*, DSC-VOL. 58, pp. 575–582, 1996.

[7] H. Gomi, Y. Koike, M. Kawato: "Human hand stiffness during discrete point-to-point multi-joint movement," in *Proceedings of the Annual International Conference of IEEE Engineering in Medicine and Biology Society*, pp. 1628–1629, 1992.

[8] A. Weltman, C. Janney, C. B. Rians, K. Strand, B. Berg, S. Tippitt, J. Wise, B. R. Cahill and F. I. Katch: "The Effects of hydraulic resistance strength training in pre-pubertal males," *Med. Sci. Sports Exerc.*, vol. 18, pp. 629–638, 1986.

[9] H. Nonaka, K. Ito, K. Mita, K. Yabe: "Biomechanical investigation of dynamics muscle contraction accompanying with viscous loading," *The Japanese Journal of Ergonomics*, vol. 34, no. 2, pp. 79–87, 1998.

[10] Y. Okajima, N. Tanaka, M. Hasegawa, N. Uchida, A. Kimura, Y. Tomita, T. Horiuchi, M. Kondo, T. Sakaki: "Therapeutic Exercise Machine: Soft Motion by the Impedance Control Mechanism," *Sogo Rehabilitation*, vol. 26, no. 4, pp. 363–369, Igaku-shoin Ltd., 1998. (In Japanese)

[11] N. Hogan, H. I. Krebs, J. Charnnarong, P. Srikrishna and A. Sharon: "MIT-MANUS: a workstation for manual therapy and training II," in *Proceedings of Telemanipulator Technology - SPIE - The International Society of Optical Engineering*, vol.1833, pp. 28–34, 1993.

[12] T. Noritsugu, T. Tanaka and T. Yamanaka: "Application of rubber artification muscle manipulator as a rehabilitation robot," in *Proceedings of IEEE International Workshop on Robot and Human Communication*, pp. 112–117, 1996.

[13] T. Tsuji, T. Kato, T. Shibata and M. Kaneko: "The relations between the excitability of the stretch reflex system and changes in the wrist joint impedance during isometric muscle contraction in human," *Transaction of the Society of Instrument and Control Engineers*, vol.34, no.11, pp. 1698–1705, 1998.

[14] F. A. Mussa-Ivaldi: "Compliance, human movement understanding," P. G. Morasso and V. Tagliasco, Ed., pp. 161–212, Elsevier, North-Holland, Amsterdam, 1986.