Motion Dependence of Impedance Perception Ability in Human Movements

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Abstract - **The present paper investigates the motion dependence of human impedance perception ability, especially in the stiffness perception through experiments. Experimental results demonstrate that the desirable hand displacement changes according to the robot stiffness, and that the deep somatic sensation has an important role in the stiffness perception. A preliminary training test is conducted for directing to apply the experimental findings into the development of an effective impedance perception training system based on cognitive therapeutic exercise.**

Keywords- **Cognitive therapeutic exercise, deep somatesthesia, human impedance perception**

I. Introduction

A human has highly developed sensory receptors and functions that allow him/her to survive and recognize various kinds of external information. Paradoxically it becomes difficult, or almost impossible for a human with sensorial or perceptual disorder, to gain sufficient information about his environment when his sensory system does not function properly. Many rehabilitation methods have been proposed for training damaged senses and perception based on the well-known evidence that motion has an important influence on the abilities of the senses and of perception. It is because perception ability relates with sensory-motor ability, which arises through the integration of motion and the senses [1].

Recently, a cognitive therapeutic exercise based on neurophysiology and learning theory has been put forward as a new approach to therapeutic exercise [2]–[4], in which a trainee is asked to recognize and perceive hardness and softness of objects, such as a spring, a sponge, and a weight; that is, the mechanical impedance properties of the objects. However, it is not possible to present a wide variety of the relevant impedance properties in the cognitive therapeutic exercises using easily obtained objects. Moreover, an effective design method for a training program that takes into account the level of a patient's disorder has not been established, nor has a quantitative evaluation method for training effects been put forward. If a robotic device could be developed to present various impedance properties to a trainee easily, it would be well worth establishing a cognitive therapeutic exercise. For this, it is necessary to investigate human impedance perception ability and to clarify the important functions associated with impedance perception.

There have been several studies on human perception of viscoelastic properties [5]–[8]. For example, Jones and Hunter [5] reported that a human can perceive changes in stiffness. In their experiment, a subject was asked to match the stiffness of the rotary motor on his left hand to the perceived stiffness of another motor on his right hand. Similar experiments involving viscosity were also carried out [6]. Srinivasan and LaMotte [7] conducted experiments exploring the human ability to distinguish an object's hardness, in which subjects were asked to press on an object with the tip of a finger and to recognize its stiffness using only the deep somatic sensation without the presentation of the tactile sense. Through these experiments, they argued for the importance of the deep somatic sensation and the tactile sense. Fujita et al. [8] discussed the contributions of the deep somatic sensation as well as the tactile and visual information to the stiffness perception of an object in finger grips from the discrimination gain of the perceived to real stiffness value. None of these previous studies carries out a quantitative analysis of impedance perception ability with regard to values of robot impedance. In addition, the mechanical factors that influence the perception ability have not been investigated.

On the other hand, Tsuji et al. [9] investigated the human perception accuracy and the discrimination ratio for robot impedance parameters through a set of experiments with normal subjects, and reported that the human impedance ability fulfilled Weber's law. They also reported the importance of sensory-motor integration for the impedance perception from the differences between a patient with cerebellar ataxia and healthy subjects in the perception abilities and the characteristics of hand movements [10]. However, they did not discuss the relationship between the impedance perception accuracy and the hand motion characteristics in detail although a human subject senses force stimuli resulting from his/her hand movements.

The present paper examines the motion dependence of the human impedance perception ability, especially in the stiffness perception, and argues what kinds of hand movements are desirable to gain the external information needs for the impedance perception. Experimental findings of this paper has the potential to utilize as basic data for the design of an effective training program for the impedance perception training using a robotic system.

This paper is organized as follows: Section II explains a human impedance perception training with showing typical results. In Section III, the motion dependence of the impedance perception is analyzed in the different two types of hand motion patterns. Finally, Section IV discusses the influence of passive impedance and the important role of the deep somatic sensation on the human impedance perception.

II. Human Impedance Perception [9], [10]

A. Experimental Apparatus

Fig. 1 shows an overview of the experimental apparatus, which includes a linear motor table with one degree of freedom (Nihon Thomson Co., Ltd., encoder resolution: 2 [μm]), used to present impedance characteristics to subjects, a computer for robot control, and a display that shows training information such as position and hand force in the training. A handle and a six-axis force/torque sensor (BL Autotec Co., Ltd., resolution ability: force x axis, y axis: 0.005 [N], z axis: 0.15 [N], torque: 0.003 [Nm]) are attached to the moving part of the robot to measure the operating hand force F imposed by a subject. The handle (hand) position x is measured by an encoder built into the linear motor table. The operational direction ϕ is changed by the rotary motor set under the table.

The dynamics of an impedance-controlled robot [11] can be expressed as

$$M_r\ddot{x} + B_r\dot{x} + K_r(x_r - x) = F \tag{1}$$

where M_r is the robot inertia; B_r the robot viscosity; K_r the robot stiffness; and x_r the equilibrium of K_r. The experimental system can realize a wide variety of robot impedance properties accurately by changing the impedance parameters.

B. Perception Ability during Free Movements

An impedance perception test is carried out along the following way that a subject is instructed to report the perceived value of the robot impedance parameter through moving the handle attached at the impedance-controlled robot as he desired. The perceived values of robot impedance are not revealed to the subject. Before the perception test, the subject spends five minutes memorizing the feelings for some standard values of robot impedance parameter: the four values of stiffness K_r = 0, 500, 1000, 1500 [N/m].

Fig. 2 illustrates the typical experimental results of the stiffness perception for the two healthy subjects with the correlation coefficient r between the true and perceived impedance values. The vertical axis is the perceived impedance K, while the horizontal axis is the true robot impedance K_r. The robot stiffness K_r was randomly presented within $0 \sim 1500$ [N/m] with a 1 [N/m] resolution under the robot viscosity B_r = 0 [Ns/m] and the robot inertia M_r = 2.0 [kg], in which the number of trials was set at 300.

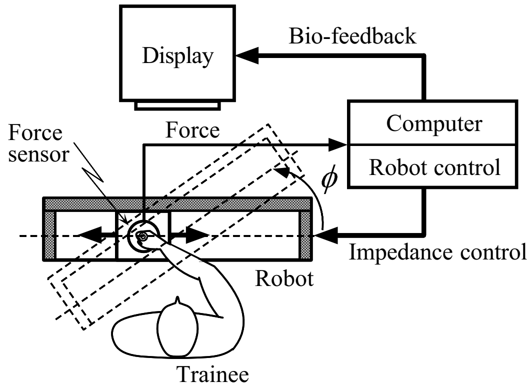

Fig. 1. An overview of the impedance training system

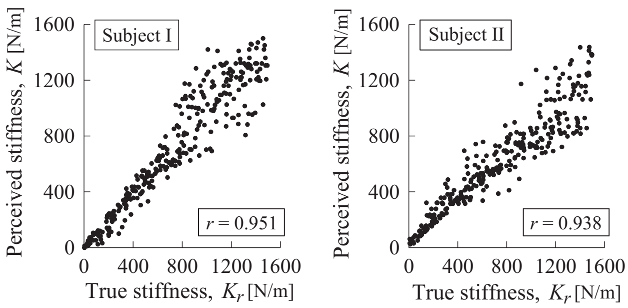

Fig. 2. Examples of the stiffness perception results under free movements

As shown in Fig 2, the human subjects can perceive the presented values of robot stiffness with high accuracy by moving the robot handle freely.

III. Motion Dependence of Human Impedance Perception Ability

In general, a human subject needs to sense the reaction force from environments as well as the resultant motion (position, velocity, acceleration) using his/her own sensory receptors to perceive the impedance characteristics of a given object. As a result, the human impedance perception accuracy would be much affected by his/her hand movements. This section analyzes the motion dependence of such human impedance perception.

A. Experimental Procedure

Since the force stimuli (the driving force) F in the stiffness perception is proportional to the robot impedance K_r and the hand displacement D $(= x_r - x)$, that is, $F = K_rD$, this paper investigates the stiffness perception ability in the following two patterns of hand motion:

Pattern I:

A subject is instructed to periodically move the handle between the equilibrium x_r and the specified point with the displacement D at the cycle time T toward the left hand side.

Pattern II:

A subject is instructed to move the handle toward the left hand side and to retain its position with the displacement D from the equilibrium x_r.

To quantitatively evaluate the stiffness perception ability, a perception gain E is defined as

$$E = \frac{1}{N} \sum_{i=1}^{N} \frac{K(i)}{K_r(i)}, \tag{2}$$

where i denotes the trial number; N the total number of trials. Note that the impedance perception ability increases as the gain $E \rightarrow 1$.

Experiments were conducted with 4 healthy subjects (male university students; aged $22 \sim 24$). They had never taken part in the impedance perception test.

B. Perception Ability depending on Cycle Time of Hand Motion

Fig. 3 shows changes of the stiffness perception gain E for Subject A under the condition of Pattern I depending on the cycle time of hand motion T = 2/3, 4/5, 1, 4/3, 2, 4 [s] with the displacement D = 0.04 [m]. The mean values of the 20 trials are plotted with the standard deviations by a black circle ($E < 1.0$) and a white circle ($E \geq 1.0$) in each for the presented stiffness K_r. The presented value of robot stiffness was randomly selected from K_r = 400, 700, 1000, 1300 [N/m] under B_r = 0 [Ns/m] and M_r = 2.0 [kg], while the subjects reported the perceived values with a 1 [N/m] resolution.

It can be found that the stiffness perception gain E is almost constant for the change in the cycle time T for the presented values of robot stiffness K_r. In addition, the gain E tends to decrease as the robot stiffness K_r decreases under the specified displacement $D = 0.04$ [m]. The similar characteristics were observed for other subjects.

Fig. 4 shows the typical hand movements for Subject A during the stiffness perception tests under the cycle time T = 2/3 and 2 [s], where the box represents the true and perceived robot stiffness. Although obvious differences between the different two conditions can be seen in hand movements, the subject perceived almost same values. These results indicate that the stiffness perception ability is scarcely affected by the cycle time of motion pattern T.

C. Perception Ability depending on Hand Displacement

Fig. 5 shows changes of the stiffness perception gain E for Subject A under the condition of Pattern II, depending on the hand displacement D = 0.01, 0.02, 0.025, 0.03, 0.04, 0.05, 0.06 [m]. The presented robot stiffness was randomly selected from K_r = 100, 400, 700, 1000, 1300, 1500 [N/m]

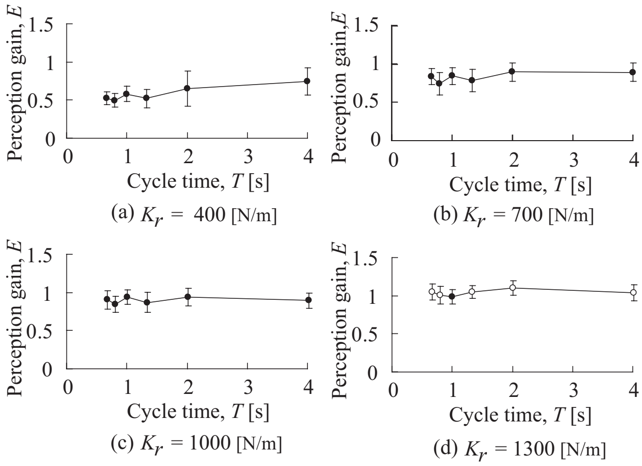

Fig. 3. Changes of the perception gain E depending on the cycle time of hand motion (Subject A)

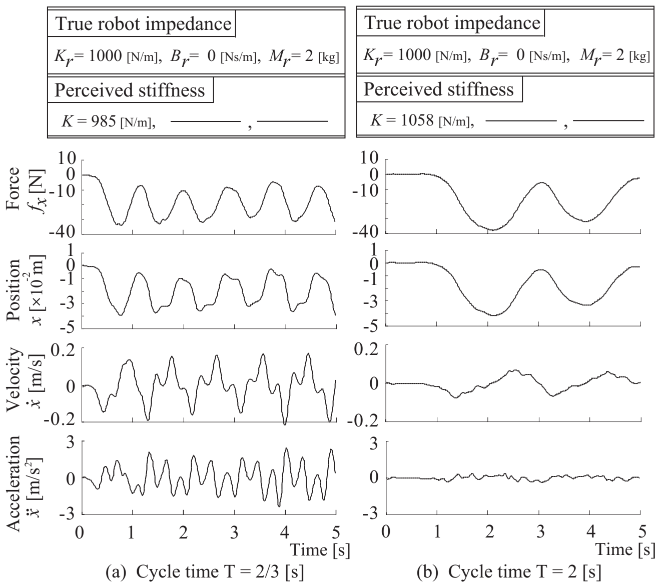

Fig. 4. Typical hand movements under the cycle time T = 2/3, 2 [s]

under B_r = 0 [Ns/m] and M_r = 2.0 [kg], while the subjects reported the perceived values with a 1 [N/m] resolution. The maximum value in each of the hand displacement D was determined with consideration of the performance of the employed robot. The mean values of the 20 trials are plotted with the standard deviation by a black circle ($E < 1.0$) and a white circle ($E \geq 1.0$) in each value of the presented stiffness.

The stiffness perception gain E much changes according to the hand displacement D. The larger displacement would be desirable for the stiffness perception of small values and vice versa because of the gain $E \approx 1$ with a small

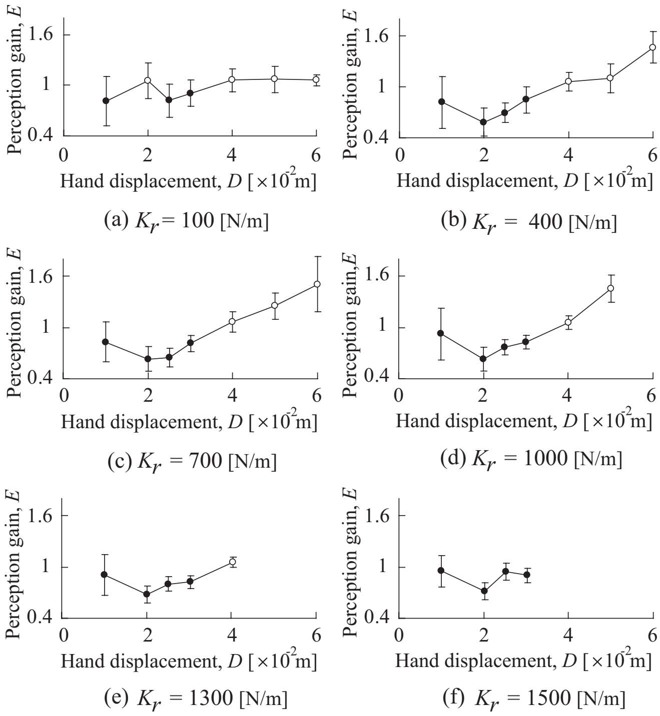

Fig. 5. Changes of the perception gain E depending on the hand displacement (Subject A)

TABLE I

MEAN VALUES AND STANDARD DEVIATIONS OF THE AVERAGE GAIN E FOR ALL SUBJECTS

Displacement, D [m]			0.01	0.02	0.025	0.03	0.04	0.05	0.06
Robot stiffness, K_r [N/m]	100	Ave.	1.26	1.28	1.25	1.38	1.35	1.15	1.13
		SD.	0.55	0.46	0.47	0.65	0.32	0.18	0.09
	400	Ave.	1.14	1.03	1.14	1.10	1.21	1.26	1.16
		SD.	0.28	0.46	0.39	0.32	0.19	0.21	0.27
	700	Ave.	0.96	0.86	0.95	0.98	1.15	1.23	1.25
		SD.	0.17	0.22	0.23	0.17	0.15	0.03	0.17
	1000	Ave.	0.91	0.81	0.89	0.94	1.09	1.28	–
		SD.	0.05	0.14	0.11	0.10	0.11	0.14	
	1300	Ave.	0.91	0.80	0.86	0.92	1.04	–	–
		SD.	0.05	0.09	0.08	0.07	0.08		
	1500	Ave.	0.87	0.79	0.93	0.92	–	–	–
		SD.	0.06	0.06	0.02	0.03			

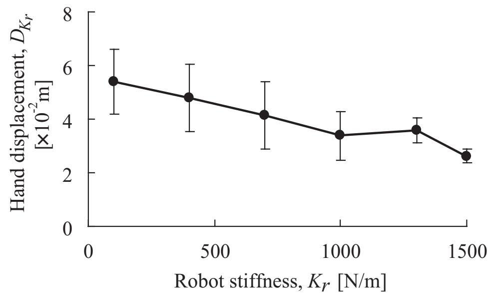

Fig. 6. Desirable hand displacement D_{K_r} for the stiffness perception

standard deviation. Note that Subject A rarely perceived the stiffness values correctly under D = 0.01 [m] because the standard deviation is quit large compared to other conditions although the gains are close to 1. These results demonstrate that the stiffness perception ability is affected by the hand displacement and there exists a desirable displacement for each value of robot stiffness.

Table I shows the mean and the standard deviation of the perception gains for all subjects in each of the specified conditions. When both the robot stiffness K_r and the displacement D are small, the gain is not close to 1 and the standard deviation is quit large compared to ones under the other conditions. This indicates that it is difficult for a human subject to correctly perceive small values of robot stiffness with small hand displacement.

Fig. 6 shows changes of the mean and the standard deviation of the desirable hand displacements D_{K_r} for Subjects A, B, C, and D depending on the presented robot stiffness. The displacement D_{K_r} is defined as the expected displacement at which the perception gain $E = 1$, and is calculated using the regression line for the gain E on the instructed displacement D, except for D = 0.02 [m], in each of the experimental results by the subjects as shown in Fig. 5. It can be confirmed that the desirable hand displacement D_{K_r} for the stiffness perception changes according to the value of robot stiffness K_r while decreasing as K_r increases. It is expected that the perception ability of a trainee can be improved by utilizing the displacement D_{K_r} as a quantitative training target of hand movements in the stiffness perception training. The experimental findings obtained in this paper may be well worth establishing an effective training method of human impedance perception ability.

IV. INFLUENCE OF PASSIVE IMPEDANCE ON IMPEDANCE PERCEPTION ABILITY

From the anatomy of a human being, it can be naturally considered that the deep somatic sensation senses the force stimulus filtered by passive impedance elements of the palmar skin contacting the robot handle. This section discusses the influence of such passive impedance on the impedance perception ability and also the important role of the deep somatic sensation.

A. Perception Ability with and without Passive Impedance

Experiments were conducted under the condition in which a subject puts a cast on his hand to eliminate the affect of passive impedance as much as possible. The robot stiffness K_r was randomly presented within $0 \sim 1500$

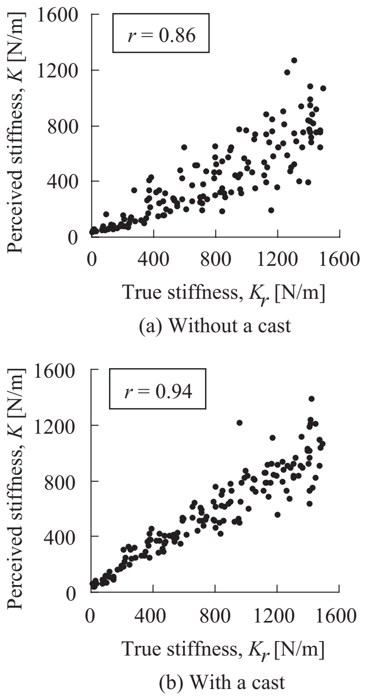

Fig. 7. Stiffness perception ability with and without a cast under the hand displacement D = 0.01 (Subject A)

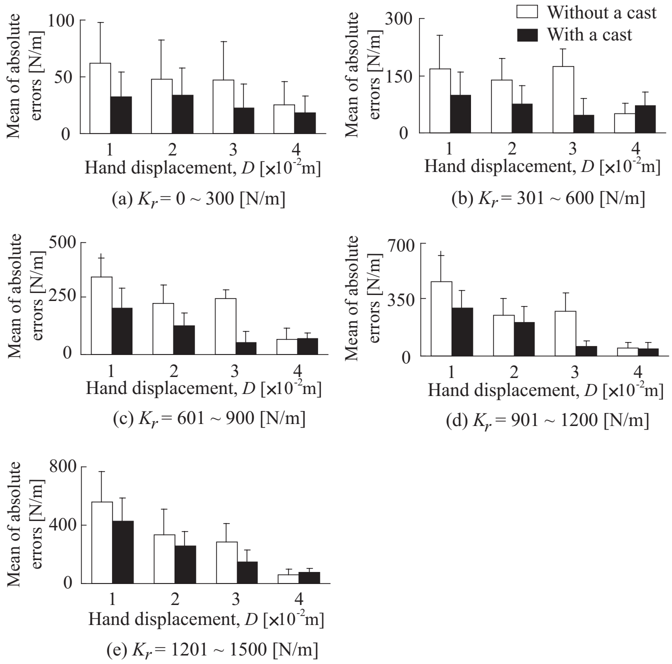

Fig. 8. Stiffness perception errors with and without a cast depending on the hand displacement (Subject A)

[N/m] by a 1 [N/m] resolution under B_r = 0 [Ns/m] and M_r = 2.0 [kg], in which the number of trials was set at 150 for each hand displacement.

Fig. 7 shows examples of the stiffness perception results for Subject A with and without a cast, where the subject perceived the presented values under the condition of Pattern I with the hand displacement D = 0.01 [m]. It can be seen that his perception ability obviously improved by putting a cast on his hand in the overall range of the presented stiffness.

Fig. 8 shows the mean and standard deviation of the stiffness perception errors between the true and perceived values by a 300 [N/m] range within K_r = 0 $\sim$ 1500 [N/m], depending on the hand displacement D = 0.01, 0.02, 0.03, 0.04 [m]. The vertical axis is the displacement D, while the horizontal axis is the perception error. The perception errors much decrease when the subject put a cast in his hand within D = 0.01 $\sim$ 0.03 [m] as shown in Fig. 8. On the contrary, the differences between the results with and without a cast are little at D = 0.04 [m].

These results demonstrate that the human impedance perception ability is decayed by the effect of passive impedance of the skin when the hand displacement is below 0.04 [m] especially under the condition in which the presented value of robot stiffness is small.

B. Analysis of Reaction Force

The effect of passive impedance is analyzed by using a simple model of the human-robot system as shown in Fig. 9. The dynamics of the model can be given by

$$\begin{bmatrix} M_s & 0 \\ 0 & M \end{bmatrix} \ddot{X} + \begin{bmatrix} B_s & -B_s \\ -B_s & B_s + B \end{bmatrix} \dot{X} + \begin{bmatrix} K_s & -K_s \\ -K_s & K_s + K \end{bmatrix} X = \begin{bmatrix} f_{in} \\ 0 \end{bmatrix}, \quad (3)$$

where $X = [x_s, x_r]^T$; f_{in} represents the input force generated by muscles to move the hand; K, B and M are the impedance parameters of the human-robot part; K_s, B_s and M_s are the impedance parameters of the skin part.

Corresponding to the impedance perception without a cast, the stiffness of the skin part is assumed to be changed depending on the deformation of skin surface l based on the literatures [12], [13] as

$$K_s = \begin{cases} 100\ [\mathrm{N/m}] & (0 < l < 3.0 \times 10^{-3}) \\ 266\ [\mathrm{N/m}] & (3.0 \times 10^{-3} \le l < 5.0 \times 10^{-3}) \\ 3000\ [\mathrm{N/m}] & (\mathrm{otherwise}). \end{cases}$$

Here, the stiffness of the skin part is fixed at K_s = 3000 [N/m] in the simulation with a cast. The other parameters in the model were set as K = 100 [N/m], B = 20 [Ns/m], M = 2 [kg] for the robot-human part, and B_s = 1.23 [Ns/m], M_s = 0.015 [kg] for the skin part, respectively.

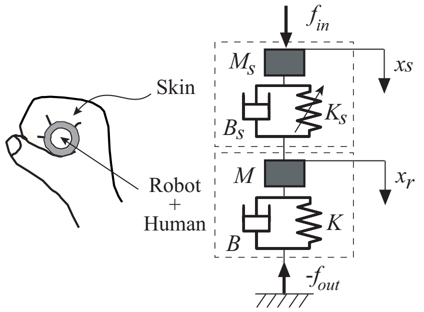

Fig. 9. A model of human movements in the impedance perception

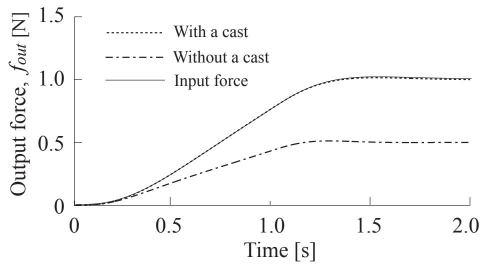

Fig. 10. Simulation results with and without a cast

Fig. 10 shows time profiles of the output force f_{out} equivalent to the reaction force from the robot handle to the deep somatic sensation with and without a cast. It can be seen that the output force without a cast is attenuated by the effect of passive impedance in the skin part.

The passive impedance suppresses external force stimuli to protect the musculoskeletal system, so that the deep somatic sensation cannot receive enough reaction force from the contacted environment to perceive its impedance properties according to circumstances. Accordingly, it becomes difficult for a human subject to perceive small values of robot stiffness with small hand displacement.

V. CONCLUSIONS

This paper experimentally analyzed motion dependence of the impedance perception and investigated the influence of passive impedance on the perception accuracy. The main results of this paper are summarized as follows:

1) The hand displacement strongly influences the stiffness perception accuracy.
2) The stiffness perception accuracy decreases by passive impedance when the robot stiffness and the hand displacement is small.
3) The deep somatic sensation has the important role in the impedance perception.
4) The experimental data of motion dependence may be useful for designing a quantitative training index for impedance perception training.

Further research should be directed to investigate the motion dependence of perception abilities for the robot viscosity and inertia to clarify the functional mechanism of human impedance perception. We also plan to develop a control structure of a power-assist system using robotic devices for the impedance perception training based on the experimental findings on the motion dependency.

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