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A Virtual Air Hockey System for Skill Training

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Abstract

Dynamic characteristics of human upper extremity 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 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, and investigates human impedance according to the degree of task difficulty.

Keywords Skill training, human impedance, virtual air hockey

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, intentionally or unintentionally, regulate the dynamic property of our limbs in playing sports. The characteristics of human movements can be generally expressed by using mechanical impedance such as stiffness, viscosity, and inertia. Many experimental studies on the human arm impedance have been carried out and made clear some distinctive features during the maintenance of arm posture [2]–[6]; for example, hand stiffness largely depends on the arm posture [2], a human can change the magnitude of stiffness but not the direction [3]–[5], the hand viscoelasticity changes in proportion to muscle contractions [6], and so on. Also, it was reported that the hand stiffness in motion changes more than that during the maintenance of the specified arm posture [7].

In the kinesitherapy for rehabilitation [8]–[11], there are several researches using human impedance. Then, Tsuji et al. [12] proposed and validated an impedance training method focusing on human impedance regulation mechanism. The impedance training, however, can be applied only to static motions during the maintenance of arm posture. Training in dynamic motion is easily conducted in actual sport, but use of impedance training involves difficulties in measuring force and position. Besides, it becomes almost impossible to apply external disturbances to human movements in the midst of a sport event in order to measure the human impedance. Some research works have been attempted to estimate the human impedance in motion from the EMG signals by utilizing neural networks [13], [14]. However, it may be difficult to accurately estimate the human impedance in motion because the impedance is much affected by the arm posture and the sensitivity of spinal reflex as well as the intensity of muscle contraction.

In order to improve the impedance training method, we have already developed the virtual tennis training system using the impedance-controlled robot and the virtual reality for the purpose of skill-level training in dynamic motion [15]. The technique of virtual reality allows us to apply external disturbances and to change environmental characteristics in training. However, the trainee's end-point motion is limited in a straight trajectory and the level of difficulty on the task cannot be changed. Thus, it is difficult to present the training program according to the motion ability of each trainee.

As a first step to realize an effective and practical virtual sports training, the present paper develops a virtual air hockey system which is composed of two linear motor tables to provide two-dimensional motion exercise, and investigates the human hand impedance just before the dymamic motion by changing the degree

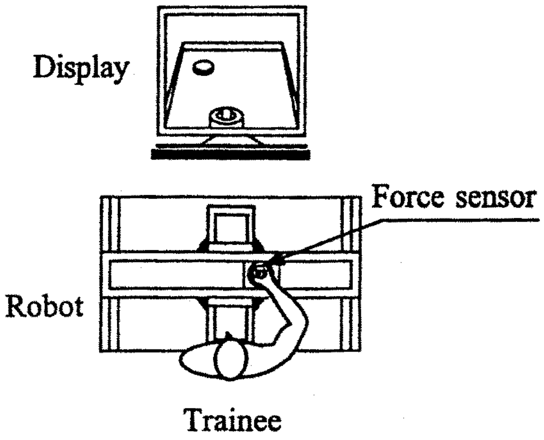


Fig.1: Virtual sports system

of task difficulty. This paper is organized as follows: Section 2 describes the structure of virtual sports system. Experiments are conducted and the human hand impedance property is investigated according to the degree of difficulty in Section 3 and 4.

2 Virtual Sports Training System

2.1 Experimental Apparatus

Figure 1 shows the virtual sports system developed in this paper, where air hockey is selected as an example of virtual sports. A trainee is instructed to hit a virtual puck with a virtual mallet in the display by maneuvering the handle attached at a robot. The robot is composed of two linear motor tables with one degree of freedom (Nihon Tomson Coop., maximum driving force: ±10 [kgf], encorder resolution: 1.0 [μm]; and Nihon Seikou Coop., maximum driving force: ±40 [kgf], encorder resolution: 1.0 [μm]), which are placed orthogonally in order to carry out the two-dimensional hand motion exercise. Also, the hand force generated by the trainee is measured by a six-axis force/torque sensor on the handle (BL Autotec Co. Ltd., resolution: force x and y axes, 0.05 [N]; z axis, 0.15 [N]; torque, 0.003 [Nm]).

The robot is under impedance control [16] for presenting a virtual impact force to the trainee in the moment of interaction between puck and mallet, so that the trainee can play virtual air hockey based on the visual information on the display.

2.2 Model of Virtual Air Hockey

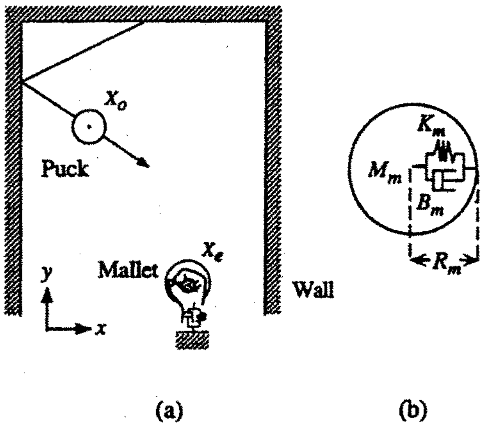


Fig.2: Model of the virtual air hockey

Figure 2 (a) shows a model of the virtual air hockey. The puck hit by the mallet reflects from a wall as shown in the figure, where $X_o, X_e \in \Re^2$ denote the center positions of puck and mallet, respectively. The mallet is expressed by a viscoelastic model with the weight M_m as shown in Fig. 2 (b), where $K_m, B_m \in \Re^{2\times 2}$ denote the stiffness and the viscosity of mallet, respectively. The puck and wall are assumed as a rigid body.

The motion equation of puck is given as

$$M_p\ddot{X}_o + B_{fp}\dot{X}_o = F_{int}, \tag{1}$$

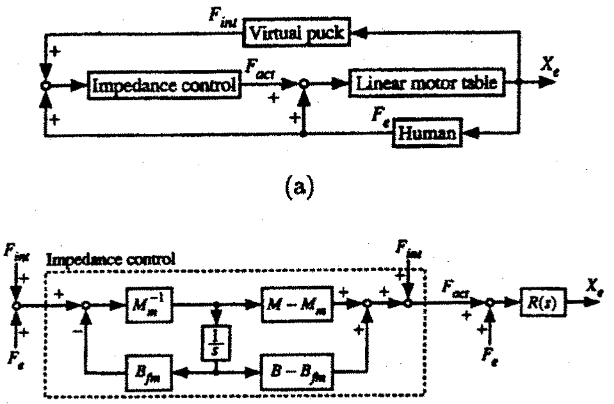
where $M_p, B_{fp} \in \Re^{2\times 2}$ represent the inertia of the puck and the viscous frinction between the puck and the air hockey table, respectively; and $F_{int} \in \Re^2$ denotes the interaction force between the puck and the mallet. In our system, F_{int} is defined with the relative position between the center positions of puck and mallet, $X_r = X_e - X_o \in \Re^2$, as follows:

$$F_{int} = \begin{cases} R(\theta)^T B_m R(\theta)\dot{X}_r + R(\theta)^T K_m R(\theta) dX_r & \\ \qquad\qquad (|X_r| \le R_p + R_m) & , \\ 0 \qquad\qquad (|X_r| > R_p + R_m) & \end{cases} \tag{2}$$

where $R(\theta) \in \Re^{2\times 2}$ is the rotational matrix from the world coordinate system to the moving coordinate system in which the origin is set at a contact point between the puck and the mallet in the moment of interaction and the X axis is selected in the tangential direction; $dX_r \in \Re^2$ is the displacement of mallet due to the collision with the puck determined by

$$dX_r = X_r - |X_r(t_c)|n\ , \tag{3}$$

$$n = \begin{cases} \dfrac{X_r}{|X_r|} & (X_r \ne 0) \\ 0 & (X_r = 0) \end{cases}\ , \tag{4}$$



(a)

(b)

Fig.3: Impedance control system for a virtual air hockey

where $X_r(t_c)$ represents the relative position between the puck and the mallet at the collision time t_c.

On the other hand, the motion equation of mallet is determined with the interaction force, F_{int}, and the hand force generated by the trainee, $F_e \in \Re^2$, as

$$M_m \ddot{X}_e + B_{fm} \dot{X}_e = F_{int} + F_e, \qquad (5)$$

where $M_m, B_{fm} \in \Re^{2\times2}$ are the inertia of the mallet and the viscous frinction between the mallet and the air hockey table, respectively. Therefore, the trainee can play virtual air hockey as if he is maneuvering the handle with the specified impedance property, and can feel an appropriate impact force F_{int} in the moment of hitting the puck. The y directional velocity of puck is reversed after the collision with the left or right wall, while the x directional velocity is reversed after the collision with the top or bottom wall.

The play area of virtual air hockey is defined as $0 \leq x \leq 1.0$ [m] and $0 \leq y \leq 3.5$ [m], where the origin of operational coordinate system is at the left and bottom side (See Fig. 2 (a)). Dynamic characteristics of the mallet are set as M_m = diag. [1.5, 1.5] [kg], B_m = diag. [0, 10] [Ns/m], K_m = diag. [0, 1000] [N/m], R_m = 0.07 [m]; the puck as M_p = diag. [0.1, 0.1] [kg], R_p = 0.05 [m]; the viscous frinctions of puck and mallet for air hockey table as B_{fp} = diag. [0.05, 0.05] [Ns/m], B_{fm}=diag. [10.0, 10.0] [Ns/m], respectively.

2.3 Impedance Control

Figure 3 (a) shows the configuration of a human-robot system used for training. F_{act} is the control input to the impedance-controlled robot [16], while the dymamic behavior of mallet confirms to (3). Figure 3 (b) shows a detailed block diagram of the impedance control part when the dynamic property of robot, $R(s)$, is modeled as:

$$R(s) = \frac{1}{Ms^2 + Bs}, \qquad (6)$$

where $M, B \in \Re^{2\times2}$ denote the desired inertia and viscosity. In this paper, these parameters are set as M=diag.[3.2, 29.0] [kg], B=diag.[42.0, 72.0] [Ns/m].

3 Human Movements in Virtual Air Hockey

3.1 Experiments

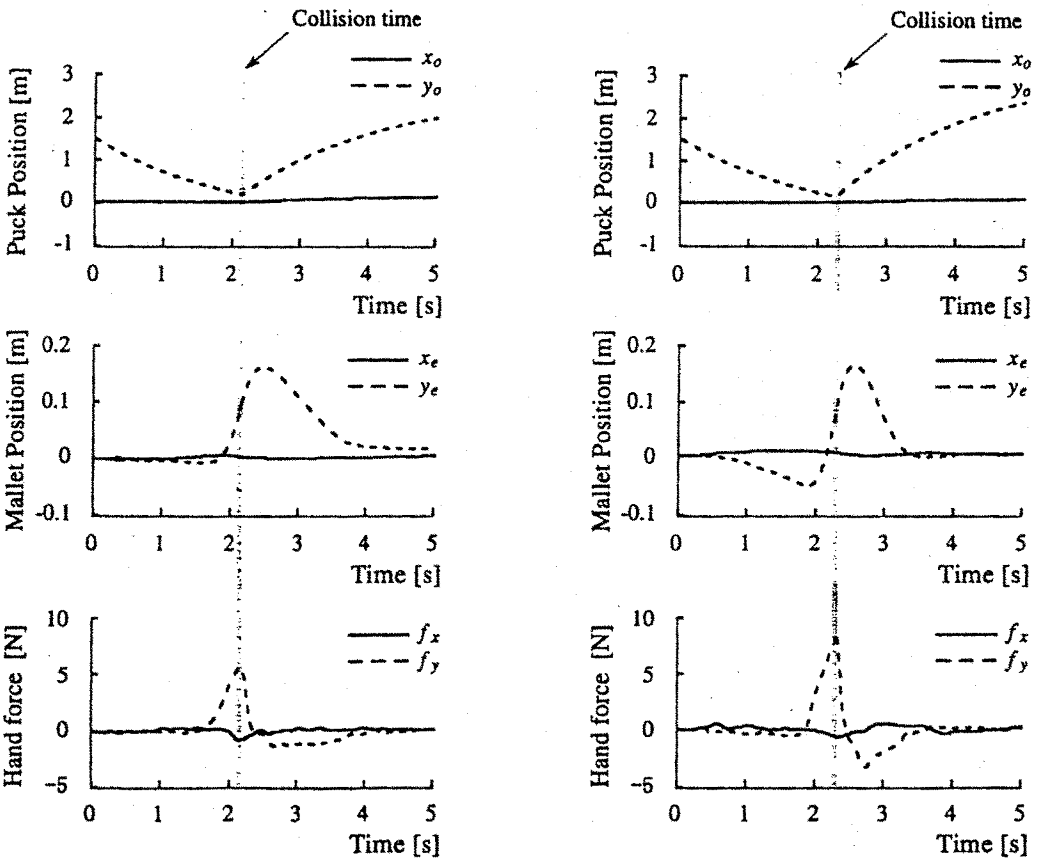
Experiments with a subject (a male university student) were conducted to investigate human hand movements in the virtual air hockey. The subject was asked to return the puck coming from the initial position X_o = (0.5, 1.65) [m] with the initial velocity $\dot{X}_o$ = (0.0, −1.5) [m/s] by the mallet positioned at X_e = (0.5, 0.15) [m] in the initial state so as to stop it in the specified target area. Two different degrees of task difficulty were given by changing the size of target area as: Task A with $y \geq 1.75$ [m]; Task B with $y \geq 2.65$. Task B is more difficult than Task A because the target area of Task B is narrower.

3.2 Experimental Results

Figures 4 shows the examples of human hand movements in motion for Task A and Task B. The top figure for each task presents the time histories of the puck position X_o, the secound is the mallet (hand) position X_e, and the bottom is the hand force F_e.

It can be seen from the spatial trajectories of puck and mallet that the subject regulates the position of mallet carefully in the x direction to hit near the center of puck, while it moves dynamically in the y direction with some take-back actions according to the motion of puck. Also, the mallet in Task B is moved faster in the y direction with larger take-back than in Task A. It indicates that the subject tries to thrust the mallet forward to return the puck as far as possible.

On the other hand, it can be observed from the time histories of hand force that the subject regulate his hand force so as to maximize in the moment of the interaction between puck and mallet in both of tasks. The subject generates enough large hand force not to be pushed back by the interaction force. In addition, the maximum amplitude of hand force in Task B is larger than that in Task A, so that the puck moves farther away. It can be suggested that the subject acquires regulation ability of operational hand force according to the task difficulty.



(a) Task A

(b) Task B

Fig.4: Human hand movements in the virtual air hockey according to the task difficulty

4 Human Hand Impedance in Virtual Air Hockkey

Mechanical impedance, composed of inertia, viscosity and stiffness, is often used to express the dynamic characteristics of human movements, and many studies on the human impedance have been conducted [2]–[7]. Then, it has been reported that a human regulates his/her impedance before movements to prepare for the dynamic motion [15]. The present paper aims to investigate the human hand impedance before movements and reveal how a human regulates his/her impedance according to the degree of task difficulty.

4.1 Measurment of Human Impedance

Let us consider a case that the trainee maintains his arm posture in the l-dimentional task space. When the trainee's hand is placed from an equilibrium point by a small disturbance with short duration as shown in Fig. 5, the dynamic characteristics of the hand is approximated by the following impedance model as

$$M_e\ddot{X}_e(t) + B_e\dot{X}_e(t) + K_e(X_e(t) - X_v(t)) = -F_e(t) \,, \tag{7}$$

where M_e, B_e, $K_e \in \Re^{l\times l}$ represent the hand inertia, viscosity and stiffness, respectively; $X_e(t)$, $X_v(t) \in \Re^l$ are the hand position and the virtual hand trajectory, respectively; and $F_e(t) \in \Re^l$ denotes the hand force exerted to the environment. Assuming that the disturbance is applied at time t_0, the dynamic characteristics of the hand at the time t can be described on the basis of (7) as follows:

$$M_e d\ddot{X}(t) + B_e d\dot{X}(t) + K_e dX(t) = -dF_e(t) \,, \tag{8}$$

where $dX(t) = X_e(t)$ - $X_e(t_0)$, $dF_e(t) = F_e(t)$ - $F_e(t_0)$. If $X_e(t)$ and $F_e(t)$ can be measured, it enables to estimate the impedance parameters M_e, B_e, K_e by means of the least squares method with (8).

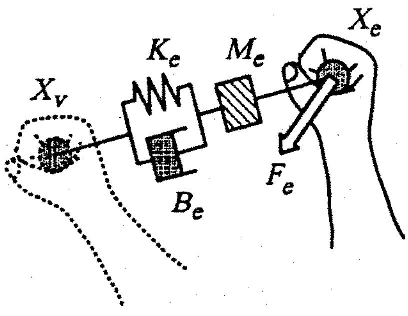


Fig.5: Schematic description of hand impedance

The virtual trajectory $X_v(t)$, however, changes during dynamic motion, and it is impossible to determine the unknown parameters M_e, B_e, K_e and $X_v(t)$ because the observable parameters are only $X_e(t)$, $\dot{X}_e(t)$, $\ddot{X}_e(t)$ and $F_e(t)$. Besides, it needs to estimate the human hand impedance in every sampling time because the human impedance changes every moment according to the arm posture and the muscle construction level. As a result, it is considerably difficult to estimate the human impedance in dynamic motion. Therefore, the present paper targets to examine the human hand impedance just before movements for the task.

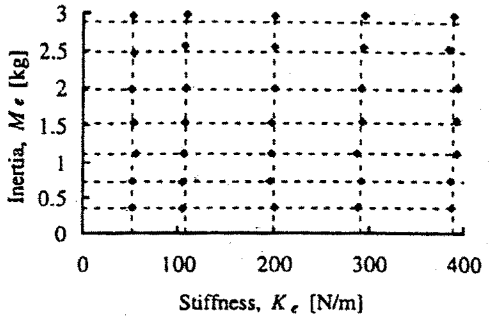
4.2 Accuracy of Estimated Impedance

Figure 6 shows the estimated impedance parameters for the known physical quantities in the x, y direction on the basis of the estimation method described in 4.1. In the accuracy testing, both stiffness (spring constant) and inertia (weight of load) are measured at the same time by which a spring is connected between the fixed environment and the handle with a load. In the figures, the dot represents a mean value of 6 trials, and each intersection point of dashed lines indicates a true value. It can be confirmed that each of estimated values almost agrees with the true value. The standard deviations on stiffness and inertia are 8.69 [N/m] and 0.05 [kg] for the x direction, 9.49 [N/m] and 0.04[kg] for the y direction.

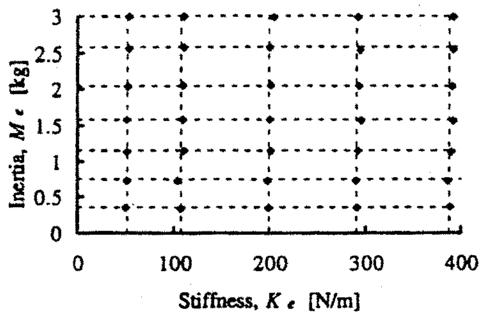
4.3 Analysis of Human Hand Impedance

Human hand impedance just before movements was estimated from the hand position and the hand force which were measured during 0.3 [s] from 0.5 [s] after the puck was thrown out.

Table 1 shows the mean value and the standard deviation of estimated impedance parameters just before movements. It can be found from Table 1 that the stiffness in Task B is larger than that in Task A. It indicates that the subject increases his stiffness as the task is difficult. On the other hand, the viscosity to the X direction in Task B is larger than another. Since the surface of table is slippery under B_{fm}=diag. [10.0, 10.0] [Ns/m], the subject increases his viscosity to stabilize the mallet's motion so that the mallet hit near the center of puck and pushes it much far away. As the remarkable influence of task difficulty dose not observed on the inertia property, it can be said that the subject dose not change his arm posture so much in this task. From the experimental results, we have found that a



(a) x direction



(b) y direction

Fig.6: Accuracy of estimated impedance

Table 1: Measured human hand impedance just before movements

		Stiffness, K_e [N/m]	Viscosity, B_e [Ns/m]	Inertia, M_e [kg]
Task A	x direction	175.5±45.5	11.61±3.79	1.35±0.11
	y direction	403.6±59.5	24.38±4.19	1.24±0.13
Task B	x direction	279.6±90.8	17.89±4.22	1.24±0.12
	y direction	519.6±63.1	24.87±3.94	1.11±0.15

human changes his/her hand impedance according to the degree of task difficulty, especially the hand stiffness.

5 Conclusion

The present paper has proposed a virtual sports training system as the first step to realize a training method based on the human impedance characteristics in dynamic motion. The main characteristics clarified in this paper are as follows:

1. There are some differences on movements between skilled and unskilled subjects.
2. A subject moderates his hand force so as to hit the puck efficiently.
3. A subject changes his impedance properties according to the degree of task difficulty.

The measurement of human movements by means of the proposed virtual sport system allows us to analyze the muscular motion that takes an important role in acquiring a skill and to collect the basic data that will be used for sports training or rehabilitation.

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