Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Hybrid Impedance Control of Human Skin Muscle by Multi-fingered Robot Hand

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Abstract: This paper proposes an intelligent massage control system by using multi-fingered robot hand with hybrid impedance control, which is able to create the movement and the force of robot such as the human's massage. Therefore, the various massage points, such as the change of the stiffness of human skin muscle, can be controlled by using impedance control method. The hybrid impedance control, comprised of the two methods of the position-based and the force-based impedance control, were applied. The position-based impedance control is used to control the lateral position of massage on the human skin muscle. On the other hand, the force-based impedance control is used to control the force of the vertical direction on human skin muscle. This paper also gives the identification of human skin muscle through robot perception of impedance to decide the parameter of impedance controller. The control strategy using impedance control to implement an adaptive control system is presented, when human condition is changed with soft and hard skin muscle. Effectiveness of massage control system by using multi-fingered robot hand with hybrid impedance control is demonstrated through actual massage experiments of pushing and rubbing motion.

1. INTRODUCTION

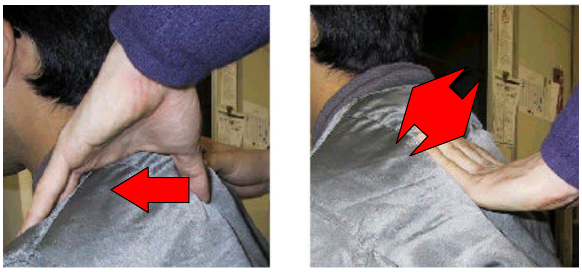
In recent years, a lot of research on multi-fingered robot hand have been studied. A multi-fingered robot hand can perform the grasping and the manipulating motion to handle objects, and can imitate the movement of a human hand (Nagai et al. [1994], Paljug et al. [1994], Howard et al. [1999]). However, these researches on multi-fingered robot hand have not given the concrete applications. Then, the authors have reported the research on human support and healthcare application of robotics and also multi-fingered robot hand (Kitagawa et al. [2002] - Tesashima et al. [2006]).

In author's group, the massage motion control for human shoulder by using feedforward type of Neural Network (NN's) with off-line learning was studied by Kitagawa et al. [2002]. In NN's method, two fingers of robot hand were applied, but the results of position and force control were insufficient, because the feedback controllers of both position and force were not included. In order to overcome this problem, a teaching-playback massage control system was developed by Minyong et al. [2003].

Feedback controllers were corporated with feedforward linearization compensation of robot's position and force. Based on these concept, authors reported that position control was used to control the robot fingertip position, until it touches shoulder. After touching, control system was switched from position control to force one. However, the lateral position is gradually shifted while doing force control for the vertical direction of human skin. Furthermore, in massage control, exact control for both of position and force is not necessary for the disturbance such as finger touches the human bone, for example. Then, robot finger is hoped to have compliance like a human finger.

Therefore, in this paper, hybrid impedance control comprised of position-based and force-based impedance control, is proposed to establish the suitable massage control system. By using impedance control technique to control the massage motion, the lateral position of the robot fingertip is controlled by position-based impedance control, while the fingertip force for the vertical direction of human skin is controlled by force-based impedance control. Hence, the massage point in the lateral can be fixed by position-based impedance control, while achieving force control of vertical direction by force-based impedance controller.

In this paper, two kinds of massage motion control are studied, where one is the pushing massage and another is the rubbing massage as shown in Fig.1. In the author's previous research (Kitagawa et al. [2002] - Tesashima et al. [2006]), the pushing massage motion control has only been done. The rubbing massage motion control is the first study all over the world in massage field using malti-fingered robot hand.



(a)Pushing (b)Rubbing

Fig. 1. Patterns of massage motion

2. MASSAGE ROBOT SYSTEM

The schematic diagram of massage system based on the multi-fingered humanoid type robot hand is shown in Fig. 2. The robot hand has 4 fingers with 13 joints. The 1^{st} finger has 4 joints and the 2^{nd} to 4^{th} fingers have 3 joints and they are arranged like human hands. The robot hand is attached at the tip of a robot arm with 5 joints.

The actuator for the robot hand is a small AC servomotor. The servomotor has an integrated harmonic gear (1/80) and encoder, and directly drives each joint. In this paper, the robot hand is controlled using the velocity mode of the servo driver. Therefore, the input torque τ of the robot hand is changed to the voltage by $v = K\tau$. Here, v[V] is the voltage supplied to the motor of robot hand. The constant K is the coefficient which changes the torque to the voltage, and was obtained by system identification. The calculation method of joint drive torque τ is explained later.

The fingertip force of the robot hand can be measured by fingertip type of 6-axis force sensors. For the measurement of a massage therapist's fingertip force, at first, the sheet type distribution pressure sensor, as shown in left hand side of Fig.2, is put on the hand of the therapist. Then, the therapist's fingertip force is measured when the therapist actually massages a human's body. However, this distributed pressure sensor can measure the pressure force of only the pushing direction. So, only one direction of force is considered in this research.

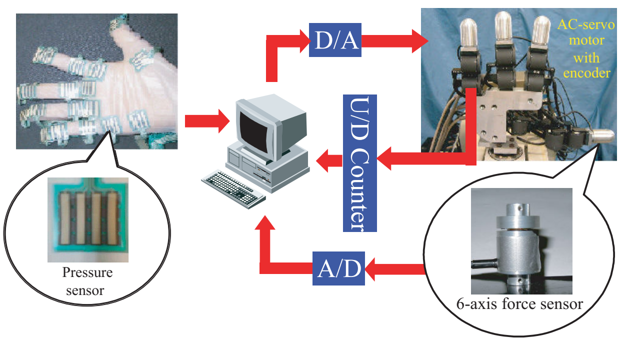


Fig. 2. Robot structure and massage system construction

3. IMPEDANCE CONTROL SYSTEM

The massage object is a human body, so the massage position is often shifted gradually during the massage by robot's force control. Thus, it is difficult to carry out the force control with keeping at the same position by fingertip force control.

To solve this problem for both of force and position control simultaneously, the hybrid impedance control is proposed for the massage control system by multi-fingered robot hand. In this control method, the position and force control are realized by the hybrid position and force impedance control. Furthermore, when the finger-tip touches the obstacle like a bone, the fingertip slip softly against the bone in order not to give the damage to the bone like a soft spring-damper. A conceptual diagram of impedance control of robot hand is shown in Fig. 3.

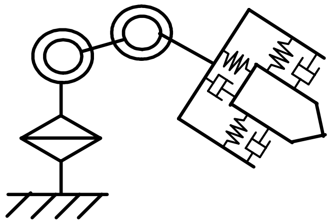


Fig. 3. Conceptual diagram of impedance control

3.1 Position-based Impedance Control

How to make the fingertip position of a robot hand follow a target position using impedance control is described. The mathematical formula of the desired impedance of massage control system with robot hand is shown in the below:

$$M_d(\ddot{x} - \ddot{x_d}) + D_d(\dot{x} - \dot{x}_d) + K_d(x - x_d) = f \qquad (1)$$

where x, $\dot{x}$ and $\ddot{x}$ are respectively the fingertip position, velocity and acceleration. And, x_d, $\dot{x}_d$ and $\ddot{x}_d$ are the reference position, velocity trajectory and acceleration until robot finger touches the object. Then, M_d, D_d, K_d and f are the desired mass coefficient, damper coefficient, spring coefficient and the action contact force on the fingertip from the environment,respectively.

A general dynamic equation of robot manipulator is shown in the below:

$$M(\theta)\ddot{\theta} + \hat{h}(\theta, \dot{\theta}) = \tau + J^T f \qquad (2)$$

where θ is the joint angle vector, $M(\theta)$ is an inertia matrix, $\hat{h}(\theta, \dot{\theta})$ is the Corriolis and centrifugal term, τ is the joint drive torque, J is a Jacobian matrix.

Thus, a position-based impedance control input from Eq.(2) becomes

$$\begin{aligned} \tau = M(\theta)J^{-1}[{M_d}^{-1}\{f + K_d(x_d - x) + \\ D_d(\dot{x}_d - \dot{x})\} - \dot{J}\dot{\theta}] + \hat{h}(\theta, \dot{\theta}) - J^T f \end{aligned} \qquad (3)$$

3.2 Force-based Impedance Control

It is possible to also make the finger-tip force follow the target force, realizing the desired impedance characteristics for the machine.

The desired impedance of massage force control system is given not by Eq.(1), but by Eq.(4), and in stationary state, the finger-tip force applied to objects agrees with target force.

$$M_d(\ddot{x} - \ddot{x}_d) + D_d(\dot{x} - \dot{x}_d) = f - f_d \tag{4}$$

Thus, a force-based impedance control input becomes

$$\tau = M(\theta)J^{-1}[M_d{}^{-1}\{f - f_d + D_d(\dot{x}_d - \dot{x})\} - \dot{J}\dot{\theta}] + \hat{h}(\theta,\dot{\theta}) - J^T f \tag{5}$$

3.3 Hybrid Impedance Control

Hybrid control comprised of position-based impedance and force-based impedance is described. Position-based impedance control is used for the horizontal direction (y,z-axis) of human skin muscle, and force-based impedance control is used for the vertical direction (x-axis) of human skin.

By performing the position-based impedance control horizontally, a massage point does not shift during a massage. Furthermore, by giving a force reference to the vertical direction (x-axis) and giving a position reference to the horizontal direction (y,z-axis), the rubbing massage motion, one-type pettern of massage, can be also realized.

The block diagram of impedance control of the massage system used in this paper is shown in Fig.4. Here, $f_x(\theta)$ is the notations to transform the variables of θ and $\dot{\theta}$ into the position x and also transform the velocity $\dot{x}$ via a Jacobian matrix of robot kinematics.

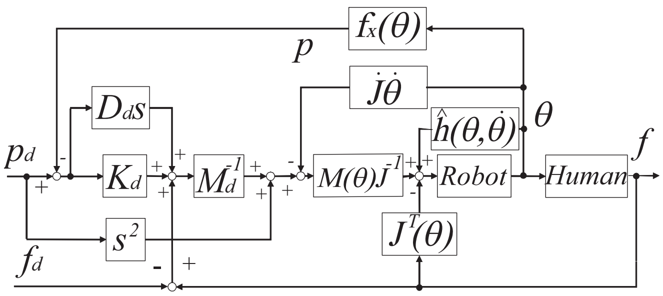


Fig. 4. Hybrid impedance control of massage system

Reference position, reference force, desired mass matrix coefficient, damper coefficient and spring coefficient is given as follows.

$$\boldsymbol{p}_d = [\,0\ \ y_d\ \ z_d\,]^T \in \Re^{3\times1} \tag{6}$$

$$\boldsymbol{f}_d = [\,f_{dx}\ \ 0\ \ 0\,]^T \in \Re^{3\times1} \tag{7}$$

$$\boldsymbol{M}_d = diag[M_{dx}, M_{dy}, M_{dz}] \in \Re^{3\times3} \tag{8}$$

$$\boldsymbol{D}_d = diag[D_{dx}, D_{dy}, D_{dz}] \in \Re^{3\times3} \tag{9}$$

$$\boldsymbol{K}_d = diag[0, K_{dy}, K_{dz}] \in \Re^{3\times3} \tag{10}$$

3.4 Experiments

Impedance control was applied to robot hand, and then the influence to robot hand was checked when external input was added to robot hand.

Table 1 shows the parameter values of K_d, D_d and M_d for each finger. Input to robot hand was 2[N] for all finger. Fig.5 shows the fingertip force and position in this condition.

Table 1. Impedance parameter of robot hand

Finger	K_d	D_d	M_d
1st	500	20	1
3rd	1000	20	1
4th	500	20	0.2

As seen from Fig.5, movements of fingertip position becomes small, when the value of K_d is given big. These results are reasonable.

Therefore, by applying hybrid impedance control, it was confirmed that robot hand can have the various compliance by changing the value of K_d, D_d and M_d. In order to establish flexible massage motion such as therapist, impedance control enables robot hand to have similar flexibility with human beings. Then, identification method is described in the following chapter to estimate parameter of human skin muscle model.

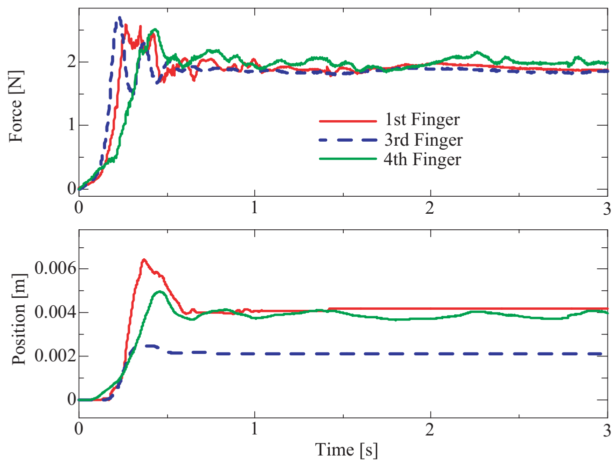


Fig. 5. Experimental results of impedance control

4. PARAMETER IDENTIFICATION OF HUMAN SKIN MUSCLE

This paper gives identification method of human skin muscle to decide the parameter of impedance controller, and also conduct the control simulation in order to predict the behavior of massage motion.

4.1 Parameter identification algorithm

In this paper, a spring-mass-damper model as shown in Fig.6 is used for a human skin muscle, and the human skin muscle model is represented by

$$f = M\ddot{p} + D\dot{p} + Kp + d \tag{11}$$

where $f(t) \in \Re^1$ is the fingertip force of robot, $p(t) \in \Re^1$ is the fingertip position of robot. K, D and M are spring, damping and mass coefficient, respectively.

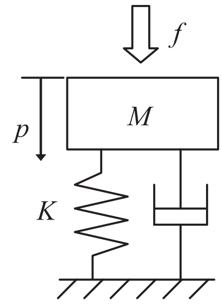


Fig. 6. Human skin muscle model

If Eq.(11) is discretized according to the literature of Kikuuwe et al. [2003], then it becomes

$$\phi_k = \Theta^T \psi_k \tag{12}$$

$$\phi_k = f_k + 2\ f_{k-1} + f_{k-2} \qquad \in \Re^1 \tag{13}$$

$$\psi_k = [\,1\ p_k\ p_{k-1}\ p_{k-2}\,]^T \in \Re^{4\times 1} \tag{14}$$

$$\Theta = [\,4c\ L_1\ L_2\ L_3\,]^T \in \Re^{4\times 1} \tag{15}$$

where $L_1 = K + 2D/T + 4M/T^2$, $L_2 = 2K + 8M/T^2$, $L_3 = K - 2D/T + 4M/T^2$ and k is a time step at time kT . Here, the derivation of L_1, L_2 and L_3 are written in the literature of Kikuuwe et al. [2003], and it is omitted.

Here, the performance index to determine skin muscle parameter of $\Theta = [4d, K, D, M]^T$ is given by

$$\begin{aligned}\min_{\theta} J_k(\Theta) &= \min_{\theta} \Sigma_{i=i_0}^{k} w_{k,i}(\phi_i - \Theta^T\psi_i)(\phi_i - \Theta^T\psi_i)^T \\ &= \min_{\theta}(\Theta^T \boldsymbol{R}_k \Theta - \Theta^T \boldsymbol{Q}_k - \boldsymbol{Q}_k^T \Theta + F_k)\end{aligned} \tag{16}$$

where $\boldsymbol{R}_k \cong \Sigma_{i=i_0}^{k} w_{k,i}\psi_i{\psi_i}^T$, $\boldsymbol{Q}_k \cong \Sigma_{i=i_0}^{k} w_{k,i}\psi_i{\phi_i}^T$, $F_k \cong \Sigma_{i=i_0}^{k} w_{k,i}\phi_i{\psi_i}^T$ and i_0 is a starting time to estimate the parameter. Furthermore, $w_{k,i}$ denotes the *forgetting factor* given by

$$w_{k,i} = r_k w_{k,i} \quad (k > i) \tag{17}$$

$$w_{k,i} = 1 - r_i \tag{18}$$

$$r_k = 2^{-\triangle u_k}, \triangle u_k = \min\left(\frac{T}{T_H}, \frac{\|p_k - p_{k-1}\|}{X_H}\right) \tag{19}$$

where T is a sampling time and T_H and X_H are the design parameters and they are determined by trial and error method. Further, $T = 2$[ms], $T_H = 0.1$ and $X_H = 0.015$ are used in this research, respectively.

The parameters are estimated such that J is minimized by using a Least Square Method. Then, the parameter estimation value of $\hat{\Theta}_k$ can be obtained by minimizing $J_k(\Theta)$ and it becomes

$$\hat{\Theta}_k = \boldsymbol{R}_k^{-1} \boldsymbol{Q}_k \in \Re^{4\times 1} \tag{20}$$

where $\hat{\Theta} = [4d, K, D, M]^T$. Finally, if we put $\hat{\Theta}' = [d, K, D, M]^T$, the following equation is obtained, and the estimation of parameter d, K, D, M can be identified.

$$\hat{\Theta}'_k = \boldsymbol{T}\hat{\Theta}_k \tag{21}$$

where

$$\boldsymbol{T} = \begin{bmatrix} 1/4 & 0 & 0 & 0 \\ 0 & 1/4 & 1/4 & 1/4 \\ 0 & Ts/4 & 0 & -Ts/4 \\ 0 & Ts^2/16 & -Ts^2/16 & Ts^2/16 \end{bmatrix} \tag{22}$$

Equation (22) is straightforwardly derived by Kikuuwe et al. [2003].

4.2 Experiments

For estimating the stiffness of human skin muscle, the force shown in a Fig.8 was inputted to human skin muscle. It is the input to a robot in order to estimate the parameter of the various stiffness (softness and hardness) of the object as shown in Fig.7. The left hand side in Fig.7 is the measurement point of soft one. On the other hand, the measurement point of hard one is shown in the right side of Fig.7. The stiffness of human skin muscle is estimated for x-direction, y-direction and z-direction at each point.

(a)Soft point (b)Hard point

Fig. 7. Measurement point of human body

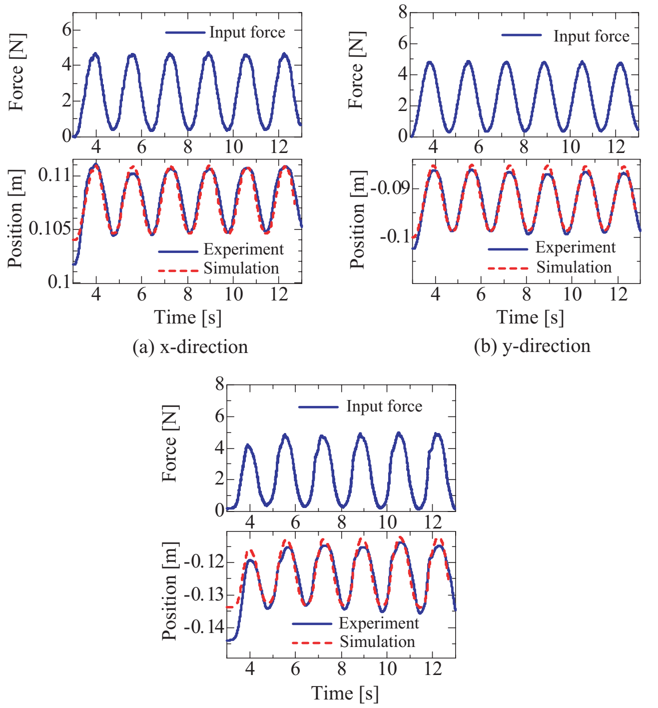
Reference input force is shown in Fig.8. The amplitude of the given input force was 5 [N]. When estimating horizontal direction (y,z-axis) of human skin muscle, the certain force was inputted to the vertical direction (x-axis) of human skin to prevent robot hand from shifting. Then, reference force was inputted horizontal direction (y,z-axis).

The estimation time was carried out after 1 [s] from the start of massage. The estimation parameters of human skin muscle in case of the soft point and the hard point at each directtion are shown in Table 2.

Fig.8 shows the comparison of the position output response between the estimated values calculated from the model of Eq.(11) and the measured position of robot fingertip in real experiments with the same input force. Simulation results almost agree with experimental results, and model validity was demonstrated.

Table 2. Estimated parameter of human skin muscle

	K	D	M
Soft position (x-axis)	706	16	0.0060
Soft position (y-axis)	324	17.6	0.0009
Soft position (z-axis)	217	9.5	0.0001
Hard position (x-axis)	1327	68	0.0180
Hard position (y-axis)	382	20.1	0.0004
Hard position (z-axis)	153	8.9	0.0025



(a) x-direction (b) y-direction (c) z-direction

Fig. 8. Estimation and experimental results of skin model

4.3 Parameter of impedance contoroller

The finger-tip position of a robot hand when massaging by the robot hand, and the relation of finger-tip force is shown in the below:

$$-f = M_o\ddot{x} + D_o\dot{x} + K_o x \tag{23}$$

where M_o, D_o and K_o are the human mass coefficient, damper coefficient and spring coefficient,respectively.

Adding Eq.(4) into Eq.(23), it can be expressed as

$$\begin{aligned} M_d(\ddot{x} - \ddot{x}_d) + D_d(\dot{x} - \dot{x}_d) &= \\ -M_o\ddot{x} - D_o\dot{x} - K_o x - f_d \end{aligned} \tag{24}$$

Here, the transfer function from the reference force to the fingertip position of a robot hand becomes a secondary delay system, and it can be expressed as

$$G(s) = -\frac{1}{(M_d + M_o)s^2 + (D_d + D_o)s + K_o} \tag{25}$$

The attenuation coefficient in this case becomes

$$\zeta = \frac{D_d + D_o}{2\sqrt{K_o(M_d + M_o)}} \tag{26}$$

An impedance parameter is decided such that this attenuation coefficient ζ is 1. The desired K_d and D_d was decided based on the impedance characteristics of soft human skin. M_d can be obtained by adding $\zeta = 1$ into Eq.(26). The impedance control parameter is shown in Table 3.

Table 3. Parameter of impedance controller

	K_d	D_d	M_d
Value	700	20	0.45

In this research, impedance characteristics of soft human skin is used as impedance parameter. By using this approach, the robot hand flexibly moves like a human against disturbance. If position control or Impedance control by using the impedance characteristics of hard human skin is used, the robot hand doesn't move flexibly like a soft spring. Therefore, the impedance control by using soft human skin is better than position control, or impedance control by using hard human skin.

5. PUSHING MASSAGE CONTROL

Pushing massage motion is reproduced by applying the proposed hybrid impedance control. "Pushing" is one of the massage techniques that give massage as if thumbs press into pressure points.

In this time, experiments were done by using third finger of robot hand to control the motion and force of robot fingertip. The position-based impedance control was used to control the massage position in y,z-directions, and force-based impedance control was used to control force in x-direction. Then, force reference is supplied in x-direction. Force reference is 5[N] amplitude and 0.6[Hz] frequency. A conceptual diagram of experimental condition is shown in Fig. 9.

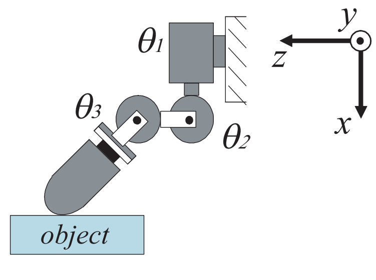


Fig. 9. Conceptual diagram of experimental condition

The experimental results of both the fingertip positions and fingertip force of 3^{rd} finger are respectively shown in Fig.10 and Fig.11. In addition, Fig.10 shows the experimental results of the soft point as shown in Fig.7 (a), while Fig.11 shows the experiment results of the hard point in Fig.7 (b). The experimental time is 10[s] and the sampling time is 2[ms]. The top, middle and bottom of each experimental results of Fig.10 and Fig.11 express the fingertip force, fingertip position and torque of each joint angles, respectively.

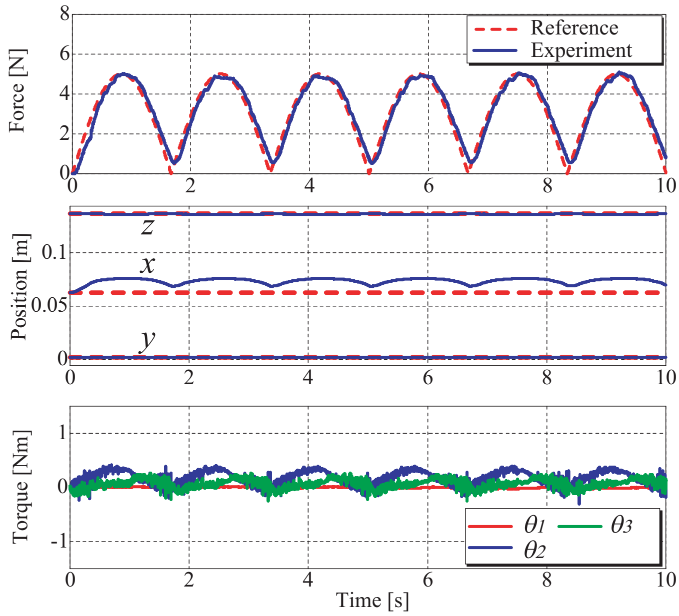


Fig. 10. Experimental results of the pushing massage motion for the 3^{rd} finger in the case of the soft point

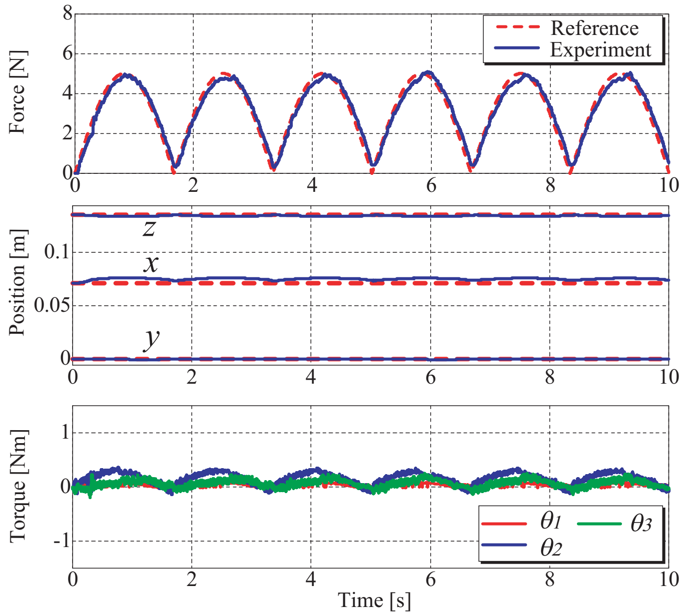


Fig. 11. Experimental results of the pushing massage motion for the 3^{rd} finger in the case of the hard point

From the experimental results of both cases, the fingertip position of robot hand was controlled by impedance control in y,z-direction, but the position of z-direction was a little moved. From the conceptual diagram of Fig.9, two motors are at x and z plane. Therefore, when moving to x-direction, a motion of a motor of θ_2 and a motor of θ_3 is completely exact, and if the synchronization cannot be taken, it will slightly shift in the z-direction.

For the fingertip force control, the maximum error of both the soft and hard case was less than 0.5[N]. The frequency and the amplitude of force exerted by the robot hand were also in good agreement with the force exerted by the expert therapist.

From these results, the position and force output well agreed with the reference values in the massage point of various stiffnes (softness and hardness). The massage motion was well achieved to realize by hybrid impedance control based on the identification of human skin muscle's impedance.

6. RUBBING MASSAGE CONTROL

"Rubbing" performs force-based impedance control in x-direction, with carrying out position-based impedance control in y,z-direction. The reference force of 3 [N] was given in x-direction, and the circular orbit of the radius 0.015 [m] was given in y,z-direction. Moreover, the obstacle was allocated as shown in Fig.12.

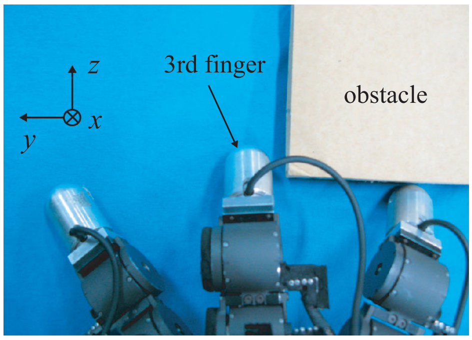


Fig. 12. Experimental condition of rubbing massage motion for the 3^{rd} finger

In this time, experiments were done by using 3^{rd} finger of robot hand to control the motion and force of robot fingertip. The experimental results of both the fingertip positions and fingertip force of 3^{rd} finger are respectively shown in Fig.13.

From the experimental result, target force of x-direction is well controlled. Moreover, the fingertip position of the robot hand on y,z-direction almost followed to the reference trajectry of the given circle. But, the small error exists between target position and fingertip position. The following reason is considered. In impedance control, a flexible motion is carried out to external force, and in the rubbing motion, friction force works in the y,z-direction. Therefore, a flexible motion is also carried out against frictional force, and the small gap has arisen in between the target position and the fingertip position of a robot hand.

Furthermore, from the experimental results, it was also checked to avoid the obstacle suitably. In impedance control, a robot hand avoided an obstacle flexibly according to the given impedance parameter. On the other hand, if position control is used, it goes to follow the position reference when there is an obstacle. Therefore, the big force will be applied to obstacles, such as a bone. Hence, the proposed control is very useful also for reducing the collision force.

If a spring coefficient is made small, force when colliding with an obstacle can also be made still smaller. However, if it is made small too much, the error between a target position and a finger-tip position will become large. Therefore, in this paper, the parameter of impedance controller was decided, based on the impedance characteristics of soft human skin. The adequate choice of these parameter will be a future problem for the optimum design.

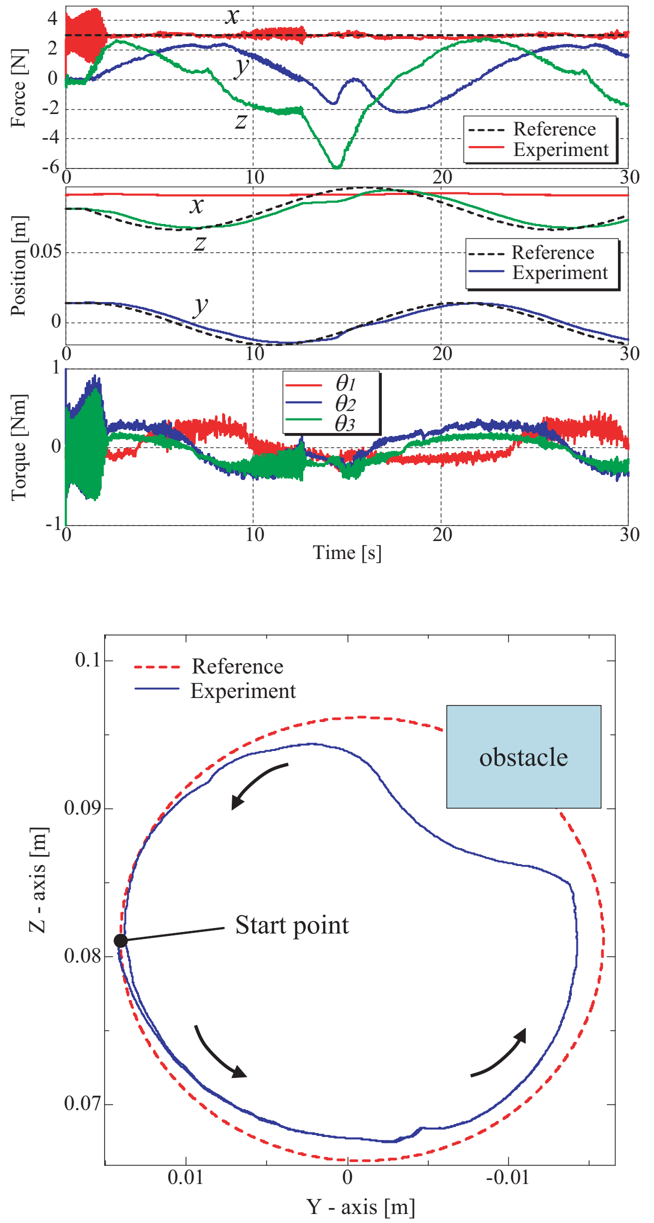


Fig. 13. Experimental results of the rubbing massage motion for the 3rd finger

7. EXPERT MASSAGE MOTION

Expert massage motion is reproduced by applying the proposed hybrid impedance control.

Massage force by therapist was detected by the sheet pressure sensor attached to therapist's hand. The detected force was given as reference of robot hand. Massage during 60 second has been conducted for the 1st to 4th finger. The situation of an experiment is shown in Fig.14.

Then force of z-direction, fingertip position of all direction, and torque of all joints were respectively as shown in Fig.15 - Fig.18.

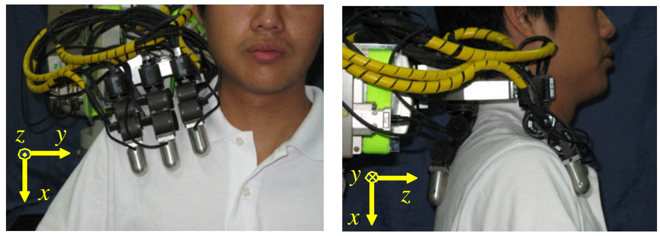


Fig. 14. Expert massage motion

As seen from these figures, massage motion by multi-fingered robot hand agrees well with expert massage by therapist, although the small difference between reference and experiments is found. Such deviation will be solved by improving control parameters, and it is now investigated.

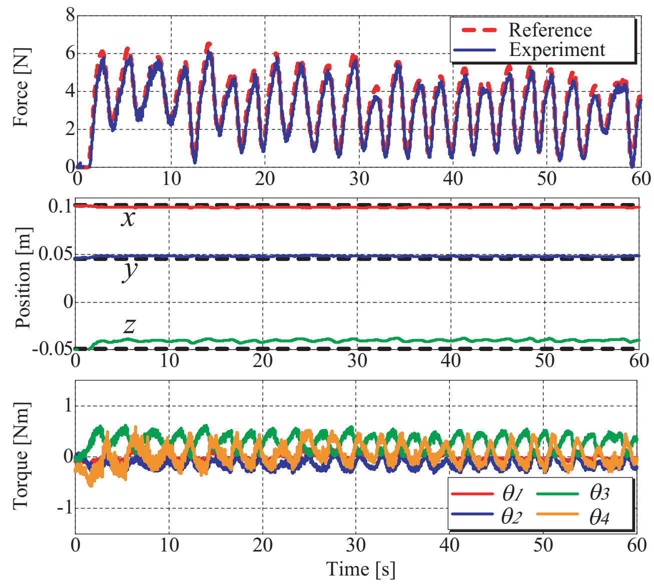


Fig. 15. Experimental results of expert massage motion by 1st finger

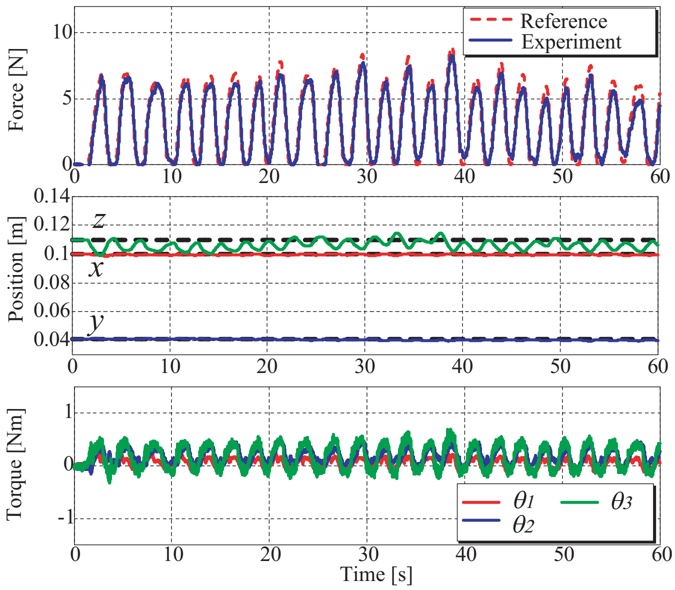


Fig. 16. Experimental results of expert massage motion by 2nd finger

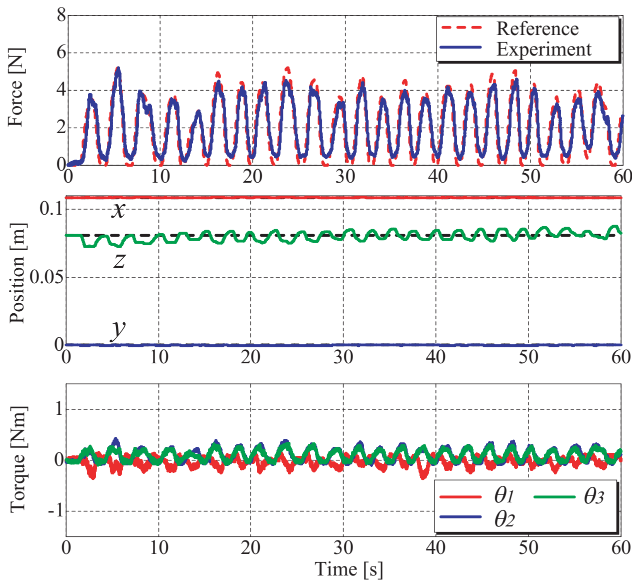


Fig. 17. Experimental results of expert massage motion by 3^{rd} finger

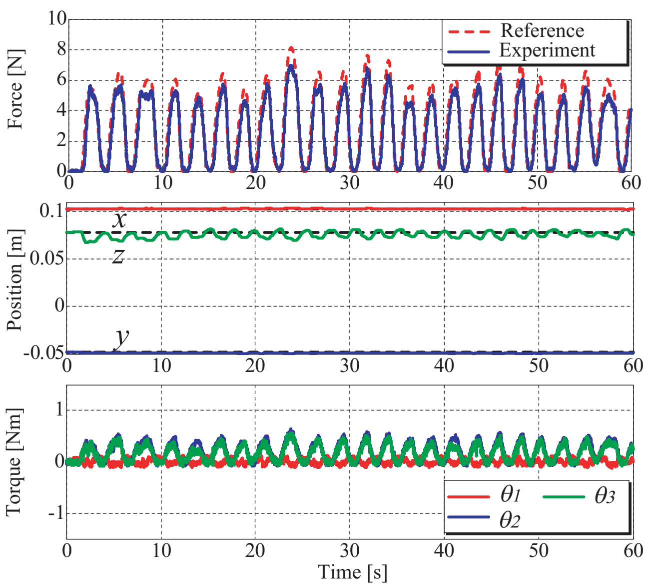


Fig. 18. Experimental results of expert massage motion by 4^{th} finger

Furthermore, autogeneration of reference force instead of expert therapist teaching is a future problem.

8. CONCLUSION

In this paper, a massage motion control system by using hybrid position-based and force-based impedance control method was proposed.

The impedance control parameter can be decided by using the estimated parameter of a human skin muscle with spring-mass-damper model. Furthermore, the pushing massage motion and the rubbing massage motion was reasonably reproduced by massage control system, respectively, using multi-fingered robot hand with hybrid impedance control.

From the above results, the hybrid impedance control was considerd as candidates of the suitable methods through a lot of experiments.

ACKNOWLEDGEMENTS

This work was supported by the 21st Century global COE Program of the Ministry of Education, Culture, Sports, Science and Technology of Japan "Intelligent Human Sensing".

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