SENSE FEEDBACK CONTROL OF HUMAN MUSCLE BY MULTI-FINGERED ROBOT HAND

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Abstract: This paper presents a massage motion control system comprised of position control and force control in a multi-fingered robot hand. First, the fingertip forces exerted by an expert human therapist was measured using sheet distribution pressure sensors, and the datas obtained was recorded in a computer. After the measurements were taken, the human expert's fingertip force was reproduced by the robot. Through simulation and experiments, the usefulness of the proposed control systems was demonstrated. Finally, in order to advance the present system, identification of human skin muscle was studied and the future concept of sense feedback control system was proposed.

Keywords: Position control, Force control, Human factors, Medical applications, PID control, Robot control

1. INTRODUCTION

Robots are needed for tasks and operations that must be performed with high speed and accuracy in various industrial fields. In recent years, however, special attention has been paid to the need for robots that can assist human beings with their health and welfare needs. Robots which can perform these specialized tasks require complex mechanisms, and the ability to realize complex motions like those performed by human beings.

Previously, welfare robots such as a walk support robot (Fujie, 1996), a food tray carrier (Kono and Kanda, 1998), and a meal assistance robot (Ishii, 1998) have been developed. In addition, there have been a number of studies on multi-fingered hand robots (Yoshikawa and Nagai, 1987), (Yoshikawa and Nagai, 1994). A multi-fingered hand can perform grasping and manipulating motions to handle objects, and can imitate the movements of a human hand (Koward and Kumar, 1999), (Paljug and Kumar, 1994).

Examples include such robots as Hadaly of Waseda University (*Humanoid Project Of Waseda University*, 1999), which is equipped with a manipulator on both arms that uses direct actuation, and the Gifu Hand of Gifu University (Komatsu and Kawasaki, 1998), which makes the same movements as a human hand. However, these researches did not give the hands concrete applications to perform. In addition, the author's, Toyohashi University of Technology (TUT), reported feedforward-type and Neural Networks(NNs) massage motion control for human shoulder by off-line learning in the TUT Hand robot (Kitagawa *et al.*, 2002). This research described how a two fingered hand was applied, but that both the force and position control were insufficient, because a feedback controller was not included due to the lack of a force sensor. Therefore, the massage motion of this hand was too limited. Because of this, researchers decided to design a multi-fingered hand such as a four-fingered hand (Minyong *et al.*, 2003). However, it took a great deal of time to solve the inverse problem presented by Neural Networks.

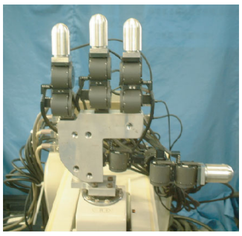


Fig.1 TUT hand with 6-axis force sensor

In this paper, an expert massage robot with hands that had four fingers and 13 joints was built to be used for welfare purposes. As a first step, the fingertip position control system and fingertip force control system in the massage motion were constructed. In addition, the fingertip force exerted by an expert human massage therapist was reproduced by the humanoid robot hand. The proposed control system was really applied to the human shoulder, and its usefulness was demonstrated via actual experiments.In order to advance the present system, human muscle model was built and identified. Then, based on this model, the future concept of autonomous sense feedback control for human muscle was addressed, which will be a great challenging problem to be solved.

2. MULTI-FINGERED ROBOT HAND'S SYSTEM

The multi-fingered, multi-jointed humanoid robot hand is shown in Fig.1. It has 4 fingers with 13 joints. The 1^{st} finger (thumb) has 4 joints, and the 2^{nd} to 4^{th} fingers have 3 joints and are arranged like those of the human hand. The thumb is opposable and redundant. It is 203.9[mm] length and 222.2[mm] width, about 1.2 to 1.5 times larger than an adult man's hand.

The small AC servomotor actuator for the robot hands is 30[mm] in diameter, 30[mm] length, 70[g] in weight, and generates 1.4 Watts. This small sized-motor was manufactured by the Yaskawa Electric Corporation (Minyong *et al.*, 2003). The servomotor has an integrated harmonic gear (1/80) and encoder, and directly drives each joint. The fingertip force sensors are the fingertip type of 6-axis force sensors made by BL Autotech Ltd., and is shown in Fig.2(a). By using this sensor, three components of force (F_x, F_y, F_z) and three components of momentum (T_x, T_y, T_z) could be measured. The human expert's fingertip forces was measured by sheet distribution pressure sensors, as shown in Fig.2(b). These sensors, which are manufactured by the Nitta Corporation, are comprised of 4 points × 4 points × 20 blocks, and have a measurement range of 0.02-0.2kgf/cm^2. By using the sheet-type force sensor as shown in Fig.2(b), the fingertip force exerted by the expert massage therapist was measured, and these measurements were recorded by computer. Next, the stored expert's fingertip force was reproduced by a robot hand, and the fingertip force of the robot hand was fedback with a 6-axis force sensor, as shown in Fig.2(a).

(a) 6-axis force sensor

(b) Sheet-type glove sensor

Fig.2 Force sensors

3. FINGER MOTION BY EXPERT MASSAGE THERAPIST

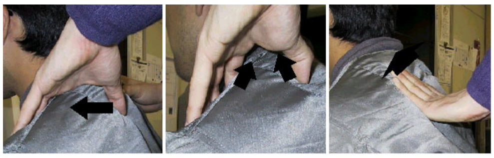
The typical kinds of finger movements performed by an expert massage therapist consists of "pushing," "picking up," and "rubbing" (Tanaka, 1993) as shown in Fig.3. Fig.3 illustrates the movements the massage expert performs when massaging the deltoid (shoulder) muscle.

"Pushing" is done strongly by the thumb, while the other fingers are used to support the person being massaged. The tips of the other fingers touch the body while the tip of the thumb is placed on the shoulder and pushes toward the tips, as shown in Fig.3. The location of the fingertips do not change very much.

"Picking up" includes the use of the thumb and the other finger, specifically the 2^{nd} - 4^{th} fingers, to lift the muscle of muscles being massaged. During this process, all fingertips grasp the shoulder muscle and lift it.

In "Rubbing," the human body is stroked by the palm and all fingers, as shown in Fig.3, while the thumb is kept close to the palm. This is accompanied by arm movements, the force of which is used to push the body of the person being massaged.

In these massage movements, "Rubbing" involves not only finger movements, but arm movements. "Pushing" and "Picking up" are executed by movements of the hands only. As the first step in designing an expert massage robot, the fingertip force control of "Pushing" was achieved by robot hands described in this paper.



(a)Push (b)Pick up (c)Rub

Fig.3 Patterns of massage.

4. CONTROL SYSTEMS OF MULTI-FINGERED ROBOT HAND

In this paper, the input torque τ to control the robot fingers was divided into two stages comprised of the position control input torque τ_p [Nm] and the force control input torque τ_f [Nm], as shown in Fig.4.

Fig.4(a) shows the control system of the 1^{st} finger with 4 joints, and Fig.4(b) shows the control system of the 2^{nd} - 4^{th} fingers. We would like to point out here that only the dotted part is different in (a) and (b) of Fig.4, and that we explain the reason later. In Fig.4, fingertip position control is conducted until the robot hand contacts an object. After contact is made, the fingertip position control is switched to the fingertip force control.

The control system shown in Fig.4 was applied to each finger. A detailed explanation of the control system shown in Fig.4 is given below.

4.1 Position Control

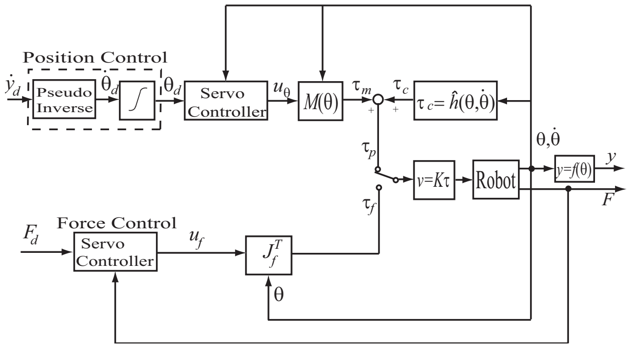
The fingertip position control input τ_p was obtained from the following equations.

$$\tau_p = \hat{h}(\theta, \dot{\theta}) + M(\theta)u_\theta \quad (1)$$

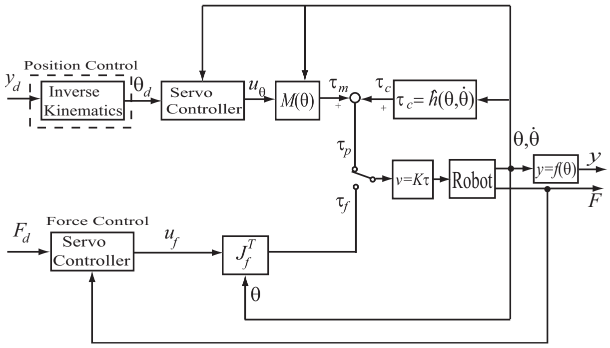
$$\hat{h}(\theta, \dot{\theta}) = h(\theta, \dot{\theta}) + g(\theta) + f(\theta) \quad (2)$$

,where τ_p is the joint drive torque of a fingertip position, $M(\theta)$ is inertia matrix, $h(\theta, \dot{\theta})$ is the centrifugal and Coriolis terms, $g(\theta)$ is gravity term, $f(\theta)$ is friction term, and u_θ is a servo compensator for the linearized compensation.

Although the 1^{st} finger of this robot hand has redundancy, the redundancy solution of the 1^{st} finger can be solved by giving a position reference with the time function of $r_{1d}(t)$, being the trajectory of the primary task, and with the time function of $r_{2d}(t)$ being the trajectory of the secondary task.



(a) Control system of the 1^{st} finger



(b) Control system of the 2^{nd} - 4^{th} fingers

Fig.4 Control system of multi-fingered robot hand

Further, a reference trajectory r_{1d} is completely realized, when the trajectory of secondary task r_{2d} is set to be $r_{2d} = \theta(t)$ =constant, where in this paper, secondary task was given as $r_{2d} = [0.4264, -1.1215, 1.1664, 1.2794]^T$.

However, the 2^{nd} - 4^{th} fingers of this robot hand have singular points, although there is no redundancy. These singular points can be avoided by solving the inverse kinematics problem, instead of using a fingertip trajectory tracking control system. By solving the inverse kinematics problem, each joint angle $\theta(t)$ is calculated from the position of the fingertip, $r(t) = [r_x(t), r_y(t), r_z(t)]$. The error between the actual joint angle $\theta(t)$ and the desired angle $\theta_d(t)$ can be compensated for by the feedback servo-controller. Then, the torque of each joint can be gotten by Eq.(1).

PID servo controller was used to compensate the error of the fingertip position as shown in Fig.4, and the u_θ^i was obtained as follows:

$$\boldsymbol{u}_\theta^i = \ddot{\boldsymbol{\theta}}_d^i + K_{pP}^i \boldsymbol{e}_\theta^i + K_{pI}^i \int_0^t \boldsymbol{e}_\theta^i dt + K_{pD}^i \dot{\boldsymbol{e}}_\theta^i \quad (3)$$

$$(i = 1, 2, 3, 4)$$

Table 1.PID controller gain of the fingertip position control

i^{th} Finger	K^i_{pP} $(\times 10^3)$	$K^i_{pI}(\times 10^2)$	$K^i_{pD}(\times 10^1)$
1^{st}	diag[1.2, 2.5, 5.5, 5.5]	diag[2.5, 2.5, 5.0, 5.0]	diag[2, 2, 2, 2]
2^{nd}	diag[1.0, 15.0, 3.0]	diag[3.0, 9.5, 2.5]	diag[3, 3, 3]
3^{rd}	diag[1.5, 2.5, 2.5]	diag[2.5, 2.5, 4.5]	diag[2, 2, 2]
4^{th}	diag[1.5, 2.5, 5.0]	diag[2.5, 2.5, 3.5]	diag[3, 5, 5]

,where $\boldsymbol{u}^i_\theta$ is a vector ($i = 1, \boldsymbol{u}^i_\theta \in R^4; i = 2,3,4, \boldsymbol{u}^i_\theta \in R^3$), e_θ denotes the fingertip angle error of $\theta_d - \theta$. Notation of i denotes i^{th} finger. In this paper, K_{pP}, K_{pI} and K_{pD} were determind by simulation and experiment as shown in Table 1.

In this paper, the multi-fingered robot hand is controled with velocity mode of servo driver. Therefore, input torque τ of robot hand is changed to voltage by $v = K\tau$. Here, $v[V]$ is voltage supplied to a motor of robot hand. Constant K is the coefficient which changes torque to voltage, was obtained from identification.

4.2 Force Control

The force control of massage motion was also shown in Fig.4, such that the required fingertip force was expressed as

$$\tau^i_{fj} = \boldsymbol{J}^{iT}_f \boldsymbol{u}^i_f \qquad (4)$$

,where i denotes the i^{th} finger, j is the j^{th} joint of i^{th} finger, $\boldsymbol{u}^i_f = [u^i_{fx}, u^i_{fy}, u^i_{fz}]^T$, $\boldsymbol{J}^{iT}_f$ is a transpose of Jacobain matrix which was given by $\boldsymbol{J}^i_f = \boldsymbol{J}^i_f = \frac{\partial \boldsymbol{r}^i}{\partial \boldsymbol{\theta}^i_j}$, and $\boldsymbol{r}^i$ is a position of fingertip for the i^{th} finger, and $\boldsymbol{\theta}^i_j$ is the angle of the j^{th} joint for the i^{th} finger. Further, $\boldsymbol{r}^i = [r^i_x, r^i_y, r^i_z]^T$. Now, for the 1^{st} finger, $i = 1, j = 1,2,3,4$; for the 2^{nd} - 4^{th} fingers, $i = 2,3,4, j = 1,2,3$.

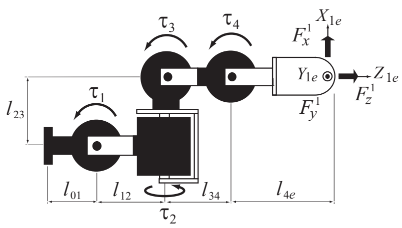


Fig.5 Side view of the 1^{st} finger

The case of the 1^{st} finger is shown in Fig.5. For the 2^{nd}- 4^{th} fingers, they are same coordination and same structure and size. As a representative, the 2^{nd} finger is shown in Fig.6.
PI control is used to realize the tracking control of the fingertip force. The $\boldsymbol{u}^i_{f(\cdot)}$ was obtained as follows:

$$\boldsymbol{u}^i_{f(\cdot)} = \boldsymbol{K}^i_{fP(\cdot)} \boldsymbol{e}^i_{f(\cdot)}(t) + \boldsymbol{K}^i_{fI(\cdot)} \int_0^t \boldsymbol{e}^i_{f(\cdot)}(s) ds \qquad (5)$$

$$(i = 1,2,3,4)$$

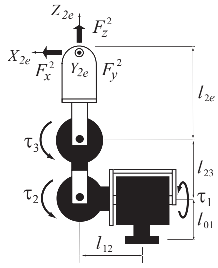


Fig.6 Side view of the 2^{nd} finger

,where $\boldsymbol{e}^i_{f(\cdot)}$ denotes $\boldsymbol{e}^i_{f(\cdot)}(t) = \boldsymbol{F}^i_{d(\cdot)}(t) - \boldsymbol{F}^i_{(\cdot)}(t)$ and $\boldsymbol{F}^i_{d(\cdot)}$ is a reference fingertip force. $\boldsymbol{F}^i_{(\cdot)}(t)$ is an output fingertip force of the i^{th} finger, and $(\cdot)$ demotes x, y and z, respetively, Notation, $\boldsymbol{u}^i_{f(\cdot)} \in R^{3\times1}$, $K^i_{fP(\cdot)} \in R^{3\times3}$, $K^i_{fI(\cdot)} \in R^{3\times3}$, $\boldsymbol{e}^i_{f(\cdot)} \in R^{3\times1}$. In this paper, $\boldsymbol{K}^i_{fP(\cdot)}$ and $\boldsymbol{K}^i_{fI(\cdot)}$ was respectively shown in Table 2.

Table 2.PI controller gain of fingertip force control

i^{th}Finger	$K^i_{fP(\cdot)}$	$K^i_{fI(\cdot)}$
1^{st}	diag[50, 0, 0]	diag[40, 0, 0]
2^{nd}	diag[40, 0, 0]	diag[30, 0, 0]
3^{rd}	diag[40, 0, 0]	diag[30, 0, 0]
4^{th}	diag[45, 0, 0]	diag[35, 0, 0]

5. EXPERIMENTAL RESULTS OF EXPERT MASSAGE MOTION BY ROBOTS

In order to produce the reference force data for the robot hand finger, the actual "pushing" force data from the 1^{st} to 4^{th} fingers performed by an expert massage therapist was measured by making the expert wear a rubber glove with sheet pressure sensors, as shown in Fig.7. To measure its fingertip force, the sheet pressure sensor shown in Fig.2(b) can measure only the vertical direction for the contacting surface. Therefore, only the F_x component could be measured, and the F_y and F_z components were zero. In addition, the reference trajectory of the fingertip position was given with trapezoidal velocity, such that the initial position of the fingertip could be transferred to the end-point position.

Fig.8 shows the massage control by using a robot hand to massage the human shoulder. At the first, the palm state of all fingers is set to be opened, and then, the fingertip position of robot hand was controlled by feedback control, as explained in section 4.1, until the fingers touched the shoulder during 3[s]. After all the fingers touched the shoulder, the fingertip position control was switched to the fingertip force control. After switching to the

Fig.7 Teaching by an expert massage therapist

Fig.8 Massage motion control by robot hand

fingertip force control, the fingertip position was not controlled. The experimental results of both the fingertip positions and fingertip forces are shown in Fig.9-Fig.10. In addition, the experiment time was 30[s] and the sampling time was 2[ms].

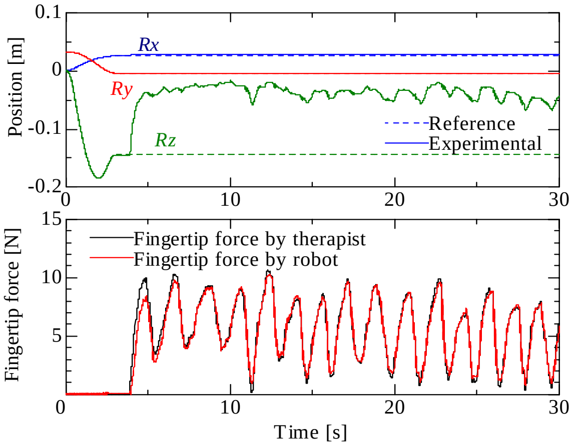


Fig.9 Experimental results of the 1^{st} finger for massage control

The robot's massage motion was in good agreement with the expert massage motion performed by the therapist, because the maximum error was 0.4[N], and the period and amplitude of the massage motion were almost the same.

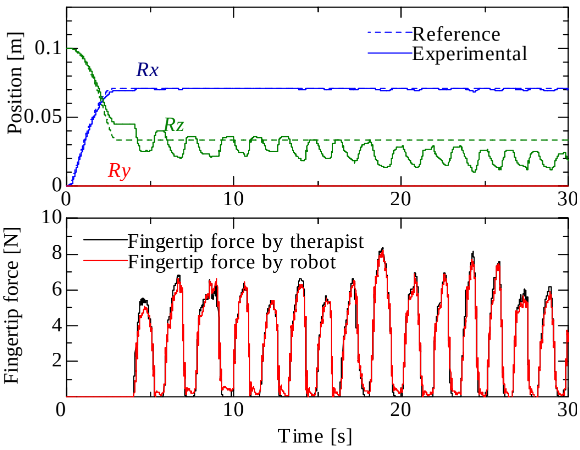


Fig.10 Experimental results of the 4^{nd} finger for massage control

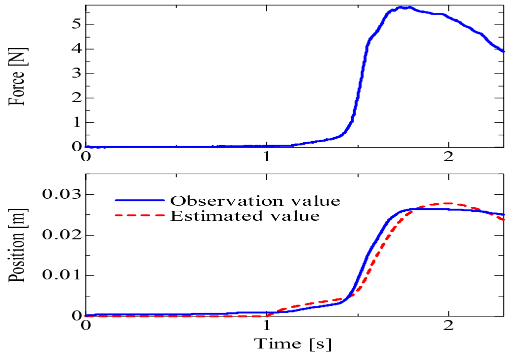
6. DISCUSSION ON AUTONOMOUS SENSE FEEDBACK CONTROL FOR RELAXATION OF HUMAN BODY AND HEART

In the present paper, feedback controller design for force-sense feedback was conducted by trial-and-error method of experiments. The reason is owed to the lack of human muscle model in block diagram of Fig.4.

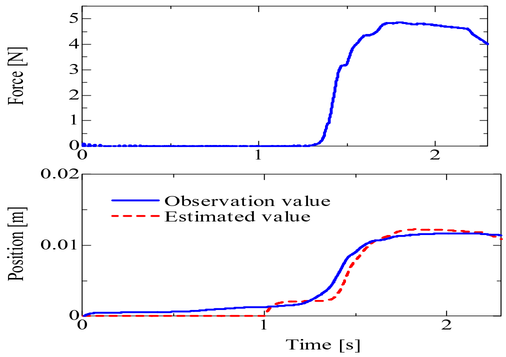
Hence, in order to realize the reasonable control design, the model representing human skin muscle must be built.Then, we are now considering a spring-mass-damper model as human muscle model in the following:

$$f(x) = M\ddot{x} + C\dot{x} + kx + d \qquad (6)$$

when f:force, M:mass, C:damping coefficient,K:spring coefficient, d : deviation of equilibrium points and$x(t)$:position.



(a) Human arm (soft-side)



(b) Human palm (hard-side)

Fig.11 Identification result of human muscle

Each parameter was identified by least-square-method (Kikuuwe and Yoshikawa, 2003). Simulation results agreed well with experimented results. Especially, the difference between hard and soft muscle were well represented by model. Detailed study on model building for human muscle are now being done, and will report it in near future.

Fig.12 shows the future autonomous sense feedback control system proposed by authors using the information of force and position of muscle and autonomic nerve such as EMG, brain wave and blood flow. For relaxation of human body and heart, it is now studied by authors. The construction of the proposed autonomous sense feedback system is as follows:

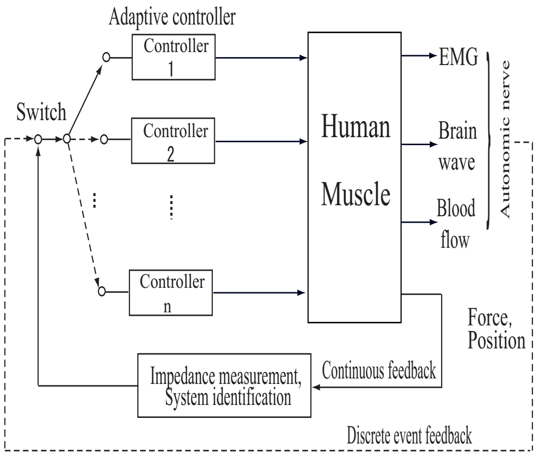


Fig.12 Autonomous sense feedback control system of Human muscle for relaxation of human body and heart

First, the human muscular model is identified in real time. Second, based on this impedance measurement, adaptive controller is applied such as self-tuning controller, or, gain scheduling controller as shown in Fig.12. In real massage by therapist, professional therapist executes massage motion strongly when the pushing part is hard, or stiff, and vice versa. Thus, by adequately using the information of system identification, reference and controller will be suitably switched for hybrid dynamical system. Further, this system includes fedback control by using autonomic nerve information such as EMG, Brain wave, and blood flow. However, this information is feedback in longer sampling period, compared with that of force and position.

By using these information, adaptive massage robot will be completed, which can be applied for any people in any time. It is worthy that this paper is a basic research to realize the autonomous sense feedback control of Human musscle in near future.

Under this concept, we are now studying to develop the autonomous control system described in Fig.12

7. CONCLUDING REMARKS

In this paper, a massage control system using a humanoid robot hand was built. The robot hand could perform a massage similar to that performed by a human expert massage therapist, with a safe amount of fingertip force.Throughout this paper, the massage operation of "pushing" was considered for the embodiment of an idea. The results obtained here show that it is possible to develop an expert massage system capable of performing more general massage motions. Further, model of skin muscle were introduced, and the concept of autnomous sense feedback control system for human muscle were discussed to develop the present paper towards future.

Acknowledgments

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