Modeling of Human Skin Muscle and Massage Control by Using Multi-fingered Robot Hand

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Abstract: The purpose of this paper is to propose adaptive and flexible expert masssage robot using multi-fingered robot. Towards this goal, the present paper gives a modeling of human skin muscle through robot perception of impedance, and control strategy using impedance control to implement adaptive control system, even if human condition is changed, or massage position is shifted, and person to be massaged is different. The model validity is demonstrated via many experimants by using multi-fingered robot hand and human body. Based on robot perception of human muscle impedance, control strategy for developing an adaptive massage robot and impedance control are proposed by givining the concept of controller switching and sense feedback.

Keywords: Human skin muscle model, multi-fingered robot hand, massage control.

1 Introduction

In recent years, a lot of research on muli-fingered robot hand have been studied. A multi-fingered robot hand can perform the grasping and manipulating motions to handle objects, and can imitate the movements of a human hand [1]-[8]. However, these researches on multi-fingerd robot hand did not give the concrete applications [1]-[4]. Then, the authors have reported researches on human support and healthcare application of robotics and also multi-fingered robot hand [5]-[8].

Authors presented feedforward-type and Neural Network (NN's) [8] massage motion control for human shoulder by off-line learning in TUT (Toyohashi University of Technology) robot hand. This research described how a two fingered hand was applied, but both results of 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.

In order to solve this restriction, feedback controller in adittion to linearization compensation was constructed for four fingered hand. In the literature [5], [7], position control was used before fingertip of robot hand touches to shoulder, and after touching, controller was switched from position control to force control. Reference massage force was taught by expert therapist, and those data were memoried into computer by using sheet sensor. These teaching data were realized by robot hand using teaching-playback method. Reference force was exactly achieved by using fedback control. Precision of reproduction by robot of expert massage of therapist was well realized [5], [7]. Massage motion should be suitably executed according to the current state of the human skin muscle. However, in the previous system, reference massage motion must be taught by therapist's teaching whenever the change of human body condition and massage position were occurred. Further, feedback controller was experimentally determined by try and error method, because human muscle was assumed to be a rigid body. Therefore, theoretical analysis and simulation analysis for force control were impossible. Hence, development of auto-tuning adaptive massage robot is expected to appropriately adjust massage motion following to the impedance of human skin muscle.

In present society, there are many health support machine such as massage machines [12] - [14]. Especially, in Japan, highly developed massage machine was produced [14]. Many pattern of massage motion are installed according to body condition and human preference, and adjusted by manually switching. Further, massage motion of most massage machine is realized by using roller's movement and swing. Then, the movable places for massage by the present machine is limitted, and it is expected to extend the possible region to conduct the massage. Therefore, the development of flexible massage robot by using multi-fingered hand is a challenging subject, in recent decades.

Thus, in this paper, we present a model of human skin muscle by using multi-fingered robot hand to know impedance of human skin muscle and control strategy by means of impedance control to implement adaptive control system, even if human condition is changed, or massage position is shifted, and person to be massaged is different.

First, actuator and sensor systems on an expert massage robot with hands that had 4 fingers and 13 joints are explained. Second, human muscle model is built and identified. Here, a kind of spring-mass-damper model is applied for robot perception of impedance. Experimental results are addressed, and model validity has been shown. Furthermore, adaptive control strategy using impedance control is proposed to execute appropriate massage motion, based on the human muscle.

2 Massage Robot 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 has 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 servo motor actuator for the robot hand is 30 [mm] in diameter, 30 [mm] length, 70 [g] in weight, and generates 1.4 [Watts]. The small sized-motor was manufactured by the Yaskawa Electric Corporation. The servomotor has an integrated harmonic gear (1/80) and encoder, and directly drives each joint. The fingertip force sensor is 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 could be also 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 $\times$ 4 points $\times$ 20 blocks, and have a measurement range of 0.02 - 0.2 [kgf/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(b).

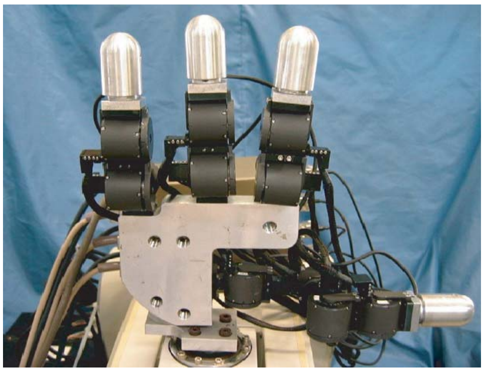
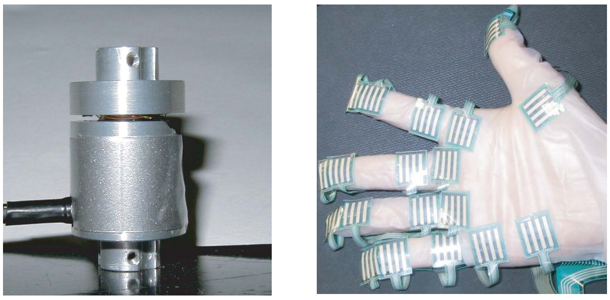


Figure 1: TUT hand with 6-axis force sensor



(a) 6-axis force sensor (b) Sheet-type glove sensor

Figure 2: Force sensors

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

"Pushing" is done strongly by 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 (a). The location of the fingertips do not change very much.

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

In"Rubbing", the human body is stored by the palm and all fingers, as shown in Fig. 3 (c), 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 the massage movements, "Rubbing" involves not only finger movements, but also arm movements.

"Pushing"and "Picking up" are executed by movements of the hands only. As the first step on designing an expert massage robot, the fingertip force control of "Pushing" was achieved by robot hands described in this paper

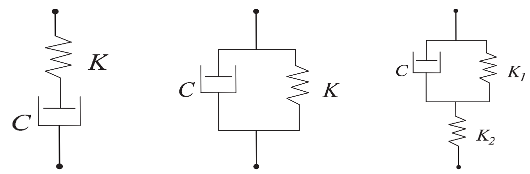
(a) Push (b) Pick up (c) Rub

Figure 3: Pattern of massage

Figure 4: Massage motion control by robot hand

3 Modeling of human skin muscle and parameter estimation

As human skin model, a lot of models are proposed by using viscosity-elastic theory. However, each model is insufficient, and therefore it is impossible to completely explain all phenomena of muscle state by one model [9], [10]. Some of these models are shown in Fig. 5.



(a) Maxwell model (b) Kelvin (Voigt) model (c) 3-element model

Figure 5: Visco-elasticity model

Then, in this paper, we shall consider spring-mass-damper model with the correction term of error, and also consider to investigate the state of human skin muscle in real time.

Skin muscle model is represented by

$$f(t) = d + Kp(t) + C\dot{p}(t) + M\ddot{p}(t) \tag{1}$$

, where $f(t) \in R^1$; fingertip force of robot hand, $p(t) \in R^1$; fingertip position of robot hand, K; spring coefficient, M; mass weight, C; damping coefficient, and d; deviation.

If "(1)" is discretized, then it follows

$$\phi_k = \Theta^T \psi_k \tag{2}$$

, where

$\phi_k = f_k + 2f_{k-1} + f_{k-2} \in R^1$, $\psi_k = [1, p_k, p_{k-1}, p_{k-2}] \in R^4$, $\Theta = [4d, L_1, L_2, L_3]^T$, $L_1 = K + \frac{2C}{T} + \frac{4M}{T}$, $L_2 = 2K - \frac{8M}{T^2}$, $L_3 = K - \frac{2C}{T} + \frac{4M}{T^2}$ and k is a time step at time kT.

Then, the forgetting factor is given by

$$w_{k,i} = r_k w_{k-1,i} \qquad (k > i) \tag{3}$$

$$w_{k,i} = 1 - r_k, \qquad r_k = 2^{-\Delta u_k}$$

$$\Delta u_k = min\left(\frac{T}{T_H}, \frac{\parallel p_k - p_{k-1} \parallel}{X_H}\right) \tag{4}$$

, where T is sampling time, and T_H and X_H are design parameter. In this research, we used T = 1 [ms], T_H = 0.1, X_H = 0.015.

Here, performance index to determine the estimated parameter $\Theta = [4d, K, C, M]^T$ is given by

$$\begin{aligned} J_k(\Theta) &= \sum_{i=i_0}^{k} w_{k,i}(\phi_i - \Theta^T\psi_i)(\phi_i - \Theta^T\psi_i)^T \\ &= \Theta^T \boldsymbol{R}_k \Theta - \Theta^T \boldsymbol{Q}_k - {\boldsymbol{Q}_k}^T \Theta + \boldsymbol{F}_k \end{aligned} \tag{5}$$

, where $\boldsymbol{R}_k \triangleq \sum_{i=i_0}^{k} w_{k,i}\psi_i{\psi_i}^T$, $\boldsymbol{Q}_k \triangleq \sum_{i=i_0}^{k} w_{k,i}\psi_i{\phi_i}^T$, $\boldsymbol{F}_k \triangleq \sum_{i=i_0}^{k} w_{k,i}\phi_i{\phi_i}^T$, and i_0 is a starting time to estimate the parameter.

Explanation about the forgetting factor of "(3)" and "(4)" follows. When motion is fast, the position shift will be large every sampling, while the position shift will be small if motion is slow.

Thus, it is thought to be reasonable that the data should be forgotten in constant rate if the position shift is large. On the other hand, the past data should be stored during long interval without forgetting soon if the position shift is small in every sampling.

Parameter is estimated such that J is minimized. The details of deriving parameter estimation is written in the literature [11] for robot perception of impedance which is a kind of Least Square Method.

Then, the parameter estimation value $\hat{\Theta}_k$ becomes

$$\hat{\Theta}_k = {\boldsymbol{R}_k}^{-1}\boldsymbol{Q}_k \qquad \in R^4 \tag{6}$$

Here, if we put $\hat{\Theta}'_k = [d, K, C, M]^T$, the following equation is obtained, and the parameter $\{d, K, C, M\}$ can be identified.

$$\hat{\Theta}'_k = \boldsymbol{T}\hat{\Theta}_k \tag{7}$$

, where

$$\boldsymbol{T} \triangleq \begin{bmatrix} 1/4 & 0 & 0 & 0 \\ 0 & 1/4 & 1/4 & 1/4 \\ 0 & T_s/4 & 0 & -T_s/4 \\ 0 & T_s^2/16 & -T_s^2/16 & T_s^2/16 \end{bmatrix} \tag{8}$$

Fig. 6 shows the simulation results to estimates the parameters of "(1)". Reasonable estimation results were obtained by the present identification method. Then, each parameter of M, K, C and d were well estimated as shown in Fig. 6.

Fig. 7 shows the measurement position to measure the impedance of human arm (a) and hand (b). Position (a) is the hard side of human hand, and position (b) is the soft part of human arm. Experimental results to check the model validity were shown in Fig. 8 and Fig. 9.

Reference input force with amplitude of 5 [N] and period of 1.884 [rad/sec] was given from robot finger to human skin muscle in experiments.

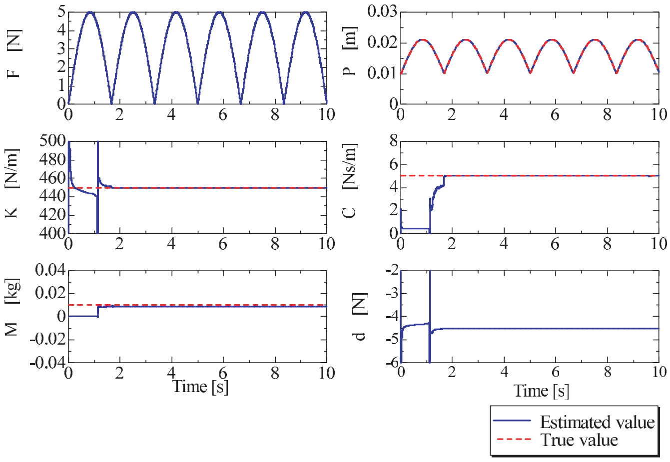


Figure 6: Simulation results to estimate *M, K, C* and *d*

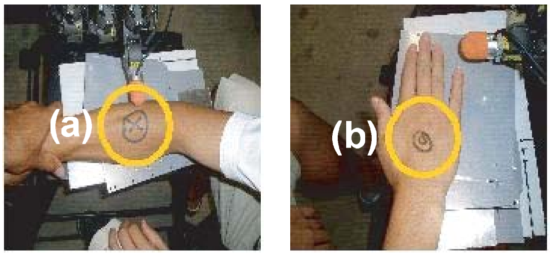


Figure 7: Measurement position of human body

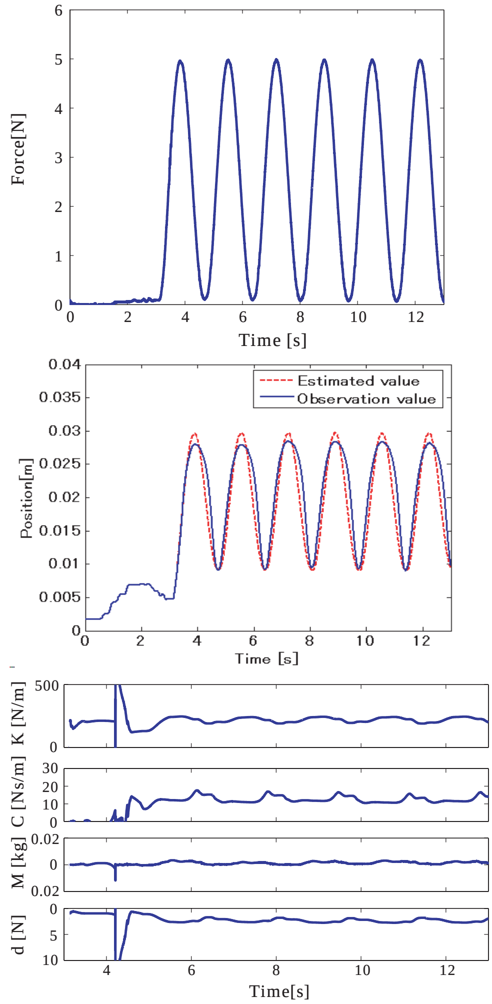


Figure 8: Experimental results of model validity (at the position (a))

Table 1: Estimated parameter of human skin muscle for each position

	K	C	M	d
(b)	879.9	27.61	0.0128	-17.31
(a)	233.29	11.41	0.0015	-2.38

Table 1 shows the estimated values of K,C,M and d for the measured position (a) and (b), while Fig. 8 and Fig. 9 shows the comparison between observation value in real experiments and estimated value calculated from model of "(1)" using the estimated parameter. From both results, model validity was shown.

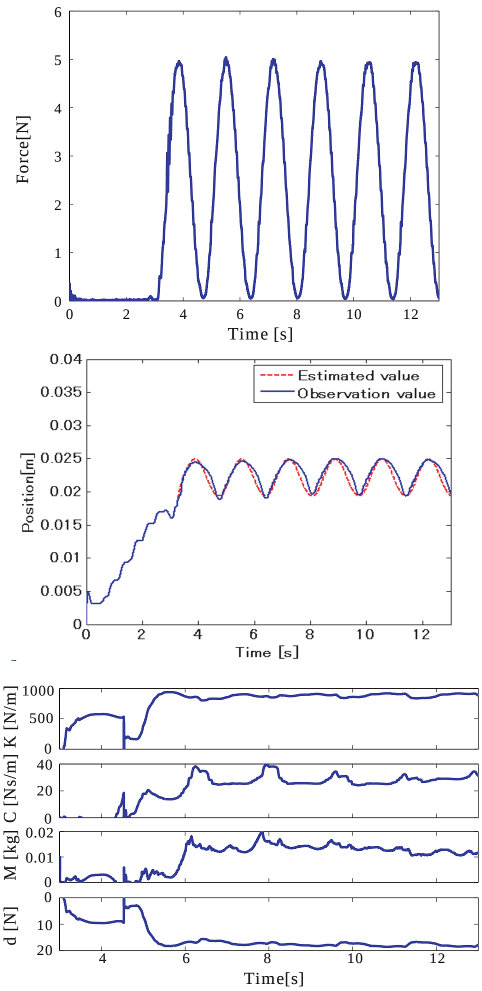


Figure 9: Experimental results of model validity (at the position (b))

4 Control Strategy of massage robot

Control strategy of expert massage robot which can adapt for human muscle condition is shown in Fig. 10.

Human muscle condition by robot perception of impedance is estimated, and then based on the muscle condition, controller is suitably selected. For example, strong impedance control is executed for the hard muscle, while weak impedance control for the soft muscle. Impedance of human muscle is measured by means of force and position's information using multifingered robot hand in short sampling period such as 10 [msec]. Furthermore, sense information such as blood pressure, cardiac rate, brain wave, etc is measured in long sampling period such as 60 [s], and hence, massage control will be appropriately adapted by feedback of both impedance and sense information.

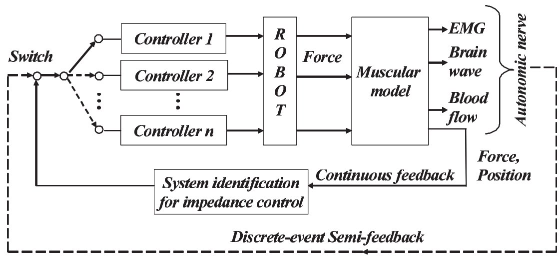


Figure 10: Schematic diagram of adaptive control system for developing expert massage robot

As a basic study to implement a final goal shown in Fig. 10, impedance control was designed, where the impedance controller [15] - [17] is shown as controller i (i = 1, 2, ... n). In the pushing massage control after robot hand touches the skin muscle, position control is useless because comfort is obtained by the force added to the skin muscle. However, only force control is not sufficient, because force magnitude should be changed following the body position and conditions. Further, simultaneous control of force and position is not possible, because the shift quantity of skin muscle by pushing is uniquely determined by the given finger force according to the impedance characteristics of human skin muscle.

Therefore, from the above viewpoint, impedance control is thought to be most adequate control method, if we apply the impedance control appropriately according to the current impedance characteristics of human skin muscle.

Block diagram of impedance control used in this paper is shown in Fig. 11.

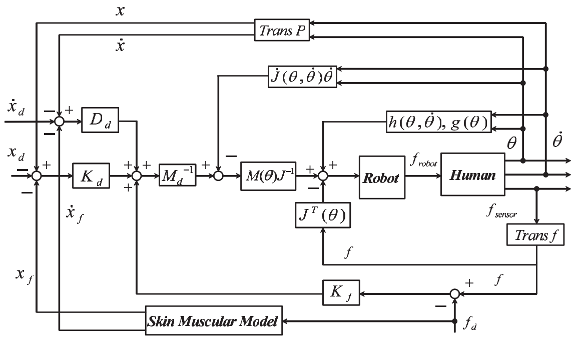


Figure 11: Block diagram of impedance control

Impedance characteristics of impedance control is given by

$$\begin{aligned} &\boldsymbol{M}_d\ddot{\boldsymbol{x}} + \boldsymbol{D}_d(\dot{\boldsymbol{x}} - \dot{\boldsymbol{x}}_d - \dot{\boldsymbol{x}}_f) + \boldsymbol{K}_d(\boldsymbol{x} - \boldsymbol{x}_d - \boldsymbol{x}_f) \\ &= \boldsymbol{K}_f(\boldsymbol{f} - \boldsymbol{f}_d) \end{aligned} \tag{9}$$

, where $\boldsymbol{f} \in R^3$ is fingertip force, and $\boldsymbol{x} \in R^3, \dot{\boldsymbol{x}} \in R^3, \ddot{\boldsymbol{x}} \in R^3$, are fingertip position, velocity, acceleration, respectively. $\boldsymbol{f}_d \in R^3$ is reference force, $\boldsymbol{x}_f \in R^3$ is reference position trajectory until robot finger touches human skin muscle and $\boldsymbol{x}_d \in R^3$ is reference position trajectory after robot finger touches human skin muscle.

$\boldsymbol{x}_d$ is calculated by using human skin muscle model "(1)" when reference force $\boldsymbol{f}_d \in R^3$ is given. $\boldsymbol{M}_d$, $\boldsymbol{D}_d$ and $\boldsymbol{K}_d$ are respectively reference impedance coefficients. Then, in this paper, $\boldsymbol{M}_d$, $\boldsymbol{D}_d$ and $\boldsymbol{K}_d$ were given as $\boldsymbol{M}_d = \boldsymbol{I}$, $\boldsymbol{D}_d = 2\sqrt{\boldsymbol{M}_d(\boldsymbol{K}_d + \boldsymbol{K}_f K)} - \boldsymbol{K}_f C$ and $\boldsymbol{K}_d$ is a design parameter to be chosen by the designer.

Then, control law having the reference impedance characteristics is given by

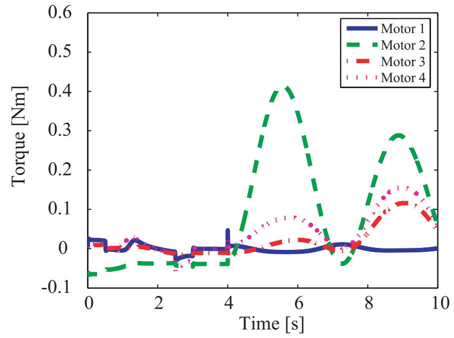
$$\begin{aligned} \tau = &\boldsymbol{M}(\theta)\boldsymbol{J}^{-1}[\boldsymbol{M}_d^{-1}\{\boldsymbol{K}_f(\boldsymbol{f} - \boldsymbol{f}_d) - \boldsymbol{D}_d(\dot{\boldsymbol{x}} - \dot{\boldsymbol{x}}_d - \dot{\boldsymbol{x}}_f) \\ &- \boldsymbol{K}_d(\boldsymbol{x} - \boldsymbol{x}_d - \boldsymbol{x}_f)\} - \dot{\boldsymbol{J}}\dot{\theta} + \hat{\boldsymbol{h}}(\theta, \dot{\theta})] - \boldsymbol{J}^T\boldsymbol{f} \end{aligned} \tag{10}$$

, where $\boldsymbol{M}(\theta)$ is an inertia term of robot hand, $\hat{\boldsymbol{h}}(\theta, \dot{\theta})$ is a non-linear term of centrifugal force, coriolis, gravity and friction term, and $\boldsymbol{J}$ is a Jacobian matrix. $\boldsymbol{K}_f$ is a feedback gain as $\boldsymbol{K}_f = diag[0.2225, 0.2225, 0.2225]$.

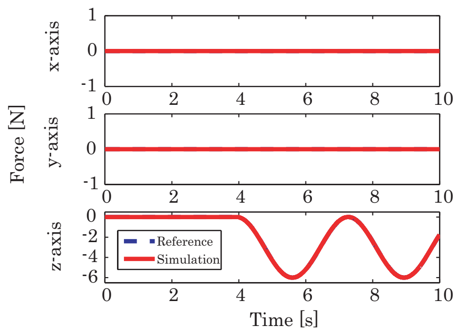
As a force reference, sinusoidal wave such as magnitude in z-direction is 3 [N] and frequency is 0.3 [Hz] was given.

Control simulation using two fingers was conducted. In each finger, the same impedance characteristics was given by considering the massage motion of expert therapist.

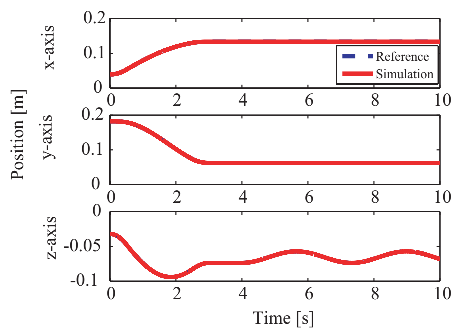
The control results are given in Fig. 12 and Fig. 13, where Fig. 12 is for the 1^{st} finger, and Fig. 13 is for the 2^{nd} finger.



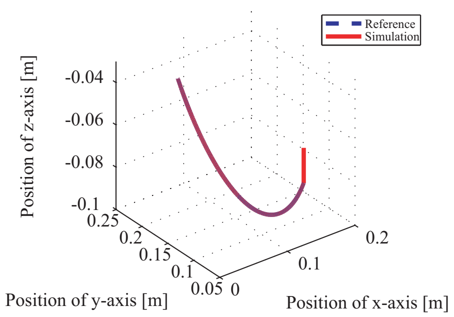
(a) Torque of each motor



(b) Force of fingertip



(c) Position of fingertip

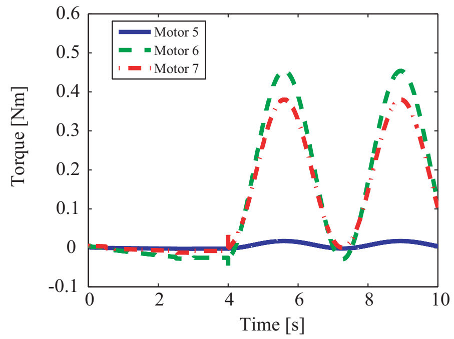


(d) Trajectory of fingertip

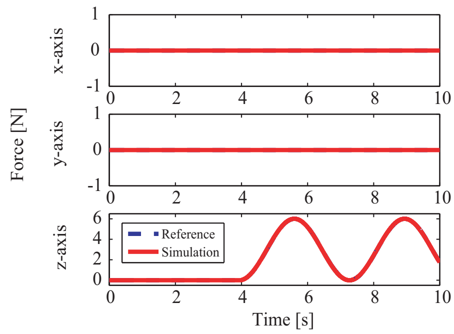
Figure 12: Simulation for massage motion of 1^{st} finger

In this simulation, the model parameter of human skin muscle for 1^{st} and 2^{nd} finger was given by $M = 0.001$, $K = 360$, $C = 18$, $d = 0$. Under this model, $\boldsymbol{x}_d$ is calculated when $\boldsymbol{f}_d$ is given. Furthermore, $\boldsymbol{M}_d = \boldsymbol{I}$, $\boldsymbol{K}_d = diag[1000, 1000, 1000]$ and $\boldsymbol{D}_d = diag[61.73, 61.73, 61.73]$.

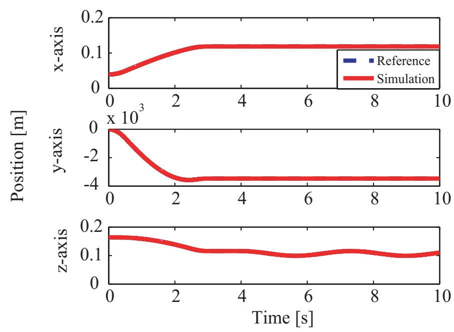
From Fig. 12 and Fig. 13, position and force output well agreed with reference values. Massage motion was well achieved to realize the ideal impedance according to the impedance of human skin muscle in this time.



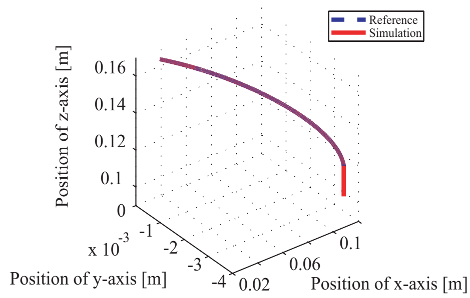
(a) Torque of each motor



(b) Force of fingertip



(c) Position of fingertip



(d) Trajectory of fingertip

Figure 13: Simulation for massage motion of 2^{nd} finger

5 Conclusions

In this paper, modeling of human skin muscle and parameter identification has been presented for the purpose such as exactly know the state of human muscle and conduct adaptive massage according to impedance information based on the model of human skin muscle. Model validity has been demonstrated through many experiments using a lot of position in human body. Then, using this model, it has been made clear that massage robot can understand the current state of human skin muscle. Finally, adaptive control strategy for implementing an expert massage robot to be adjusted for various conditions has been proposed. Control experimental results will be reported in near future.

6 Acknowledgments

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