Computer modelling of multifingers hand driven by muscle activation and application to artificial upper-limb system

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Abstract

Multifingers hand of a living human driven by muscle activation has been analysed using multibody dynamics approach, based on the updated Lagrange method. Based on the similarities of multi-fingers system of a living human, an artificial four fingers manipulator driven by wire-stepping motors has been developed. Combined it with artificial biorobotics arm, so far developed, we have developed an exclusive and artificial multifingers hand-arm system. Some manipulation tests have been carried out and the applicabilities of the system developed have been successfully clarified.

1 Introduction

Conventional robotics system so far developed has been used mainly in production line of manufacturing, and it is not easy to apply the system to support such as elderly human life in community space, because of the dangerous environmental condition. However in most elderly assistive technology of human community space it is strongly expected to develop such human-friendly robotics as applicable to community space.

Multibody dynamics of multi-fingers system of a living human, driven by muscle activations, has been formulated and solved a using the update Lagrange method. Based on the characteristics of each joint motions the dynamics of artificial system is designed and the control system is established. Then an artificial four-fingers hand system driven by wire-stepping motors which is set at remote field has been
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developed using similarity concept to multi-fingers hand of living human.

An artificial upper limb system, which consists of upper arm, fore arm and hand, had been developed previously by ours. Combined, the artificial multi-fingers hand system and the artificial upper limb system, we have developed an exclusive upper limb-multi-fingers hand system. They are driven and controlled separately in two step manner, for reaching motion of upper limb and for manipulating motion of multi-fingers hand respectively. Some manipulation tests are carried out and the applicabilities of the system developed has been verified.

2 Multibody dynamics analysis of multifingers system

2.1 Definitions and structure

A joint motion of a finger in a living human is induced by cooperative work of counter muscles as shown in Fig. 1 (a). Most muscles of a finger are situated in fore arms and their contractions are transmitted to each finger joint by connecting tendon. Typical joint of a fore finger is shown in Fig. 1 (a) to be CM, MCP, PIP, and DIP; and
other fingers except thumb have similar joint constructions. Each joint is driven by muscle-tendon system such as FS, FP, ED and IO as shown in Fig. 1 (b). Each finger has four links except thumb of three links. Bent motion of a finger is defined (\(x_i, y_i\)) plane and rotative motion for out-of the plane is defined by angle \(\beta\) shown in Fig. 1 (d). Thumb can rotate in angle \(\beta\) in x-z plane and in angle \(\alpha\) of x-axis rotation as shown in Fig. 1(c), in addition to the in plane bent motion. The combined rotations \((\alpha, \beta)\) can change the bent plane of thumb from common direction with other 4 fingers motion to the opposite direction of them as shown in Fig. 1 (a) and (c).

The global coordinate system \(\Sigma_0(X_0, Y_0, Z_0)\) is set at ground plane and the link coordinates are defined at each joint as shown in Fig. 1 (a), (c) and (d) to be \((x_i, y_i, z_i)\). Below we formulate typically the link motion of fore finger. The mass in a link element \(i\) is to be \(m_i\), the mass moment of inertia around each axis to be \(I_{x_i}, I_{y_i}\) and \(I_{z_i}\) and rotational damping and spring constants to be \(\{C_i\} = \{c_{x_i}, c_{y_i}, c_{z_i}\}^T\) and \(\{K_i\} = \{k_{x_i}, k_{y_i}, k_{z_i}\}^T\) respectively. In order to express the contact condition a gripping motion between the obstacle and the finger tips due to the lateral motion of thumb and fore fingers, the positional vector \(r_{s_i}\), the spring constants \(k_{s_i}\) and \(\tau_{s_i}\), and damping parameter \(c_{s_i}\) and \(T_{s_i}\) are defined as in Fig. 2. (a). If we transform the above relation from the element coordinate \(\Sigma_i\) to global coordinate \(\Sigma_0\), the coordinate transformation relation, can be written by.

\[
[S^{i,0}] = [S^{1,0}] \cdots [S^{i-1,0}][S^{i-1,1}] \cdots [S^{i,0}]
\]

where "c" and "s" denote cosine and sine, and

\[
[S^{i,i-1}] = [R^{\alpha_i}][R^{\beta_i}][R^{\gamma_i}]
\]

\[
= \begin{bmatrix}
  c\beta c\gamma & s\alpha \beta - c\alpha c\beta s\gamma & c\alpha \beta + s\alpha c\beta s\gamma \\
  s\gamma & c\alpha c\gamma & -s\alpha c\gamma \\
  -s\beta c\gamma & s\alpha \beta + c\alpha c\beta s\gamma & c\alpha \beta - s\alpha c\beta s\gamma
\end{bmatrix}
\]

2.2 Multibody dynamics analysis

As shown in Fig. 2(a), the position vector between adjacent joint centers \((i, i-1)\) is defined to be \(\{\xi_i\}\), \(\{p_i\}\) joint center to center of gravity in an element \(i\), and \(\{qi\}\), the position vector between both end joints in an element, respectively. Then we can express the vector of gravity center in an element \(i\), to be

\[
\{x_{k,0}\} = \sum_{i=1}^{k-1} \{\xi_{i-1,0}\} + \sum_{i=1}^{k-1} \{(qi, 0)\} + \{p_{k,0}\}
\]

\[
= \sum_{i=0}^{k-1} [S^{i-1,0}][\xi_i] + \sum_{i=1}^{k-1} [(S^{i-1,0})\{qi\}] + [S^{k,0}][p_{k}]
\]
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where

\[
\{q_{i,0}\} = [S^{-1,0}] \{q_i\}, \quad \{p_{i,0}\} = [S^{i,0}] \{p_i\}, \quad \{z_{i,0}\} = [S^{-1,0}] \{z_i\},
\]

\[
\{q_i\} = \{q_{ix} q_{iy} q_{iz}\}^T, \quad \{p_i\} = \{p_{ix} p_{iy} p_{iz}\}^T, \quad \{z_i\} = \{z_{ix} z_{iy} z_{iz}\}.
\]

from which we obtain the explicit form of mass center vector \(\{x_{m(i)}\}(i=1, 2, 3)\), expressed by global coordinate system as,

\[
F \{x_{m1}\} = \{\xi_0\} + [S^{10}] \{F p_1\}
\]

\[
F \{x_{m2}\} = \{\xi_0\} + [S^{10}] \{F q_1\} + [S^{10}] [S^{21}] \{F p_2\}
\]

\[
F \{x_{m3}\} = \{\xi_0\} + [S^{10}] \{F q_1\} + [S^{10}] [S^{21}] \{F q_2\} + [S^{10}] [S^{21}] [S^{32}] \{F p_3\}
\]

\[
F \{x_{m4}\} = \{\xi_0\} + [S^{10}] \{F q_1\} + [S^{10}] [S^{21}] \{F q_2\} + [S^{10}] [S^{21}] [S^{32}] \{F q_3\} + [S^{10}] [S^{21}] [S^{32}] [S^{43}] \{F p_4\}
\]

\[
\tau \{x_{m1}\} = \{\xi_0\} + [S^{10}] \{\tau p_1\}
\]

\[
\tau \{x_{m2}\} = \{\xi_0\} + [S^{10}] \{\tau q_1\} + [S^{10}] [S^{21}] \{\tau p_2\}
\]

\[
\tau \{x_{m3}\} = \{\xi_0\} + [S^{10}] \{\tau q_1\} + [S^{10}] [S^{21}] \{\tau q_2\} + [S^{10}] [S^{21}] [S^{32}] \{\tau p_3\}
\]

Fig. 2 Modeling of multilink-muscle system for gripping
In the same way, the contact points of a finger tip to the gripping obstacle, \( \{x_{ij}\} \) (\( i = 1 \sim 4 \)), can be written by global coordinate system as,\n
\[
\{F_{x_{ij}}\} = \{\xi_0\} + \left[ S^{10} \right] \{F q_1\} + \left[ S^{10} [S^{21}] \right] \{F q_2\} + \left[ S^{10} [S^{21}] [S^{32}] \right] \{F q_3\} + \left[ S^{10} [S^{21}] [S^{32}] [S^{43}] \right] \{F r_{4i}\}
\]

\[
\{T_{x_{ij}}\} = \{\xi_0\} + \left[ S^{10} \right] \{T q_1\} + \left[ S^{10} [S^{21}] \right] \{T q_2\} + \left[ S^{10} [S^{21}] [S^{32}] \right] \{T r_{4i}\}
\]

Furthermore, referring to Fig.1(b), the positional vector of each muscle-tendon system can be expressed using the notations of the positional vector \( \{F_{x_{rk,j}}\} \) of a muscle-tendon system \( (k, j) \), as follow, where \( F \) is the fore finger, \( k \) the link number and \( j \) the specified number of each muscle-tendon system,\n
\[
\{F_{x_{rk,j}}\} = \sum_{i=0}^{k-1} \left[ S^{i-1,0} \right] \{\xi_i\} + \sum_{i=1}^{k-1} \left[ S^{i-1,0} \right] \{F q_i\} + \left[ S^{k,0} \right] \{F r_{k,j}\} \quad (k = 1 \sim 4, j = 2, 3)
\]

\[
\{T_{x_{rk,j}}\} = \sum_{i=0}^{k-1} \left[ S^{i-1,0} \right] \{\xi_i\} + \sum_{i=1}^{k-1} \left[ S^{i-1,0} \right] \{T q_i\} + \left[ S^{k,0} \right] \{T r_{k,j}\} \quad (k = 1 \sim 3, j = 2, 3)
\]

For example, the explicit form of the positional vector of the muscle-tendon system of the 4th link of the fore finger \( \{F_{x_{r4,2}}\} \) can be expressed by,

\[
\{F_{x_{r4,2}}\} = \{\xi_0\} + \left[ S^{10} \right] \{F q_1\} + \left[ S^{10} [S^{21}] \right] \{F q_2\} + \left[ S^{10} [S^{21}] [S^{32}] \right] \{F q_3\} + \left[ S^{10} [S^{21}] [S^{32}] [S^{43}] \right] \{F r_{4,2}\}
\]

The contraction of the \( k \)th muscle-tendon system, mounted in the fore arm, give the corresponding motion to the random point \( (i) \) of \( k \)th link. The translational velocity and rotations at gravity center \( \{v_{i,0}\} \) and \( \{\omega^{i-1}\} \) are derived from time differentiation of Eq.(3), and can be expressed as follow by denoting \( \{\Omega_{i,0}\} \) to be skew matrix and \( [A] \) to be the coordinate modification matrix,

\[
[v_{i,0}] = \sum_{i=0}^{k-1} \{\dot{S}^{i-1,0}\} \{\xi_i\} + \cdots + \sum_{i=1}^{k-1} \{\dot{S}^{i-1,0}\} \{q_i\} + \{\dot{S}^{k,0}\} \{p_k\}
\]

\[
[\Omega^{i-1,0}] = \begin{bmatrix}
0 & -\omega^{i-1}_3 & \omega^{i-1}_2 \\
\omega^{i-1}_3 & 0 & -\omega^{i-1}_1 \\
-\omega^{i-1}_2 & \omega^{i-1}_1 & 0
\end{bmatrix}
\]

where

\[
[S^{i-1,0}] = [\Omega^{i-1,0}] [S^{i-1,0}]
\]
Substituting Eq.(6)-2 into Eq.(6)-1, then we obtain

\[
\{v_{k,0}\} = \sum [S^{i-1}_{\xi_i}] \{\dot{\xi}_i\} + \sum [S^{i-1}_{\xi_i}] \{\dot{A}_i\} \{\dot{\theta}_i\} + \cdots \\
+ [A_{i-1}] \{\dot{\theta}_{i-1}\} + \sum [S^{i-1}_{\theta_i}] \{\dot{A}_i\} \{\dot{\theta}_i\} + \cdots + [A_{i-1}] \{\dot{\theta}_{i-1}\} \\
+ ([S^k p_k] A_i) \{\dot{\theta}_i\} + \cdots + [S^k p_k] A_k) \{\dot{\theta}_k\})
\]

In the same way, the angular velocity in term of global coordinate can be expressed by,

\[
\{\omega_{i,0}\} = \{\omega_{1,0}\} + \{\omega_{2,0}\} + \cdots + \{\omega_{i-1}\} = \sum [S^{i-1}_{\theta_i}] \{\dot{A}_{i-1}\} \{\dot{\theta}_{i-1}\}
\]

2.3 Modeling of muscle^2

The incremental form of stress and strain in muscle can be written by

\[
S_{ij} = S_{ij}^{n-1} + \Delta S_{ij}^n, \quad \text{and} \quad E_{ij} = E_{ij}^{n-1} + \Delta E_{ij}^n,
\]

\[
\{\Delta E_{ij}\} = \frac{1}{2} \left[ \frac{\partial D_{\beta}}{\partial X_j} + \frac{\partial D_{\beta}}{\partial X_i} \right] \Delta \beta + \frac{\partial D_{\beta}}{\partial E_{ij}} \Delta E_{ij} + \frac{\partial D_{\beta}}{\partial E_{ij}} \Delta \dot{E}_{ij}
\]

\[
\{\Delta \dot{E}_{ij}\} = \left[ \frac{\partial D_{\beta}}{\partial \dot{E}_{ij}} \right] \Delta \dot{E}_{ij} + \left[ \frac{\partial D_{\beta}}{\partial \dot{E}_{ij}} \right] \Delta \ddot{E}_{ij} + \cdots \\
+ \{D_{\beta}^p\} \{\Delta E_{ij}^n - \delta_{mi} \Delta E_{0m}^n\} + \frac{\partial D_{\beta}}{\partial E_{ij}} \Delta E_{ij} ((E_{ij})^{n-1}) \\
+ \{\Delta \dot{E}_{ij}\} + [D^P] \{\Delta E_{ij}\} + \frac{\partial I^3}{\partial E_{ij}} \{\Delta h\}
\]

where \(u_i\) is the displacement, \(X_i\) the coordinate before deformation.

Then, the incremental virtual work equation can be written by neglecting the notation \(n\), as
where $T_{0i}$ and $F_{0i}$ are body force and surface force. Using Eq. (9), the incremental stiffness equation of an element can be rewritten by

$$[K_L] \{\Delta u_i\} = \{\Delta p_{a}\} + \{\Delta p\} + \{R\} \quad \Delta D^T = \Delta D^a_T + \Delta D^p_T$$

(12)

where $L$ is the coordinate

$$[K_L] = \int_{v} \begin{bmatrix} \hat{B}^T B^T & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} T^{-1} & D_{ev} \\ D_{ev} & 1 \end{bmatrix} \begin{bmatrix} \hat{B}^T B^T & 0 \\ 0 & 1 \end{bmatrix} dv + \int_{v} \begin{bmatrix} [\hat{B}]^T [T]^{-1} [S_{ik}^{n-1}] [T] \hat{B} \\ 0 \end{bmatrix} dv$$

(13)

$$[S_{ik}^{n-1}] = [S_{ik}^{an-1}] + [S_{ik}^{pn-1}],$$

$$\{\Delta p_{a}\} = \int_{v} [\hat{B}^T B^T] [T]^{-1} [\Delta D^a_T] [T] \{\Delta E_{0m}^a\} dv$$

and $R$ is the residual force up to the step, $n-1$, $N$ the shape function, $[B]$ and $[B^T]$ being given in [2]. The other notations are given by

$$\Delta D^a_T = \sum_{i=1}^{4} \Delta D^a_T, \quad \Delta D^p_T = \sum_{i=1}^{2} \Delta D_i^p, \quad \Delta D^a_T = \frac{\partial D_m^a}{\partial \beta} \Delta \beta, \quad \Delta D^2_T = \frac{\partial D_m^a}{\partial E_{ij}} \Delta E_{ij}$$

$$\Delta D^3_T = \frac{\partial D_m^a}{\partial E_{ij}} \Delta \hat{E}_{ij}, \quad \Delta D^4_T = D_m^a, \quad \Delta D^p_T = \frac{\partial D_m^p}{\partial E_{ij}} \Delta E_{ij}, \quad \Delta D^2_T = D_p^T, \quad D_{ev} = \frac{\partial I_3}{\partial E_{ij}}$$

(14)

By assembling element stiffness Eq. (11) for whole muscle elements, and transforming them by global coordinate system, we obtain the governing stiffness equation of whole muscles. It should be noted that in Eq. (11), the load vector $\{\Delta F_p\}$ is induced as the force equivalent to muscle free contraction, shown in Fig. 1(c), and it is especially important to obtain the exact stress in muscle.

### 3 Updated Lagrange Equations of Motion

The Lagrange equation of motion can be expressed by
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\[ \frac{d}{dt} \left[ \frac{\partial L}{\partial \dot{u}_j} \right] - \frac{\partial L}{\partial u_j} + \frac{\partial F}{\partial \dot{u}_j} = Q_j \]

where

\[
L = T - U, \quad T = T_{lg} + T_{rot} \nonumber
\]

\[
T_{lg} = \sum_{i=1}^{k} \frac{1}{2} \{v_{i,0}\}^T [m_i] \{v_{i,0}\} \nonumber
\]

\[
T_{rot} = \sum_{i=1}^{k} \frac{1}{2} \{\omega_{i,0}\}^T [I_i] \{\omega_{i,0}\} \nonumber
\]

\[U = \sum_{j=1}^{k} U_j + \sum_{j=1}^{k} U_{mj} \quad [m_i] = \begin{bmatrix} m_i & m_i & \vdots & m_i \end{bmatrix} \quad [I_j] = \begin{bmatrix} I_1 & I_1 & \cdots & I_1 \end{bmatrix} \quad (15) \]

The potential energy stored in each joint spring \( U_1 \) and the potential energy \( U_2 \) stored in the contact fingers are

\[ U_1 = \sum_{i=1}^{k} \frac{1}{2} ([S_{i-1,0}] [A_{i,i-1}] [\Theta_i])^T [K_i] ([S_{i-1,0}] [A_{i,i-1}] [\Theta_i]) \]

where \([K_i] = [K_{\alpha\beta} K_{\beta\alpha}] K_{\gamma \gamma} \]

\[ U_2 = \sum_{i=1}^{5} ([S_{i-1,0}] [F x_{rj}])^T [F k_{rj}] ([S_{i-1,0}] [F x_{rj}]) \]

\[ + \sum_{i=1}^{3} \frac{1}{2} ([T x_{rj})^T [T k_{rj}] ([S_{i-1,0}] [T x_{rj}]) \quad (16) \]

Fig.3 Joint torque balance model of muscle
where \( \{F_t x_f\} = \{F_t r_{4, j}\} - \{F_t r_{4, j}\} \), and \( \{T_t x_f\} = \{T_t r_{3, j}\} - \{T_t r_{3, j}\} \).

The notations of \( \{F_t r_{4, j}\} \) and \( \{T_t r_{3, j}\} \) are given in Fig. 2 (c) and the notation \( k_t \) is the spring constant of finger tip and obstacle. The potential energy of the muscles can be obtained from Eq. (11) by assembling them for joint muscles shown in Fig. 2 (b).

The generalized force \( \{Q_i\} \) is the sum of joint rotating damper force \( \{Q_d\} \), gravity force \( \{G_i\} \) and gripping reaction force \( \{R_i\} \), and can be expressed by

\[
\{Q_i\} = [A^{i,j-1}]^T [S^{i-1,0}]^T [C_i] [S^{i-1,0}] [A^{i,j-1}] \{\dot{\theta}_i\},
\]

\[
\{G_i\} = [g_i] [m_i] [S^{i-1,0}] \left\{ \frac{\partial x_m}{\partial x_0} \right\},
\]

\[
\{Q_2\} = [A^{i,j-1}]^T [S^{i-1,0}]^T [C_i] [S^{i-1,0}] [A^{i,j-1}] \{\dot{\theta}_i\}
\]

where \( g_i \) and \( m_i \) are gravity and mass matrices for element \( i \) respectively. The updated Lagrange equation can be obtained by assembling above equations in incremental form and can be expressed by

\[
d\frac{\partial \Delta L}{\partial \Delta \dot{\theta}_j} - \frac{\partial \Delta L}{\partial \Delta \theta_j} = \sum \{ \Delta Q_i \},
\]

\[
\Delta L = \Delta T - \left( \sum_{j=1}^{m} \Delta U_{mj} + \sum_{j=1}^{2} \Delta U_j \right) \{ \Delta Q_i \} = \sum \{ \Delta Q_{il} \} + \sum \{ \Delta Q_{2i} \} + \sum \{ \Delta G_i \}
\]

where \( \Delta U_{mj} \) are the incremental potential energy of joint skeletal muscles, given in Eq. (13) as \( \{\Delta p_{mj}\} \), and it includes isolated two parameters for generation of motion \( (\Delta \varepsilon_1) \) and the constraint force components \( (\Delta \varepsilon_2) \) of the muscle contraction. Then the governing equations of motion and dynamic equilibrium equations can be expressed by

\[
[M] \{\Delta \dot{\theta}_i\} + [C] \{\Delta \dot{\theta}_i\} + [K_m (\Delta \varepsilon_1)] \{\Delta \theta_i\} = \sum \{\Delta Q_{ex}\} + \sum \{\Delta Q_{il}\} + \sum \{\Delta Q_{2i}\} + \sum \{\Delta G_i\}
\]

Based on the discretized form of Eqs (19) we can solve any gripping problems induced by multimuscle activation.

4 Computer Simulation of Manipulation Process of Multifinger Hand

Based on the modeling stated above, the equations of motion and dynamic equilibrium equations in incremental form have been formulated using Newmark- \( \beta \)
method, and the computer simulation system has been developed. Some gripping motion tests shown in Fig.2 have been carried out, and motions in thumb and fore finger were measured, and EMG levels of skeletal muscles of each finger were also measured. The equations of motion include the exciting forces and motions induced by joint muscle contraction, and dynamic equilibrium equations also include the internal joint torques induced by muscle activations, which is induced by mutual constraints of counter muscles contraction. Once the measurement result of the link motion and EMG levels of joint muscles are substituted to above equations, then the activation levels of the driving muscles for generation link motion can be obtained from inverse dynamics approaches, and the internal torques induced by joint counter muscles can also be found by solving dynamic equilibrium equations using link posture calculated from above motion equations and additional contact conditions shown in Fig.3 (b). The governing equations of compatibility and equilibrium equations for contact displacements and forces can be obtained from Fig.2 (b) easily by using the relation(1). Some illustrative calculations for reaching and manipulation have been carried out and typical results are shown in Figs.4 (a) and (b). Fig. (a) shows the calculation results of reaching process of thumb and fore finger in gripping of the obstacle, and Fig.4 (b) shows joint torques induced by interior muscles during gripping.

5 Design and Development of Artificial Multifinger Hand and Upper Limb Systems

5.1 Artificial multifinger hand (AMFH) system

An artificial multifinger hand (AMFH) system, similar to living human’s, has been designed and manufactured by replacing the muscle-tendon system to wire-stepping motor system, which is set at remote position. The link mechanism of AMFH
The motion of each joint is driven and controlled by the wire-motor system, and when the force is transmitted to each joint, the joint velocity is replaced by equivalent voltage of D/A converter board and control the motion by varying the step number, of the stepping motor according to the gap between planned pass and real trajectory. Once the access point of the obstacle manipulation is determined, the reaching process for gripping is performed by judging contacting, penetration, deformation, contact pressure, sliding condition, force balance between opposite pair of the hand tips, and so on.

5.2 Artificial Upper Limb (AUL) System

An artificial upper limb system similar to living human had been developed previously, based on the model shown in Fig.6. The arm-link system of the limb consist of upper arm, forearm and hand, and joint system of shoulder, list and hand grip with each 2 D.O.F. respectively. The driving and control systems of the AUL system are similar to those of AMFH system. Some tests of AUL system have been done in order to judge that the system can be applicable to community space for getting human-friendly motion. The redundancy for external disturbance such as collision et al are examined and the typical results are shown in Fig.8. When the
In order to review the applicability of coupled AUL and AMFH System, some experiments on manipulation have been carried out. After AMFH System is attached to the tip of the AUL System, the manipulation test for gripping of a square box and then carrying it to the different position has been done in two steps of controlled condition, and the results show the applicability of the coupled system to be satisfactory as in Fig.9.

5.3 Manipulation Tests for Coupled AUL and AMFH Systems

In order to review the applicability of coupled AUL and AMFH System, some experiments on manipulation have been carried out. After AMFH System is attached to the tip of the AUL System, the manipulation test for gripping of a square box and then carrying it to the different position has been done in two steps of controlled condition, and the results show the applicability of the coupled system to be satisfactory as in Fig.9.
6 Concluding remarks

Multibody dynamics approach of a multifingers hand system of a living human, driven by muscle action, has been formulated and successfully applied to develop the exclusive and artificial hand-arm system. Some manipulation test results clarified the applicabilities of the software and hard ware systems developed.

References