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Study on wearable system for daily life support using McKibben pneumatic artificial muscle

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Abstract— **This paper proposes the basic technologies in order to develop a wearable hand assistive system for daily life support. Current prosthetics have some problems for wearability. We focus on the load caused by weight of wearable system. The actuator is one of the heaviest parts in wearable systems. Therefore we propose to use the McKibben pneumatic artificial muscle which is lightweight and compact in size. At first, we propose a new method to control air pressure of artificial muscle without pressure sensor in order to reduce the size of system. Second, we investigate variable stiffness of human finger to perform human finger dexterity and simulate it by using our proposed polyarticular tendon drive system.**

Fig. 1. Wearable hand assistive system

I. INTRODUCTION

Current prosthetic hands, although functional, have the potential of being significantly improved[1]. However, there are some problems for wearability. In particular, a functional prosthetic hand is rarely used because this system is too heavy. Most of the upper extremity amputees use cosmetic prosthesis that is lighter and more comfortable. In addition, conventional orthotics requires relatively small force because passive function such as immobilizing a joint or body segment against activities of wearer is important. However wearable assistive system needs to immobilize more segment of body and apply more force in order to support paralyzed patients. Therefore, we developed the technology to improve wearability of wearable assistive system in order to perform daily life support. At first, we focus on the weight of wearable system.

In our laboratory, we developed the wearable hand assistive system[2] shown in Fig.1. A system controller is mounted on wearer's forearm. An exoskeleton for finger support is on the outside part of wearer's hand and fingers, and a parallel link mechanism for support of wrist activities is connecting the controller with the exoskeleton. In wearable system like this one, the weight of system stresses the wearer directly. In particular, wearing the heavy system is dangerous for a person with physical challenges that cannot support the weight of the system.

In order to reduce the load caused by the weight of the system, there are two approaches. First, the weight of wearable system itself supports by a grounding part of the system. For example, heavy parts such as actuators are placed away from the body, and assistive force is transmitted by transmission mechanism such as a link mechanism. However, this system becomes too large and heavy. Another example is that the system supports the weight both wearable system and wearer by using the assistive system covered all body. This system can be used anywhere because the wearer can move himself with the system, however this system is redundant for hemiplegic patients, because if patients want to support only arm, this system must be worn all body. The second approach is reducing the weight of the wearable system. We develop a light and small wearable system by using McKibben pneumatic artificial muscle that is suitable for reduction in size and weight. Furthermore, we propose the pressure control method without pressure sensor in order to downsize the system.

Besides, we focus on a drive mechanism for an exoskeleton shown in Fig.1 to simulate the similar stiffness of the human finger. The exoskeleton is attached to a human finger to augment the grasping force of human fingers by pushing the human finger from outside and then the cooperative system of human finger and the exoskeleton grasps an object. A stiffness of the cooperative system, that is an inverse of the compliance, is sum of the stiffness of the human finger and the stiffness of the exoskeleton. Therefore fingertips of the exoskeleton should have the same stiffness as the stiffness of the human fingertip so that a stiffness of the cooperative system could be controlled according to a target task in order to perform the same dexterity as human finger. Actually the stiffness of a human finger automatically increases as the grasping force of the finger increases. The exoskeleton should have the same variable stiffness as a human have.

This paper is organized as follows. The system structure in our system is introduced in section II. In section III, IV and V, we estimate the model of McKibben pneumatic artificial muscle by using least squares method and valuate the model. In section VI, we investigate the fingertip stiffness of human finger and polyarticular tendon drive system proposed in our

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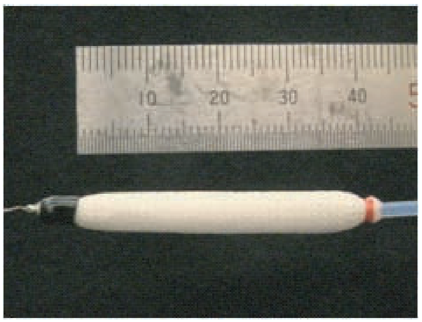

Fig. 2. The regular type McKibben pneumatic artificial muscle

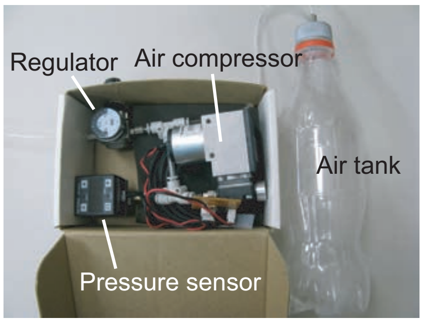

Fig. 3. Air pressure source

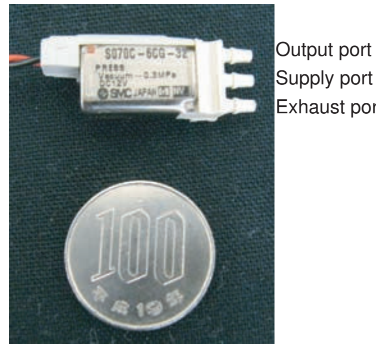

Fig. 4. Solenoid valve

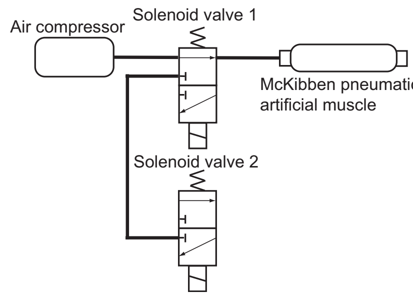

Fig. 5. Pressure control system

previous study. In section VII, we conclude and discuss on the experimental results.

II. System structure

A. McKibben pneumatic artificial muscle

McKibben pneumatic artificial muscle is the actuator that generates axial contraction force. The systems actuated DC motor such as conventional industrial systems injure a person at the time of collision or failure because these systems are too heavy and stiff. On the other hand, the systems using pneumatic device are kind and safety for people because this actuator is light and soft one. In particular, McKibben pneumatic artificial muscle is suitable for using in an environment with people because the driven part of this actuator is flexible.

The McKibben pneumatic artificial muscle used in this study is shown in Fig.2. We use the artificial muscle developed by SQUSE. This actuator has high contraction ratio, and the weight of this actuator is about 1[g] in spite of the size of actuator is similar to DC motor that use in our previous hand assistive system. The hand assistive system requires a lot of actuators in order to simulate human finger dexterity[3]. Therefore, the weight of system reduces according to reduce the weight of motor. In addition, this pneumatic device realizes fast responsivity and silent driving because this actuator drives with a little air.

B. Air pressure source

The air compressor is a mechanical device that increases the pressure of an air by reducing its volume. In order to use pneumatic device continuously, air pressure source with air compressor is required. However, the current air compressors have some drawbacks, including their large size, heavy weight, and high power consumption. Accordingly, we design the portable air pressure source.

We use the compressor developed by SQUSE. This compressor can increase the air pressure until 0.4[MPa]. The weight of this compressor is about 180[g]. This compressor is enough to drive our McKibben pneumatic artificial muscle because the maximum allowed pressure of this artificial muscle is 0.2[MPa].

The overview of air pressure source is shown in Fig.3. This system is installed air compressor, regulator, pressure sensor and air tank. The PET bottle is used as the air tank. Pressure sensor measures the air pressure of the air tank. The pressure sensor controls air compressor to keep the air pressure of the air tank between $0.25[MPa]$ to $0.38[MPa]$. Total weight of the air pressure source is 500[g].

C. Air pressure control system

In conventional study about the system using McKibben pneumatic artificial muscle, air pressure of pneumatic artificial muscle is controlled by feedback control with pressure sensor. However, hand assistive system requires a lot of actuators in order to support movement of fingers that have multi degree of freedom. Therefore, we propose the feedforword control method by controlling switching time of solenoid valve in order to make the light and compact wearable system.

We use the solenoid valve developed by SMC. Fig.4 shows the solenoid valve used in this study. This valve has three ports (supply, output, and exhaust port), and switches two conditions (supply and exhaust). If the solenoid valve switches supply condition, air flows from supply port to output port. If the solenoid valve switches exhaust condition, air flows from output port to exhaust port. In addition, this valve has very small size and light weight ($7 \times 12 \times 26[mm], 5[g]$).

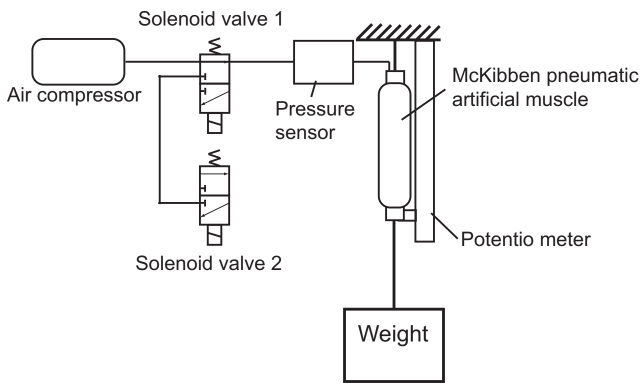

Fig. 6. Experimental setup for investigation the static characteristics of McKibben pneumatic artificial muscle

Besides, this valve can switch fast because the responsivity is 3msec or faster.

In our system, we must maintain air pressure at constant in order to generate grasping force continuously. However, The solenoid valve that we use cannot maintain air pressure. Therefore we propose to add the maintaining condition by using two solenoid valves.

The overview of air pressure control system is shown in Fig.5. Supply port of the solenoid valve 1 is connected to the air pressure source, and output port is connected to McKibben pneumatic artificial muscle. Besides exhaust port of solenoid valve 1 is connected to supply port of solenoid valve 2. When the solenoid valve 1 is supply condition, the air pressure source supplies McKibben pneumatic artificial muscle with air pressure. If the solenoid valve 1 switches exhaust condition and the solenoid valve 2 is exhaust condition, the air pressure of McKibben pneumatic artificial muscle is maintained at constant. Finally, if the solenoid valve 2 switches supply condition, air pressure is exhausted from McKibben pneumatic artificial muscle.

III. Modeling

In order to control air pressure of McKibben pneumatic artificial muscle by using feedforword control with solenoid valve switching time control, the proper dynamic model is required. At first, we investigate properties of McKibben pneumatic artificial muscle and make a dynamic model.

A. Static characteristics of McKibben pneumatic artificial muscle

Fig6 shows experimental setup for investigation static characteristics of McKibben pneumatic artificial muscle. At first, we hang McKibben pneumatic artificial muscle and hook the load to under part of artificial muscle. Next, we increase air pressure of McKibben pneumatic artificial muscle. In this time, we measure the contraction ratio by using potentio meter that puts along artificial muscle, the air pressure by using pressure sensor and the time to reach the air pressure of McKibben pneumatic artificial muscle to 0.2[MPa].

The measurement results are shown in Fig.7. The horizontal axis shows the air pressure of McKibben pneumatic artificial muscle from atmospheric pressure, and the vertical axis

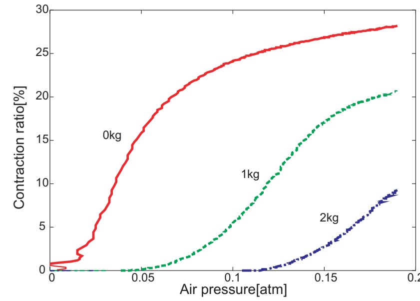

Fig. 7. Relationship between air pressure, contraction value and tension

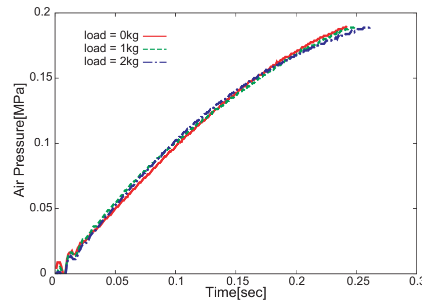

Fig. 8. Time transition of air pressure

shows the contraction ratio of McKibben pneumatic artificial muscle. The weight of load is expressed by color and kind of lines. The maximum contraction ratio is about $25[\%]$ in no-load condition and the maximum contraction ratio reduce according to weight of load. In addition, Fig8 shows the relationship between the supply time of air pressure and air pressure of McKibben pneumatic artificial muscle. The relationship between supply time and air pressure is almost constant even if the weight of load changes. Therefore, air pressure can control by controlling supply time. We approximate relationship between supply time $t[sec]$ and air pressure $P[MPa]$ by

$$t = \alpha P^2 + \beta P + \gamma \tag{1}$$

The parameters α, β, γ are obtained by using least squares method. The identified parameters are shown in Table I. The mean square error between measurement and estimation results is $0.122 * 10^{-3}$.

B. Model

In conventional way, the model of pneumatic actuator is shown by energy budget[4]. When the air pressure of McKibben pneumatic artificial muscle become $P'[MPa]$ and volume of artificial muscle $V[mm^3]$ changes to $V + dV[mm^3]$, the input work W_{in} is shown by

$$dW_{in} = (P' - P_0)dV = PdV \tag{2}$$

TABLE I

Estimated parameters for switching time control of McKibben pneumatic artificial muscle

α	β	γ
4.039	-0.002	0.018

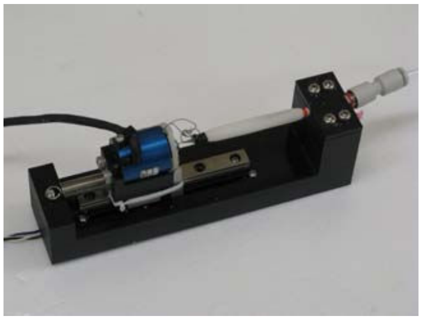

Fig. 9. Experimental setup for estimation the model of McKibben pneumatic artificial muscle

In this time, P_0 means atmospheric pressure($0.1[MPa] = 1[atm]$). In addition, when the artificial muscle generates tension $T[N]$ and the length of artificial muscle $L[mm]$ changes to $L + dL[mm]$, the output work W_{out} is shown by

$$dW_{out} = -TdL \tag{3}$$

According to principle of virtual work,

$$dW_{in} = dW_{out}PdV = -TdL \tag{4}$$

However, the dissipation term is not considered in eq.4. So we define the dissipation force F_d strutted by elastic force and friction force.

$$F_d = kL_0\varepsilon + f \tag{5}$$

ε is the contraction ratio of artificial muscle and L_0 means the natural length of artificial muscle. ε is shown by

$$\varepsilon = \frac{L_0 - L}{L_0} \tag{6}$$

Given eq.4, we obtain the following.

$$PdV = -(T + F_d)dL \tag{7}$$

Besides, the volume of pneumatic actuator $V[mm^3]$ is approximated quadratic equation[5]

$$V = C_2\varepsilon^2 + C_1\varepsilon + C_0 \tag{8}$$

The parameters $C_i(i = 0, 1, 2)$ are constant coefficient. We obtain the following according to differentiate eq.8 with respect to ε.

$$\frac{dV}{d\varepsilon} = 2C_2\varepsilon + C_1 \tag{9}$$

$$dV = (2C_2\varepsilon + C_1)d\varepsilon \tag{10}$$

In addition, dL is given by eq.6

$$dL = -L_0 d\varepsilon \tag{11}$$

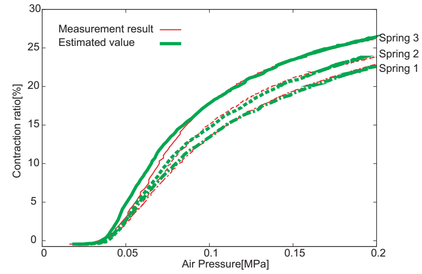

Fig. 10. Relationship between contraction ratio and estimated air pressure

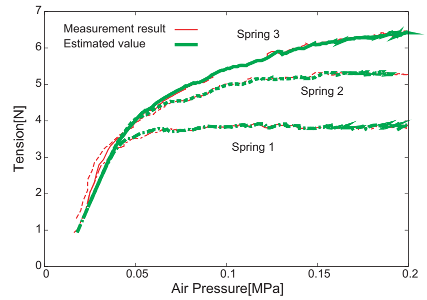

Fig. 11. Relationship between tension and estimated air pressure

Substituting eq.5, 10 and 11 into eq.7, we obtain the following.

$$P(2C_2\varepsilon + C_1)d\varepsilon = (T + kL_0\varepsilon + f)L_0 d\varepsilon \tag{12}$$

$$P = \frac{(T + kL_0\varepsilon + f)L_0}{2C_2\varepsilon + C_1} = \frac{T + b_1\varepsilon + b_0}{a_1\varepsilon + a_0} \tag{13}$$

The parameters a_1, a_0, b_1, b_0 are given by next equations.

$$a_1 = \frac{2C_2}{L_0}, a_0 = \frac{C_1}{L_0}, b_1 = kL_0, b_0 = f \tag{14}$$

C. parameter estimation

We estimate the parameters a_1, a_0, b_1, b_0 by using least squares method. The overview of the experimental system for estimation is shown in Fig.9. The end of string extended from the McKibben pneumatic artificial muscle connects to the six-axis force sensor to measure the tension. the force sensor is put on a slide table and fixed to base via a spring. A potentiometer measures a contraction of the artificial muscle at frequency of 500[Hz]. The air pressure of artificial muscle is controlled by using air pressure control system shown in Fig.5. We measure the contraction ratio, tension and air pressure when the spring constant changes.

The estimated parameters are shown in Table II. In addition, the relationship between contraction ratio and estimated air pressure is shown in Fig.10, and the relationship between tension and estimated air pressure is shown in Fig.11. The mean square error between measurement and estimation

TABLE II
ESTIMATED PARAMETERS OF MODEL OF MCKIBBEN PNEUMATIC ARTIFICIAL MUSCLE

a_1	a_0	b_1	b_0
-106.166	38.340	3.204	0.066

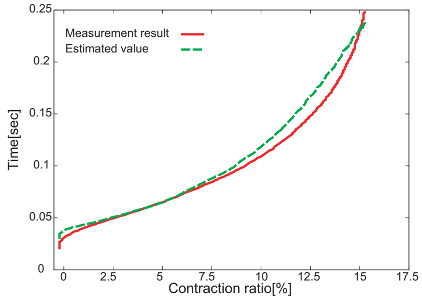

Fig. 12. Relationship between estimated time and contraction ratio

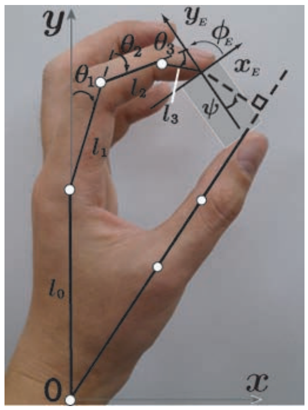

Fig. 13. Grasping posture and coordinate system

results is $2.278 * 10^{-3}$. From these results, we can estimate air pressure with high accuracy.

IV. Pressure control using switching time

We estimate switching time of solenoid valve by using eq.1,13. The estimated results are shown in Fig.12. The mean square error between measurement and estimation results is $0.147 * 10^{-3}$ and the maximum error of time is $0.02[sec]$. Therefore, We can control the air pressure of McKibben pneumatic artificial muscle by using switching time of solenoid valve.

V. Fingertip stiffness control

A human finger has the variable stiffness that could contribute to its dexterity. The exoskeleton should have the variable stiffness similar to it so that the cooperative system of human fingers and the exoskeleton could have dexterity similar to dexterity of a human finger. In our previous study, polyarticular tendon drive system can simulate the variable stiffness of human finger. However, this drive system is required linear spring into each tendon. Because McKibben pneumatic artificial muscle has non-linear elastic properties, we considered that the hand assistive system using McKibben pneumatic artificial muscle can simulate the variable stiffness of human finger without spring. Therefore we investigate the fingertip stiffness properties of polyarticular tendon drive system using McKibben pneumatic artificial muscle.

A. Definition of stiffness

The stiffness in this study is defined as the slope of the force-displacement curve including an effect of the system posture transfer. Stiffness of the end effector actually changes according to the posture transition, when a position of a manipulator's end effector transfers by an external force. On the other hand, the stiffness ellipse [6] that is commonly used to show system stiffness in all directions at one posture does not take the posture transition into consideration. Therefore the stiffness ellipse cannot deal with transition of system stiffness when the system posture is changing under some constraint. The stiffness transfer of the fingertip is investigated in this study when the finger posture is changed by an external force affected to a grasped object.

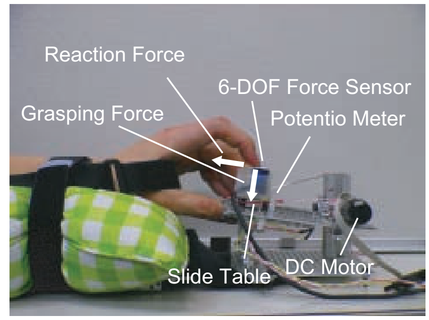

Fig. 14. Stiffness measurement system of human index finger

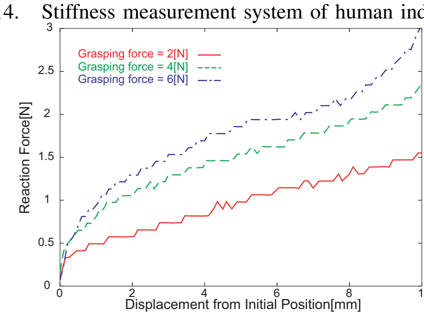

Fig. 15. Reaction force of human index finger

B. Stiffness measurement of human finger

A stiffness of a human finger is measured by using an experimental system shown in Fig. 14. A six-axis force sensor that simulates a grasped object is put on a slide table and it is pulled by a DC motor via a wire. A potentiometer measures a displacement of the force sensor at frequency of 500[Hz]. At first, an index fingertip pushes down the six-axis force sensor as if an index finger and a thumb pinch the force sensor with a certain grasping force, but a thumb does not touch the force sensor. The DC motor starts pulling the force sensor along the slide table when the pushing force measured by the six-axis force sensor reaches the target value, and then the DC motor stops pulling when the displacement reaches 10[mm]. The index finger moves with the force sensor and it also starts to generate a reaction force due to the displacement. The reaction force is measured by the force sensor. The stiffness of the finger is derived from the relationship between the reaction force and the displacement of the force sensor if it is assumed that the index finger does not slip over the force sensor. A wrist is fixed to a desk with a band in order to keep an initial position of the hand.

A world coordinate system is defined as to set its origin at a center of the wrist joint and as to set y-axis along a hand palm as shown in Fig. 13. In addition a local coordinate

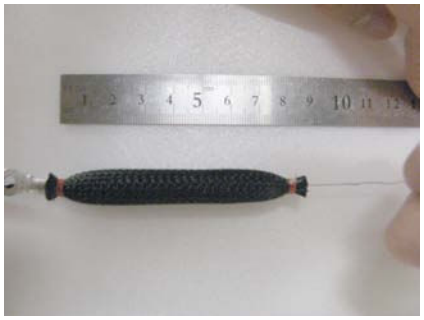

Fig. 16. The power type McKibben pneumatic artificial muscle

system is defined as to set its origin at the tip of the index finger. Y_E-axis is along the direction of the grasping force and the X_E-axis is along the direction of the reaction force. The Y_E-axis has a relative angle ψ in counterclockwise direction from the line connecting the fingertip of thumb and index finger as shown in Fig.13.

Fig.15 shows a reaction forces of an index finger when a grasping force of its finger is changed from 2[N] to 6[N]. The stiffness of the index finger that is an inclination of the reaction force and the displacement curve increases as the grasping force increases.

C. Stiffness measurement of the polyarticular tendon drive system

The polyarticular tendon drive system as shown in Fig.17 is developed in order to measure the fingertip stiffness. The tensions are initially controlled by McKibben pneumatic artificial muscle so that the fingertip generates the reference grasping force. The three tendons are arranged along the parameters estimated by numerical simulations in previous study in order to simulate the variable stiffness of human finger. The six-axis force sensor mounted on the slide table, the potentiometer, and the DC motor are arranged in the same way as shown in Fig.14.

In this system, the second tendon requires to generate large tension in order to generate reference grasping force. However, the McKibben pneumatic artificial muscle shown in Fig.2 cannot generate enough tension. Therefore, we use another McKibben pneumatic artificial muscle shown in Fig.16. This artificial muscle can generate large tension. In this artificial muscle, the parameters $\alpha, \beta, \gamma, a_1, a_0, b_1, b_0$ in eq.1, 13 are estimated in same way written in section III. The estimated parameters are shown in Table III

Fig.18 shows the stiffness of the polyarticular tendon drive system. The stiffness increases as the grasping force increases. This result is similar to the stiffness of a human

TABLE III

ESTIMATED PARAMETERS OF POWER TYPE MCKIBBEN PNEUMATIC ARTIFICIAL MUSCLE

α	β	γ
9.329	0.897	-0.043

a_1	a_0	b_1	b_0
-1010.69	269.508	-25.853	10.362

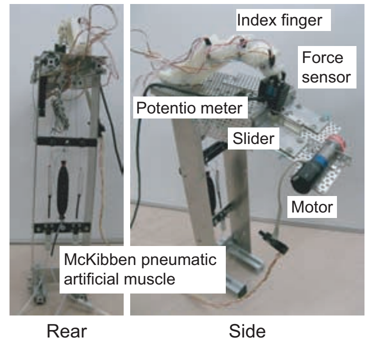

Fig. 17. Polyarticular tendon drive system for fingertip stiffness measurement.

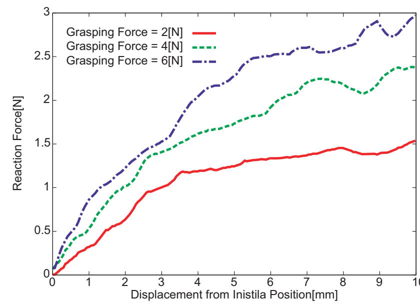

Fig. 18. Reaction force of polyarticular tendon drive system

index finger.

VI. CONCLUSION

We propose the control method of McKibben pneumatic artificial muscle without pressure sensor by using dynamic model and switching time control in order to reduce weight and size and validate this method. Next, we investigate the fingertip stiffness of system by using our proposed polyarticular tendon drive system in order to simulate human finger dexterity.

In our future work, we design the shell structure that can disperse pressure from wearable system.

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REFERENCES

[1] R. Doshi, C. Yeh, M. LeBlanc, ”The design and development of a gloveless endokeletal prosthetic hand”, Journal of Rehabilitation Research and Development, Vol.35, No.4, pp.388-395, 1998

[2] Y. Hasegawa, Y. Mikami, K. Watanabe, Z. Firouzimehr and Y. Sankai, “Wearable Handling Support System for Paralyzed Patient,” IEEE International Conference on Intelligent Robots and Systems, pp.741-746, 2008

[3] M. Iwaki, Y. Hasegawa, Y. Sankai, ”Fingertip stiffness control using antagonistic pair of polyarticular tendons drive system,” IEEE International Conference on Robotics and Biomimetics, pp.925-930, 2009

[4] N. Tsujiuchi, T. Koizumi, H. Kan, H. Takeda, T. Kudawara, M. Hirano, ”Modeling and Control of a Joint Driven by Pneumatic Actuator,” IEEE Industrial Electronics Society, pp.2291-2296, 2009

[5] F. Daerden and D. Lefeber, ”The concept and design of pleated pneumatic artificial muscles,” International Journal of Fluid Power, Vol.2, No.3, pp.41-50, 2001

[6] F.A. Mussa-Ivaldi, N. Hogan and E. Bizzi, “Neural, mechanical and geometric factors subserving arm posture in humans,” The Journal of neuroscience, vol.5, pp.2732-2743, 1985