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Development of Prosthetic Arm with Pneumatic Prosthetic Hand and Tendon-Driven Wrist

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Abstract—**Recently, various prosthetic arms have been developed, but few are both attractive and functional. Considering human coexistence, prosthetic arms must be both safe and flexible. In this research, we developed a novel prosthetic arm with a five-fingered prosthetic hand using our original pneumatic actuators and a slender tendon-driven wrist using a wire drive and two small motors. Because the prosthetic hand's driving source is comprised of small pneumatic actuators, the prosthetic hand is safe when it makes contact with people; it can also operate flexibly. In addition, the arm has a tendon-driven wrist to expand its motion space and to perform many operations. First, we explain the pneumatic hand's drive mechanism and its tendon-driven wrist. Next, we identify the characteristics of the hand and the wrist and construct a control system for this arm and verify its control performance.**

I. INTRODUCTION

Recently, various prosthetic hands have been developed, including both cosmetic prosthetic hands and functional prosthetic hands. A cosmetic prosthetic hand is beautiful, but its operating performance is poor. On the other hand, a functional prosthetic hand can work flexibly, but it looks bad. To address such a trade-off, we developed a prosthetic hand that is both beautiful and functional. We also need to produce a hand that is safe during contact with people.

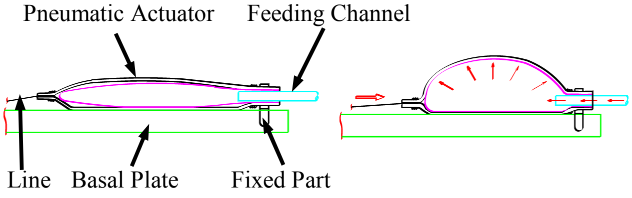
Considering the above situation, in this research we developed a state-of-the-art prosthetic arm, made an original muscle-type pneumatic actuator [1] (hereinafter pneumatic actuators), and applied it to a five-fingered prosthetic hand that can satisfy flexible motions. Using our pneumatic actuator as the driving source makes the prosthetic hand safe because the actuator has an air compressibility effect. Pneumatic actuators have been studied for a long time, but since conventional ones are too big, they cannot be directly applied to prosthetic hands [2],[3].

In addition, we developed a tendon-driven wrist so slender that it can be implemented in a prosthetic arm. This wrist, which is driven by small two motors and a wire, can operate two different motions. The mechanism that harmonized the two motors can generate high torque. To implement the wrist in a prosthetic arm, the hand's motion space must be expanded so that it can operate more tasks. When applying the prosthetic arm to humans, we need to control its motions using biosignals, including myo-electric signals. We conducted an experiment to control the arm motions.

II. PNEUMATIC PROSTHETIC HAND

A. Pneumatic Actuator

First, we explain the mechanism of our pneumatic actuator. Its most outstanding feature is its simplicity and convenience based on the compressibility of air. The actuator is composed of a rubber balloon, a net that covers the balloon, and a feeding channel that injects compressed air into the balloon. Expanding the rubber balloon shortens the net in the longitudinal direction and generates force. The expansion and contraction operations can be controlled by adjusting the pressure in the rubber balloon. The McKibben-type artificial muscle is a typical actuator of this kind [4]. Many research consortiums are developing robots using such pneumatic actuators [5],[6]. Fig. 1 shows the mechanism of the pneumatic actuator. The basic mechanism is identical as that of the conventional McKibben-type actuator, but our actuator can be driven by low-pressure and low-volume of compressed air. It can also fit directly in a prosthetic finger because our pneumatic actuator is much smaller than conventional ones.



(a) Initial Condition (b) Pressurized Condition

Fig. 1 Schematic of Pneumatic Actuator

B. Five-Fingered Prosthetic Hand

We developed a five-fingered prosthetic hand using a previously described pneumatic actuator that imitates a human right hand. The front and back sides of the prosthetic hand are shown in Fig. 2. The finger, which has the same movable range as a human one, can operate flexibly because the pneumatic actuator is implemented directly in the prosthetic fingers. The four fingers (forefinger, long, annular, and little) have DIP, PIP, and MP joints. In the MP joint, we arranged two pneumatic actuators for flexion and extension operations. In the DIP and PIP joints, we included a pneumatic actuator for extension operation and a rubber gum

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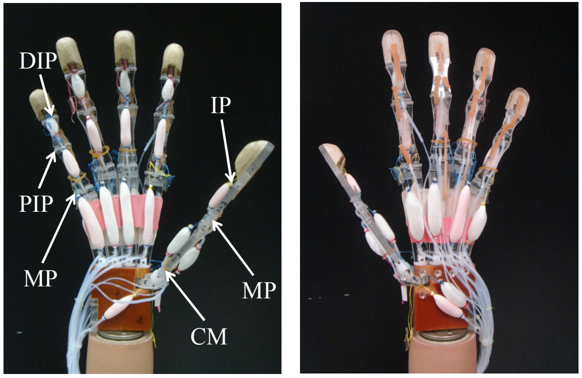
for flexion operation.

The thumb mechanism is different from the other fingers. The thumb has IP, MP, and CM joints. In the IP joint, we arranged a pneumatic actuator for flexion operation and a rubber gum for extension operation. In the MP joint, we placed two pneumatic actuators for flexion and extension operations. To give the degree of freedom of palmer adduction, the CM joint has three actuators to rotate the palm direction.

Since we designed such a five-fingered prosthetic hand and expanded its motion space to nearly resemble that of a human hand, the prosthetic hand can grasp various objects like human hands. Our hand can grasp an object that weighs up to 500 [g]. Even though it is only driven by a low-volume of compressed air, it can generate enough power to hold a plastic bottle (Fig. 3).



(a) Front Side (b) Back Side

Fig. 2 Five-Fingered Prosthetic Hand

Fig. 3 Prosthetic Hand Holding an Object

C. *Dynamic Characteristics of Pneumatic Actuator*

We examined the relationship between inner pressure and the generated force of the pneumatic actuators while injecting air into the balloon and exhausting it. Three kinds of actuators (22, 37, 52 [mm]) were used in the experiment. Fig. 4 shows the relationship between the inner pressure and generated force. Even though the pneumatic actuators have hysteresis characteristics, we suppose that the relationship of the inner pressure to the generated force is almost linear and construct a control system.

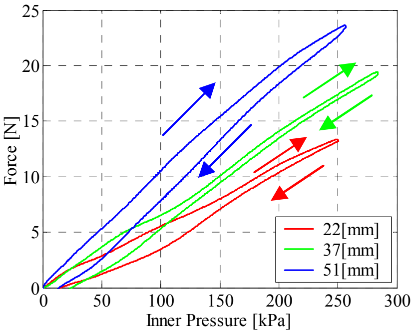
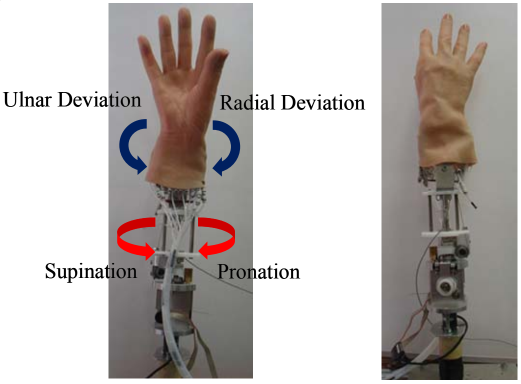


Fig. 4 Relationship between Inner Pressure and Force

III. TENDON-DRIVEN WRIST

A. *Tendon-Driven Wrist*

We developed a wire-driven wrist called a tendon-driven wrist that fits in the prosthetic hand to expand the motion space and to apply the hand to various tasks. This wrist can operate two different motions using a wire driven by harmonizing two motors. One is called pronation and supination, which means rotating the palm; the other is called radial and ulnar deviations, which means shaking hands. Harmonizing two motors generates high torque. The wrist is slender enough to be implemented in prosthetic forearms. Fig. 5 shows our tendon-driven wrist.



(a) Front Side (b) Back Side

Fig. 5 Tendon-Driven Wrist

B. *Mechanism of Tendon-Driven Wrist*

First, we explain the drive mechanism of pronation and supination. Fig. 6 shows the mechanism of the tendon-driven wrist. When we apply the same voltage to the two motors, the wire is pulled in the same direction by several motors, and the pulley in Fig. 6 is pulled. Consequently, the motion of rotation occurs in the main axis. This is the pronation mechanism. Compared with this, supination is the inverse rotation that occurs when the pulley in the counter side is pulled. The basic mechanism of pronation and supination is the same.

Next, we explain the drive mechanism of radial and ulnar deviations. Fig. 7 shows the mechanism of the tendon-driven wrist. We apply arbitrary voltage to one motor and reversed sign voltage to the other. Unlike pronation and supination, the pulley is not pulled, but the wire connecting the attached part of the prosthetic hand is pulled, and the motion of rotation occurs at that part. Radial and ulnar deviations are distinguished by the rotation direction, but the basic mechanism of the motion is the same.

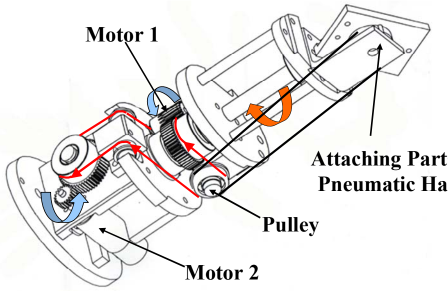


Fig. 6 Mechanism of Pronation and Supination

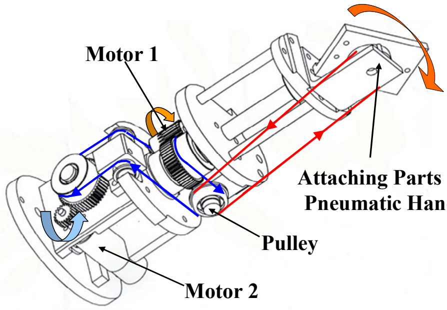


Fig. 7 Mechanism of Radial and Ulnar Deviations

C. *Dynamic Characteristics of Tendon-Driven Wrist*

We experimentally determined the dynamic characteristics of pronation and supination and discovered the relationship between the applied voltage and the angular speed of pronation and supination. The motion characteristics are shown in Fig. 8; here the relationship between the applied voltage and the angular speed is linear.

Next, we examined the dynamic characteristics of radial and ulnar deviations. The relationship between applied plus voltage and the angular speed of the radial and ulnar deviations is shown in Fig. 9. The relationship between the applied voltage and the angular speed is almost linear.

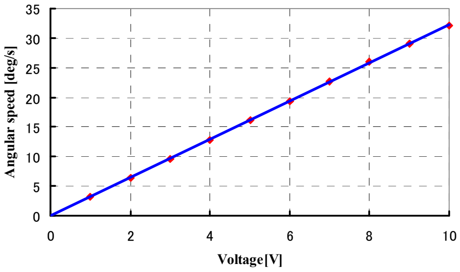


Fig. 8 Characteristics of Pronation and Supination

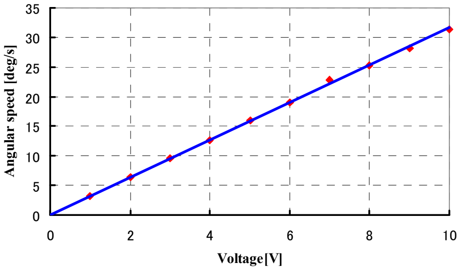


Fig. 9 Characteristics of Radial and Ulnar Deviations

IV. CONTROL OF MOTION

A. *Five-Fingered Prosthetic Hand*

In our past research, we controlled the joint model to manipulate several joints of a five-fingered prosthetic hand [7] by making a one-link model to control the joint's force and angle. We used an electro-pneumatic regulator (EVT-T11R electro-pneumatic regulator; CKD Corp.) to adjust the inner pressure of the pneumatic actuator and to control the injected air pressure. After controlling the one-link model with cascade control, the result showed very good control performance. We can also control the joint's angle using PID control with a gap. Fig. 10 shows the result of controlling the joint's angle. Applying it to a five-fingered prosthetic hand allows control of the angle of the finger joint.

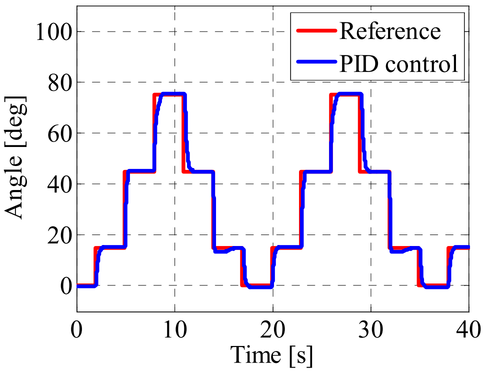


Fig. 10 Response of Staircase Signal

B. *Tendon-Driven Wrist*

We controlled the motions of the tendon-driven wrist by conducting an angle control experiment of pronation and supination and radial and ulnar deviations with fuzzy control. We used a triangular membership function to fuzzify with Mamdani-style fuzzy inference method. After that, we defuzzified with a center-average method and determined the fuzzy parameters using MATLAB/SIMULINK simulations with previously described linear characteristics. The controller is designed with these parameters and implemented with DSP (DS1005; dSPACE Inc.).

First, the angular tracking experimental results of pronation and supination for step and sinusoidal signals are shown in Figs. 11 and 12. In the pronation and supination experiment, the result shows good tracking performance.

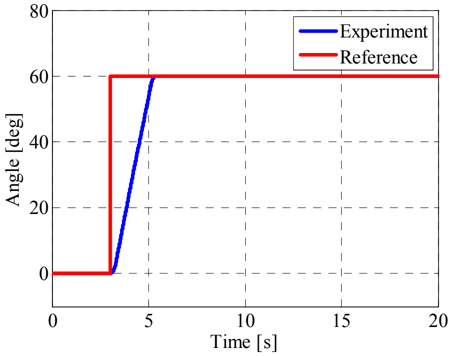


Fig. 11 Response of Step Signal: Pronation

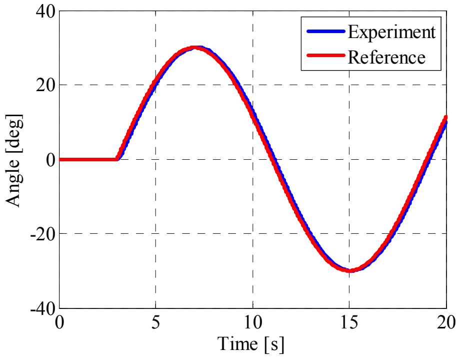


Fig. 12 Response of Sinusoidal Signal: Pronation and Spination

Next, we conducted an angle tracking control experiment of radial and ulnar deviations for step and sinusoidal signals (Figs. 13 and 14). In Fig. 13, overshoot can be found. But it recovers so fast that the result still shows good tracking performance. Comparing the sinusoidal tracking result in Fig. 14 with those of pronation and supination in Fig. 12, Fig. 14 shows poor tracking performance. But it still shows enough tracking control performance for applications to prosthetic arms.

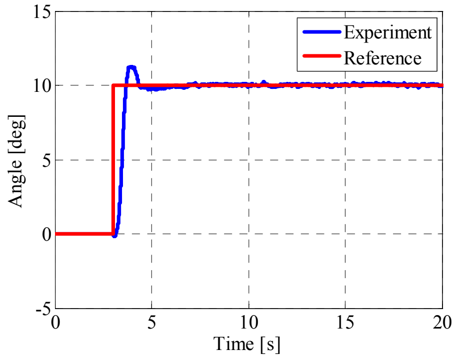


Fig. 13 Response of Step Signal: Radial Deviation

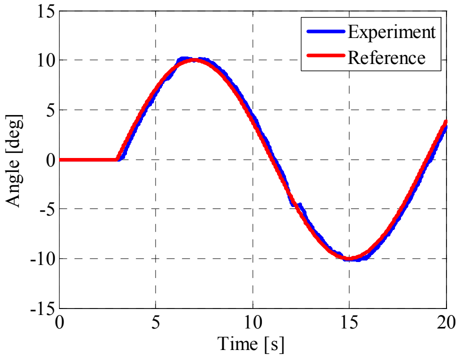


Fig. 14 Response of Sinusoidal Signal: Radial and Ulnar Deviations

In the second experiment, we simultaneously controlled the two different motions described above. First, we applied two motors to arbitrary voltage and identified the dynamic characteristics. The relationship between the sum of the applied voltage and the angular velocity of pronation and supination is almost linear. The relationship between the difference of the applied voltage and the angular velocity of the radial and ulnar deviations is also linear. With this characteristic, we designed a controller using the superposition of applied voltage and fuzzy control. Fig. 15 shows the result of simultaneous control. In consequence, simultaneous control of two motions is possible.

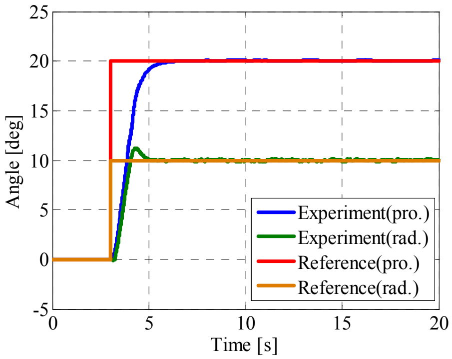


Fig. 15 Response of Step Signals: Simultaneous Control

V. CONCLUSION

In this research, we developed a flexible prosthetic arm and a five-fingered prosthetic hand with pneumatic actuators. We also developed a tendon-driven wrist that fits in the prosthetic hand. Moreover, we conducted control experiments to freely manipulate the prosthetic arm. Based on this research, we obtained the following conclusions:

1) Our five-fingered prosthetic hand operates flexibly using pneumatic actuators.
2) For expanding motion space, we developed a tendon-driven wrist that operated various tasks.
3) We can control the motions of a five-fingered prosthetic hand and a tendon-driven wrist.

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