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Development of Grip Amplified Glove using Bi-articular Mechanism with Pneumatic Artificial Rubber Muscle

Kotaro Tadano, Masao Akai, Kazuo Kadota, Kenji Kawashima

***Abstract*—In this paper, a grip amplified glove using pneumatic artificial rubber muscles (PARMs) which are covered with a exoskeleton structure is developed. A bi-articular mechanism with a PARM that is suitable for bending finger is realized. The glove has totally 10 DOFs consist of four units. To achieve power-assist motion properly, the PI control, which is based on the pressure value from the balloon sensor, is performed. This sensor makes the applied part free from electricity. To evaluate the validity of glove, the skin surface electromyography (EMG) signals of muscles are measured during grasping. These results demonstrate that the effectiveness of the power amplified glove.**

I. Introduction

Power-assist robots have been developed for amplify human muscle strength [1]. These robots are widely expected to use in various fields such as medical welfare, rescue, agriculture, physical labor in the factory and so on.

To actuate the systems, electrical motor are widely used. However, it needs effort to make it lightweight and compact. Pneumatic actuators have advantages such as high weight-power ratio, compressibility, low heat generation and clean energy. Therefore, the actuators have applied to drive power assist robots. Yamamoto et al. developed a power assist suit for nurse caring with pneumatic actuator utilizing pressure cuffs [2]. Load cells are used to detect the muscle motion of the wearer to achieve harmonic motion with the system.

Pneumatic rubber muscles (PARMs) are often used in the power assist robot due to high weight-power ratio and lightweight. The characteristics of PARMs are studied and known to have close feature to human muscle [3-7]. In order to provide muscular support for the manual worker, a "muscle suit" has been developed [8]. The muscle suit consists of a mechanical armor-type frames and PARMs. Using a new link mechanism for the shoulder joint which consists of two half-circle links with for universal joints, all motion for upper limb has been developed.

In the fields mentioned above, one hand is always in active to accomplish the task. Therefore, the hand assist device is useful. There are several researches to assist the hand [9-11]. PARMs are used in the power assist glove, in order to support activity of daily living of aged or disable person safety and easily [11]. By using PARMs, the glove can assist various daily finger tasks owing to its flexibility and lightweight [12]. However, the degree of freedom (DOF) is yet to be enough. Biological signals such as EMG signals or the hardness of skin surface are mainly used as sensing elements in the conventional wearable power-assist systems. However, as these biological signals include noises, it is not always easy to identify the motions of wearer accurately.

In this paper, a grip amplified glove using bi-articular mechanism is developed. Pneumatic artificial rubber muscles (PARM) are used as the actuator. The glove has totally 10 DOFs. To achieve power-assist motion properly, PI control, which is based on the pressure values from the balloon sensor, is performed. Synchronized actuation of the PARM adds to the user's own movements provides power and support the grasping. As the balloon type sensors are used, electric circuits can be separated from the finger parts that have advantage in the use of hostile environment. To evaluate the validity of glove, the skin surface electromyography (EMG) signals of muscles are measured during grasping.

II. POWER-AMPLIFIED GLOVE

Fig.1 shows the joints of fingers. The large joints in the hand at the base of each finger are known as the metacarpophalangeal joints (MP joints). The three phalanges in each finger are separated by two joints, called interphalangeal joints (IP joints). The one closest to the MP joint is called the distal IP joint (DIP joint). The thumb only has one IP joint between the two thumb phalanges. The IP joints of the digits also work like hinges when you bend and straighten your fingers and thumb. Proximal interphalangeal joint (PIP joint) is between the first and second phalanx. The glove is developed to assist the movement of these joints.

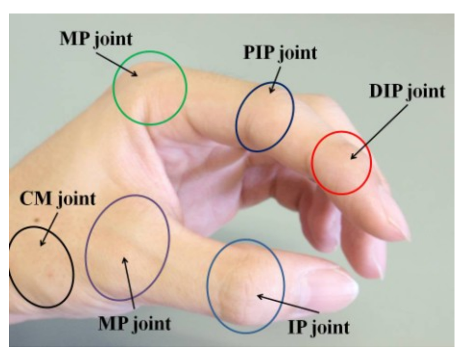

Fig.1 Joints of fingers

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Kotaro Tadano and Kenji.Kawashima are with Precision and Intelligence Laboratory,Tokyo Institute of Technology, Yokohama, Japan (phone:+81-45-924-5032;fax:+81-45-924-5486;e-mail: tadano@pi.titech.ac.jp,kkawashi@pi.titech.ac.jp).
Masao.Akai and Kadota. Kadota are with the Tokyo Institute of Technology, Yokohama,Japan(e-mail:kadota@hst.titech.ac.jp,akai.m.aa@m.titech.ac.jp)

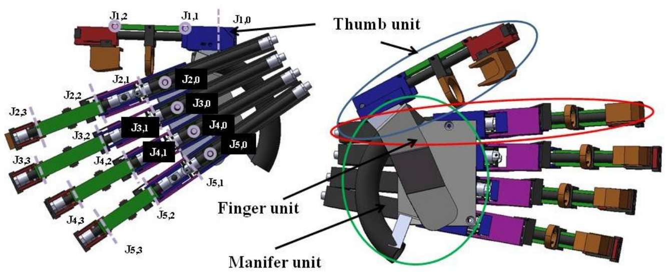


Fig.2 Power amplified glove design

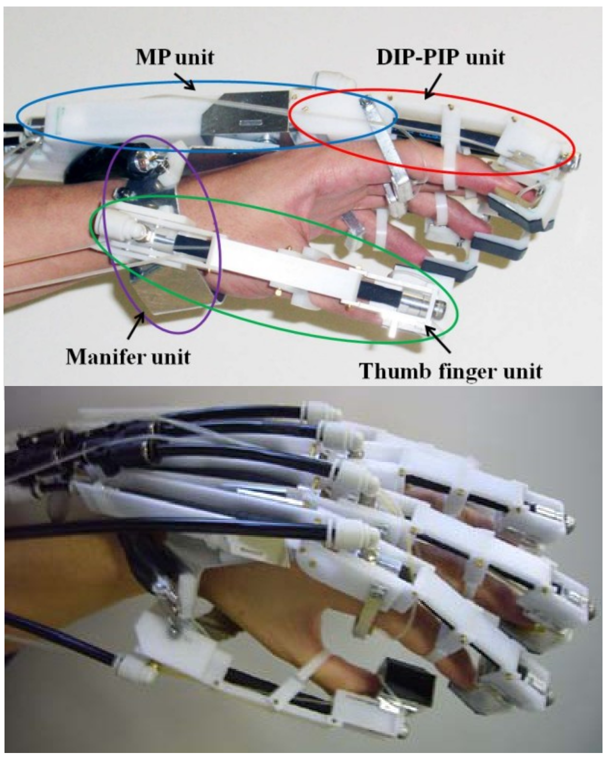


Fig.3 Developed power amplified glove

A. Bi-articular Mechanism

The schematic of the developed power amplified glove is shown in Fig.2. Photograph of the glove is shown in Fig.3. The glove consists of thumb unit, finger unit and manifer unit. The thumb and finger unit have 2 DOFs. The joints are actuated with PARMs manufactured by FESTO having the inner diameter of 5mm. The contract ratio of the muscle is 20% at the maximum and can generate 20N tension. The PARM is placed into an exoskeleton structure of the finger unit. Polyacetal resin was selected for the structure to realize lightweight. The weight of the glove is only 550g.

In this study, we developed a bi-articular mechanism which can rotate two joints with a PARM that can be helpful for grasping. Two joints from the tip of finger, called DIP and PIP joints, are actuated with the mechanism. Both ends of the PARM are fastened at the ends of the exoskeleton. This mechanism transformed contracted motion of PARM into rotary motion of two joints at the same time. When the compressed air is charged to the PARM, buckling of the PARM caused by the exoskeleton structure induce bending of joints as shown in Fig.4. The moment arms of the joints are the difference in height between the joints and connected positions of the PARM at the tip and the bottom of the unit.

B. Each unit

1) Finger unit : Fig.5 shows the schematic drawing of finger units. The units consist of MP and DIP-PIP unit. Slider mechanisms are used in the units for high adjustability to wearer. The MP unit realized bending motion by a link mechanism as shown in the upper figure of Fig.5. Proposed bi-articular mechanism is used for the DIP-PIP unit.

2) Manifer and thumb unit: The schematic drawing of manifer and thumb unit are shown in Fig.6 and Fig.7. The manifer unit for CM joint realized rotation by pulling the PARM with a wire suspended by the pulleys.

The thumb unit is almost the same as the DIP-PIP unit. The proposed bi-articular mechanism was applied for IP and MP joints.

The specifications of the units are summarized in Table 1.

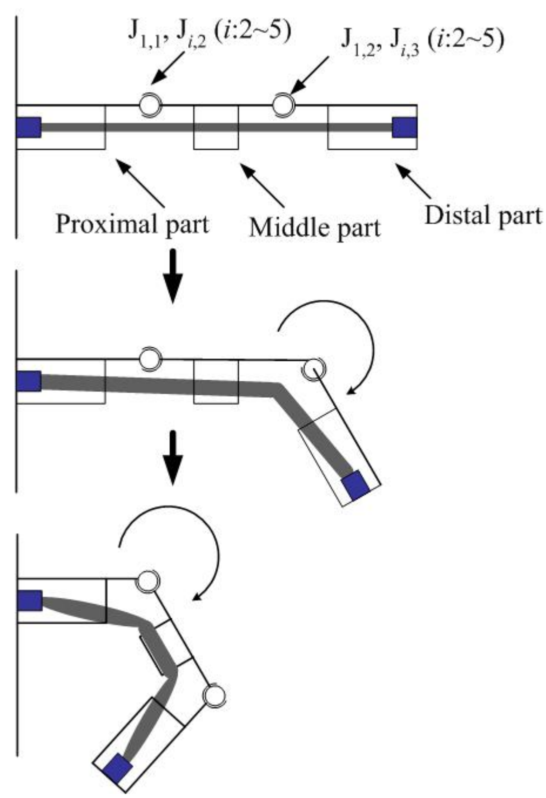
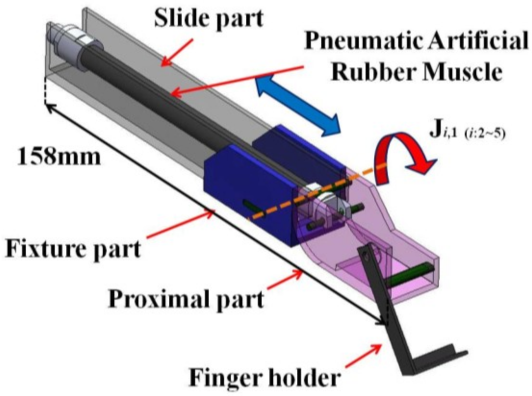


Fig.4 Proposed bi-articular mechanism



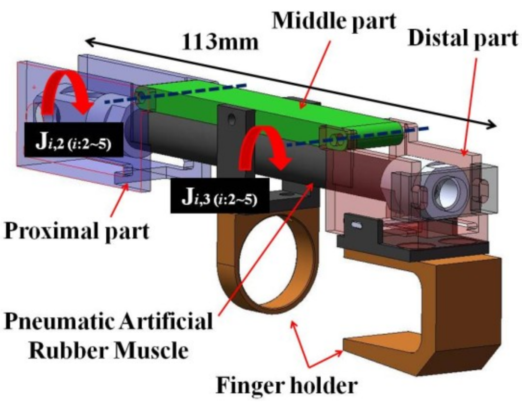


Fig.5 Finger units
(upper: MP unit, lower: DIP-PIP unit)

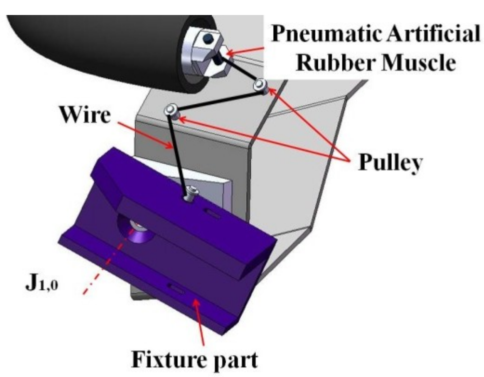


Fig.6 Manifer unit

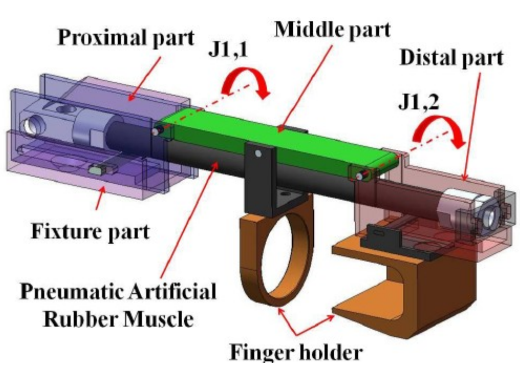


Fig.7 Thumb unit

Table 1 Specifications of finger units

Finger unit	Length [mm]	Available angle [deg]		Maximum torque [Nm]	Weight [g]
		MP, PIP,CM	DIP, IP		
DIP-PIP unit	117~113	20	30	0.2	46.4~35.6
MP unit	158	80		0.5	36.4
Thumb IP-MP	137	20	30	0.2	45.9
Thumb CM		40		0.5	

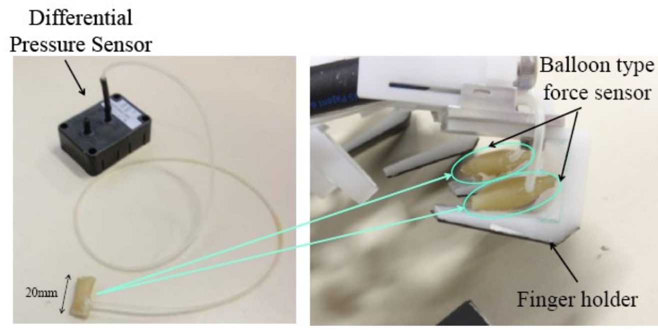


Fig.8 Photograph of balloon sensor

C. Balloon Sensor

In order to operate this glove, a balloon sensor has been developed and installed at the tip part of each unit to detect the finger motion. Fig.8 shows the photograph of the balloon sensor. This sensor is composed of a rubber tube with the outer and the inner diameter 7, 5mm and the length 20mm. One end of tube is bonded with epoxy, and the other end is connected to a differential pressure sensor (KL-17 Nagano Keiki Co., Ltd.) through a pipe line which outer diameter is 3mm. According to the deformation of the rubber sensor by the external force F, the inner pressure of the rubber sensor P_b increases. On the other hand, recovery from the deformation causes the reduction of the inner pressure. By measuring the inner pressure with the connected differential pressure sensor, the external force can be detected. The balloon sensor is equipped at the finger holder as shown in Fig.8. As electric circuits can be separated from the finger parts, the sensor has advantage in the use of hostile environment.

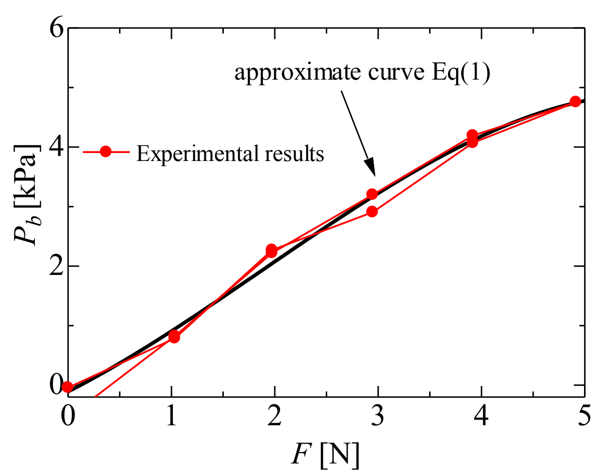


Fig.9 Static characteristics of balloon type sensor

Fig.9 shows the relation between the external force and the inner pressure of the sensor. Although small hysteresis can be observed, the relation has certain correlations. The purpose of the power amplified glove is to amplify the generated force by the wearer. Therefore, the sensor is considered to be useful even though the force measurement is not so accurate. The relation was approximated as a third order curve as follows:

$$P_b = -0.03F^3 + 0.16F^2 + 0.88F - 0.11 \quad (1)$$

III. Control System

To realize harmonic motion with the glove and finger, the detected pressure was amplified with a certain value. The image is shown in Fig.10. In the control system of the glove, the power is generated to correspond to the pressure in the PARM.

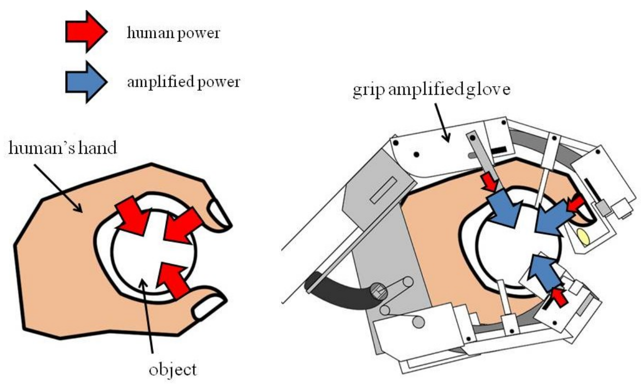


Fig.10 Image of power amplify

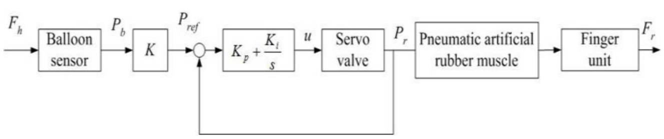


Fig.11 Block diagram of the glove system

Table 2 Parameters of controller

	Fore DIP-PIP	Fore MP	Middle DIP-PIP	Middle MP	Thumb IP-MP	Thumb CM
K [MPa/N]	8.0	22.0	15.0	40.0	5.0	25.0
Kp [V/MPa]	5.0	5.0	6.0	5.0	4.0	5.0
Ki [V/MPa･s]	0.1	0.1	0.01	0.05	0.1	0.1

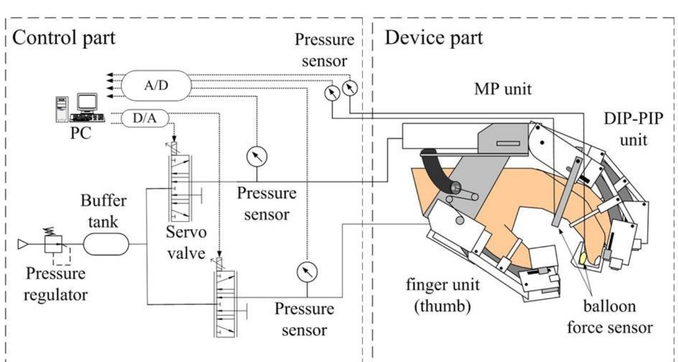


Fig.12 Experimental apparatus for grip amplified glove

The output voltage of servo valves is determined with this control system. Spool type servo valves made by FESTO were used. The block diagram of the arm unit is shown in Fig.11. The pressure is controlled by a PI control system. K is the controller gain of the force-pressure conversion factor given with the balloon sensor, and K_p and K_i are the proportional gain and the integral gain, respectively. Each gain is determined by try and error to give the best response in the experiment. The selected gains of arm unit are shown in Table 2. The control system is developed on software which is built in Visual C#.

Experimental setup of the glove can be summarized in Fig.12. The measured values are taken into PC through AD converter. The calculated control signals are given to the servo valves through DA converter. Ten servo valves are used. It is clear from Fig.12 that no electrical sensors or actuators are installed at the device part. Therefore, the glove is environmentally-resistant. Although the control part is too large and heavy to wear lightly at present, it can be used fixed working area.

IV. Experimental Result

A. Characteristics of finger unit

In order to determine the characteristics of the unit, some experiments were conducted. In the experiments, a rotary encoder was attached to the MP joint and the DIP joint using jigs to measure each rotation angle. Also, load mass was connected to the end of the finger unit. The torque was calculated from the angle and the load mass.

First, torque-angle characteristics of the units were measured with constant pressures, changing the load mass. The characteristics of torque-angle at the MP joint are shown in Fig.13, and that of the DIP joint are shown in Fig.14. The lateral axis indicates the angle and the longitudinal axis represents the pressure. It is clear from Fig.13 and Fig.14 that the MP joint and the DIP joint has maximum torque of 0.35 Nm and 0.4 Nm, respectively. The hysteresis shown in the experimental results are due to the characteristics of the PARM. We have also confirmed that the maximum torque is 0.2 Nm for PIP joint.

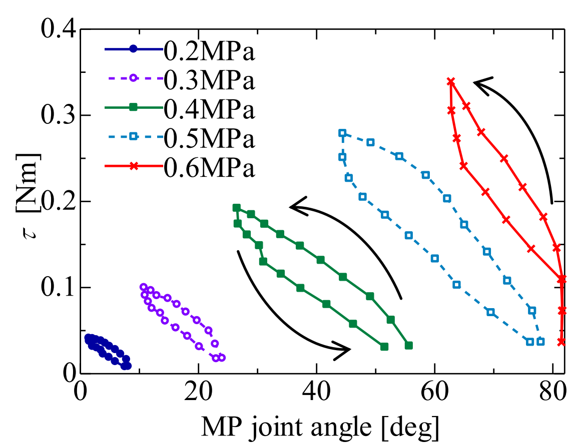


Fig.13 Relation between angle and torque of MP joint

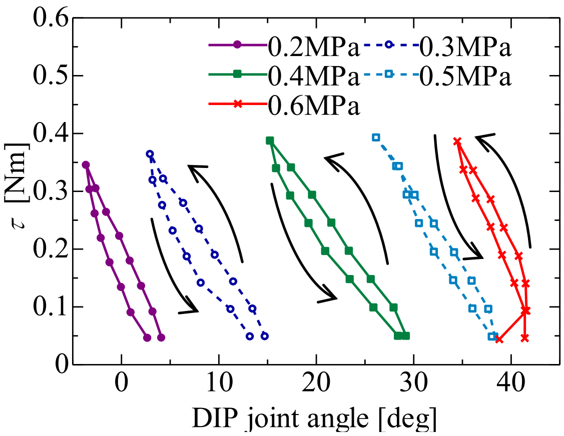


Fig.14 Relation between angle and torque DIP joint

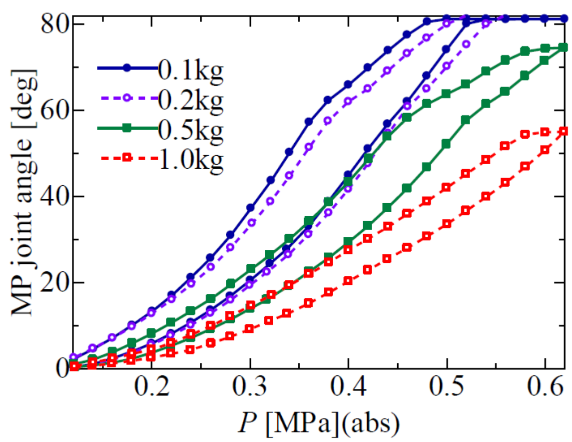


Fig.15 Relation between joint angle and pressure of MP joint

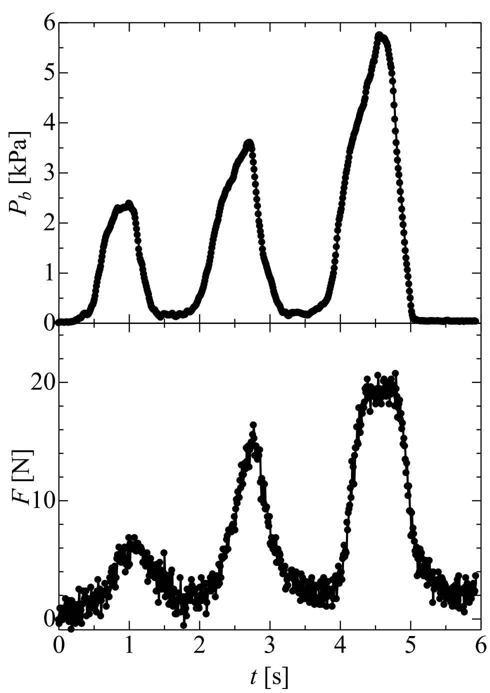


Fig.16 Experimental results of grip amplify

Fig.15 shows the relation between pressure and the joint angle. The characteristics were measured for four different load mass. It is clear that the 80 deg bending is realized with 0.2 kg load mass.

The maximum bending angle and torque for finger unit are summarized as follows: IP joint: 50 deg and 0.5 Nm. MP joint: 25 deg and 0.2 Nm. CM joint: 40 deg and 0.3 Nm.

B. Glove control results

The effectiveness of the developed glove was investigated experimentally. Firstly, a force sensor was pushed by the finger with wearing the glove and the relation between the output of the balloon sensor P_b and the output of the force sensor F were measured.

Fig.16 shows the experimental results. The upper figure shows the time depended balloon pressure and the lower figure shows that of force measured with the force sensor. Fig.16 shows that F follows well to P_b and is almost proportional to P_b. As a result, both curves show the same tendency. The figure shows that the glove amplified the input force. It is confirmed that the controller is working as we desired.

C. EMG signals

Electromyogram (EMG) is one of various bioelectrical signals generated from the human body. EMG signals are used for inspecting the effect of power-assist [13]-[15]. In this research, EMG is also used. Fig.17 shows the position of measured muscle.

Fig.18 shows EMG signals of a subject of the brachioradialis of grasping the load of 3 kg. The lateral axis shows the time. The upper, middle and the lower figure show the results with bare hand, with the glove (no power amplification) and with the glove (power amplified), respectively.

It can be seen from the figure that there is little difference in the results between bare hand and the no active glove. This means the assist glove itself is not a burden to the hand. With the power amplification, the amplitude of EMG signal becomes clearly smaller. Therefore the effectiveness of the glove is confirmed.

Finally, an object in a tank filled with water was grasped with the glove as shown in Fig.19 to prove the environmentally-resistant of the glove. We succeeded in grasping 3 kg object in the water for many times and the glove worked well even after gotten wet.

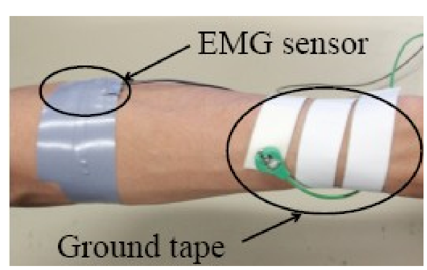


Fig.17 Position of measured muscles

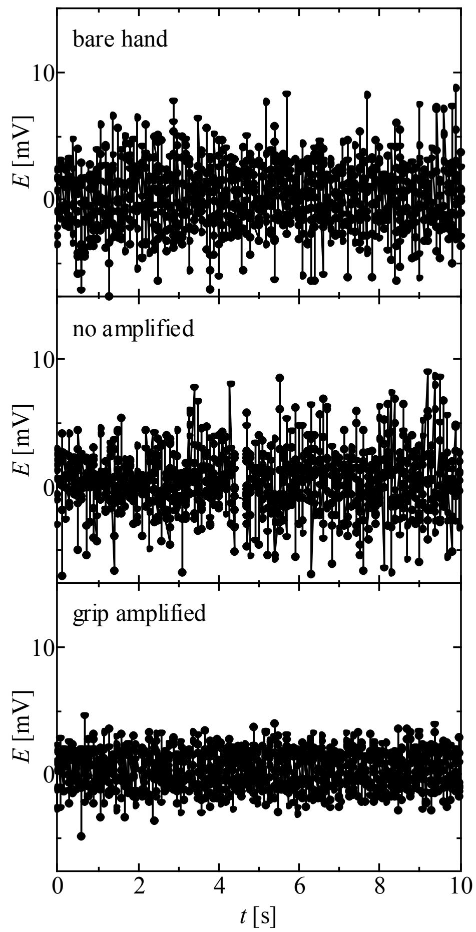


Fig.18 Measured results of EMG signals

Fig.19 Photograph of under water experiment

V. Conclusions

In this research, the power amplified glove using PARMs with a balloon sensor for assisting grasping was developed. The finger part resembles the motion of bi-articular muscles, and moves PIP-DIP joint and MP joint using one PARM.

To achieve power amplified motion properly, PI control, which is based on the pressure values from the balloon sensor, is performed. This sensor makes the applied part free from electricity. Synchronized actuation of the PARM adds to the user's own movements.

To evaluate the power-assist performance, EMG patterns of muscles were measured. These results demonstrate that the effectiveness of the power amplified glove. The validity of proposed method was demonstrated experimentally.

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