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Paper:

Development of A Five-finger Prosthetic Hand Using Ultrasonic Motors Controlled by Two EMG Signals

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This paper describes an EMG controlled prosthetic hand with five fingers actuated by ultrasonic motors. The grasping mechanism proposed is capable of determining the joint angle of each finger in a way that the five fingers can follow the shape of objects and realize a flexible grasp. Estimation of the motion intended by an amputee is realized by using a neural network involving statistical structures from surface myoelectric signals. The present paper shows that discrimination of four or six kinds of limb-functions is realized with a small number of two electrodes by utilizing the frequency characteristics of EMG signals.

Keywords: EMG prosthetic hand, five fingers, compliance control, neural network, motion discrimination

1. Introduction

EMG prosthetic hands, especially forearms, have been approved of a choice of prosthetics after amputation in Western nations. Presumably, many latent disabled need EMG prosthetic hands in Japan[1].

A variety of prosthetic hands has been studied and developed, so far. In Japan, the study was started by Kato et al., who used the rotary servo actuator, a hydraulically operated motor, as the actuator, and developed a forearm prosthetic hand with five fingers controlled by a microcomputer using pattern recognition of myoelectric signals from the skin surface[2]. Nishioka, using the Waseda hand devised by Kato et al., developed the WIME hand, an EMG prosthetic hand for forearms, which was the first to succeed in commercialization in Japan[3]. This includes two types of five- and three-finger drives and can have a cosmetic glove fitted. Ito et al. developed a forearm prosthetic hand using an ultrasonic motor as actuator, which is quiet and features low velocity and high torque. This prosthetic hand is capable of realizing six motions. i.e., wrist flection and extension, forearm pronation and supination, and hand grasping and opening[4]. Okuno et al. developed a prototype prosthetic hand controlled by an analog signal simulating motion of the human hand.[5], and Harada et al. have developed a hand with five fingers having 23 degrees of freedom[6]. Outside Japan, studies have included pioneer prototypes such as the Boston arm[7] by MIT and the Utah arm[8] by Utah State University. In China, various type of EMG prosthetic hands are being put to practical use[9].

For control of EMG prosthetic hands, there are many studies on motion discrimination by neural networks. Kelly et al. studied motion discrimination from the surface myoelectric signal using two neural networks, the Hopfield Network and Multilayer Perceptron[10]. Hiraiwa et al. realized discrimination of stationary finger motion, continuous finger bending, and estimation of the joint angle using back propagation neural networks from frequency characteristics of EMG[11]. These studies used ordinary neural networks for EMG discrimination. Tsuji et al. proposed a new neural network involving a statistical structure, and showed that discrimination accuracy is greatly improved by considering EMG statistical features[12,13].

As mentioned above, many studies have continued on mechanism and control of prosthetic hands, but almost of all the prosthetic hands actually used by amputees are so far based on the design concept of Ottobock of Germany[14]. Features of prosthetic hands by Ottobock include simple structure and durability in mechanism and control, and sufficient consideration of maintainability by part modularization. It uses a three finger mechanism centered on holding cylinders, and it is difficult to stably grasp other objects due to a lack of flexibility of the finger mechanism. The lack of flexibility means the finger mechanism itself is a "hard mechanism". Even when not holding an object, there is a danger of breaking the object in the surroundings by its fingers. This "hard mechanism" is also adopted in the five finger type WIME hand by Nishioka. In the design concept of Ottobock, one pair of myoelectric electrodes is normally used for one motion in discrimination, so the use of two pairs of electrodes enables control of only two motion on one degree of freedom (normally hand gripping and opening). Recently, controllers with built-in microcomputers enable four functions with two pair of electrodes[15] to increase operable functions by judging the level of the myoelectric signal. The user must output precisely different myoelectric signal to each electrode and the load of operation is naturally increased.

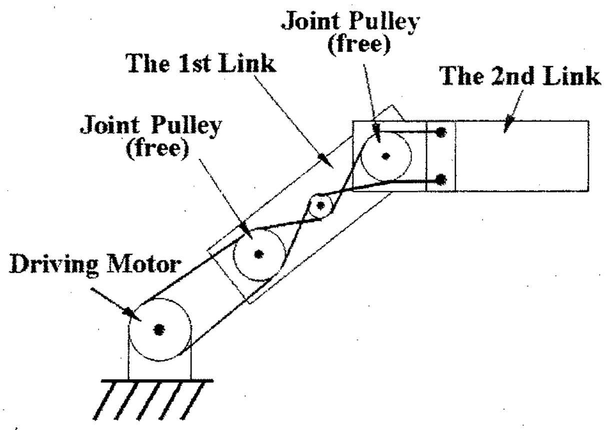

Fig. 1. Finger link mechanism.

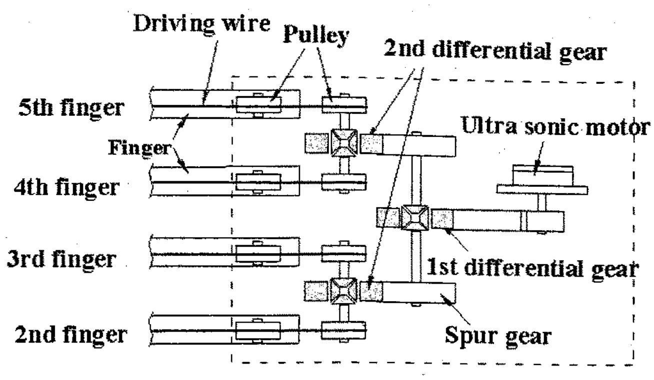

Fig. 2. Hand mechanism using differencial gear.

This paper proposes a driving mechanism for prosthetics hands with five fingers realizing a "compliance mechanism" in which the second to the fifth fingers are driven by one ultrasonic motor. The joint angle of each finger is determined in a way that the five fingers follow the shape of a grasped object. It is shown that this mechanism can realize a sufficient power grasp for objects of irregular shape and the finger mechanism is flexible even when idle. Also this paper proposes a method to estimate the limb-function intended by a human using the EMG frequency characteristics, which determined by two pair of electrodes, adopting unique neural network with a statistical structure (Log-Linearized Gaussian Mixture Neural Network). It is shown that two EMG signals are capable of discriminating four or six motions of the forearm. If discrimination of four motions is possible, control of a two degree of freedom prosthetic hand can be realized, and with six motion discrimination, control of a three degree of freedom prosthetic hand is possible. Finally, it is shown by the experiment that an amputee can operate the prototype system combined the proposed discrimination method and prosthetic hand (one axis for hand grasping and opening, and the other for forearm pronation and supination).

2. Prosthetic Hand Mechanism

2.1. Ultrasonic Motor

Conditions for choosing an actuator to drive a prosthetic hand include small size, light weight, high torque, high speed response, silence and controllability. In this paper an ultrasonic motor[16], which meets all considerations but durability is adopted. The advantages of this motor are (1) no influence from external magnetic fields, (2) low velocity and high torque, (3) compactness, (4) silent operation, (5) easy speed control, and (6) self-holding property while power off. This is suited for a prosthetic hand requiring light weight, compactness, and high torque. Silent operation effectively reduces mechanical noise, which amputees generally dislike. Self-holding eliminates the need for braking when power is turned off. Durability will be improved with advances in the industrial use of ultrasonic motors.

2.2. Driving Mechanism of Finger Joints

The driving mechanism of finger joints adopts a wire-pully driving mechanism with feature of cross multiplication (**Fig.1**). In wire-pully driving robot hands, plural actuators are generally used for one joint[17,18]. In the present mechanism, one motor simultaneously drives two joints[19]. Wire is crossed on two free rotation joint pulleys on the finger flection and extention sides, respectively. The wire edge is fixed to the second link and proper tension is applied. The two wires are crossed to put the first link between them. When the drive motor is rotated, tension differs between the two wires. This difference drives the second link and the first link, so that the finger is bent. By normal and reverse motor rotation, the finger is bent to flection and extention. As the results, by controlling motor rotation speed and torque, finger joint is controlled.

2.3. Grasping Mechanism of Irregular Shape Objects

The major feature of the hand is the grasping of irregular objects with varying cross-sectional shapes, e.g., wine glasses, by holding the object as wrapping it by displacement of the five fingers to follow the object shape. To combine 2-wire driving and irregular object holding, a differential gear from the drive transmission of an automobile is implemented[20] (**Fig.2**). Three differential gears are used between the second and third fingers, between the fourth and fifth fingers, and between these two sets, and power is transmitted from the ultrasonic motor through a spur gear. Even when two fingers, for example the fourth and fifth fingers, are restrained from outside, power is transmitted to two others, the second and third, by the first differential gear. Even when the third finger is constrained, power is transmitted to the second finger by the second differential gear. For objects whose shape is unknown, this method is capable of holding like wrapping the object by following its shape.

Figure 3 shows the prototype prosthetic hand developed based on this mechanism. The maximum grasping holding force of this hand is 14[N]. At the top of each finger, the maximum force of 3[N] can be applied at the four fingers, and 9[N] at the top of the thumb. The hand weighs 400[g] by using titanium for the gear unit and FRP for the frame, resulting in light weight.

2.4. Compliance of Grasping Mechanism

Use of the finger link and irregular object grasping above makes it possible to react compliantly to external forces on the prosthetic hand. First, **Fig.4** shows the response to the external force without grasping. The four fingers are compliant by stopping the actuator at an intermediate position except in complete loosening and complete gripping. Even when the object hits the prosthetic hand as shown in **Fig.4**, the impact force is expected to be absorbed by the four fingers, so that, damage to fingers and the object can be avoided to some extent.

Fugure 5 shows compliance to external force in removing a held object. When removal force is applied, the second and third fingers move to keep stable grasping against changing posture by irregular shape object, securing the grasped object. When external force is removed, the prosthetic hand goes back to the beginning position, and has been grasping the object.

Compliance against external force could cause problems when holding heavy objects, for example, but it is capable of realizing stable grasping by the friction force between fingers and the object, because grasping is done by the five fingers. It is interesting to study how to control the force by wire tension and while grasping.

The mechanism proposed enables fingertip compliance. Several prosthetic hands[21-24] have also realized compliance by control. In contrast, the proposed prosthetic hand realizes compliance mechanically. Compliance is realized by the proposed method in addition to the wire's natural compliance, so that even when a specific finger is fixed, other fingers can move by using the differential gear.

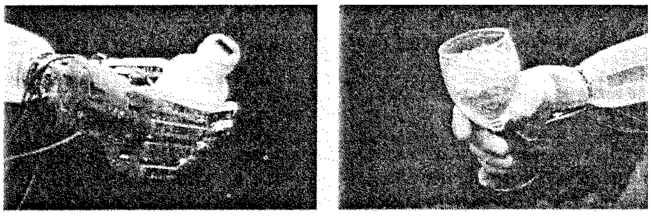

Fig. 3. Five-finger prosthetic hand controlled by EMG signals.

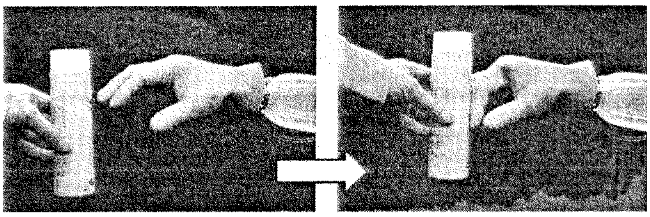

Fig. 4. Response to the external force.

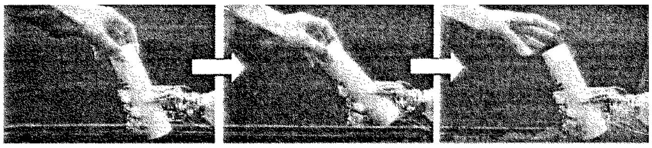

Fig. 5. Grasping compliance.

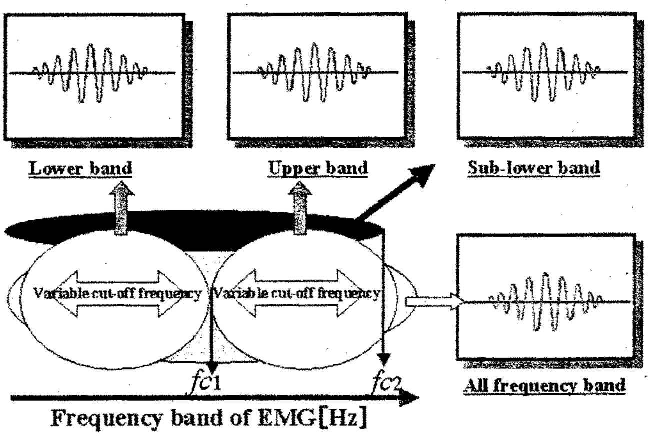

Fig. 6. Frequency component extraction.

3. Prosthetic Hand Control

3.1. Motion Discrimination

To operate the proposed prosthetic hand, it is necessary to discriminate, based on EMG, the motion intended by an amputee. Given the mental and physical load of attaching electrodes and complexity of the peripheral circuit to process the signal, the number of electrodes to sample EMG should be minimized. This paper attempts to construct a system in which the number of electrodes used is two pairs on the forearm and is capable of discrimination of four or six motions. Limiting the number of electrodes to two pairs may compromise motion discrimination, so this system uses the EMG frequency characteristics to compensate for the limited information[25]. The Log-Linearized Gaussian Mixture Network (LLGMN)[26] proposed by Tsuji et al. is used for motion-discrimination. This network has the structure involving the mixture normal distribution model, and the statistical performance of the user's EMG can be acquired by learning. To meet the variation of muscular contraction, the system uses the signal after normalization so the sum of all channels is 1[27].

3.2. EMG Signal Processing

EMG measured by the two pairs of electrodes is amplified by the myoelectric amplifier and sent to frequency characteristics extraction part, four allotted for each channel, and amplitude characteristics extraction part, four

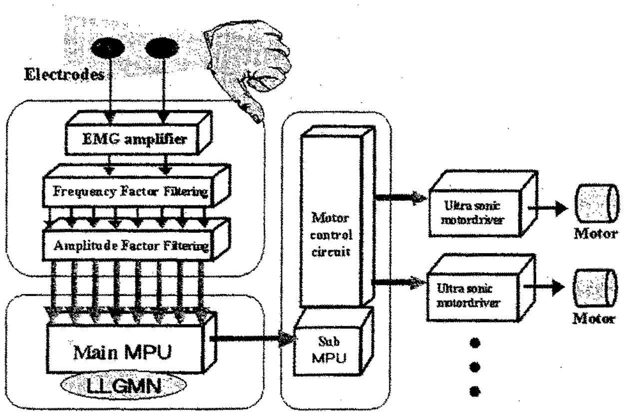

Fig. 7. Block diagram of prosthetic hand control.

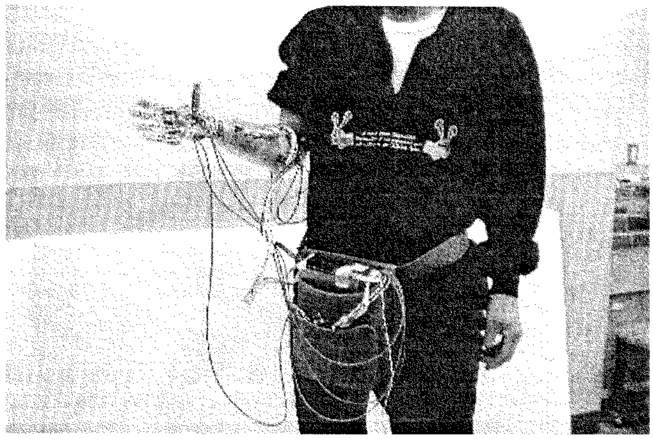

Fig. 8. Amputee wearing the developed prosthetic hand.

allotted. The eight kinds of signals thus obtained are input to LLGMN and six kinds of motion are determined.

For the myoelectric amplifier, which used INA114 made by BURR-BROWN, a marketed measurement amplifier, and set magnification so EMG becomes several volts. To restrain fluctuation of the base line by user's movement and power noise, a fourth order butterworth high pass filter with cutoff frequency of 70[Hz] is used. Frequency characteristics extraction part receives signals from the myoelectric amplifier, conducts filter processing detailed below, and sends results to amplitude characteristics extraction part. Amplitude characteristics extraction part receiving signals after rectification in the absolute value circuit, does smoothing using a second order butterworth low pass filter with a cutoff frequency of 1[Hz], then outputs the signal to the LLGMN.

3.3. Frequency Component Extraction

Figure 6 shows the concept of frequency characteristics extraction part. EMG of each channel is passed through the band pass filter (BPF) of the four kinds shown below, and sends the processed signals of eight kinds to amplitude characteristics extraction part. This paper uses the following bandwidth of four BPFs:

- BPF1: 0[Hz] ~ ∞
- BPF2: 0[Hz] ~ $fc1$[Hz]
- BPF3: fc1[Hz] ~ ∞
- BPF4: 0[Hz] ~ $fc2$[Hz]

BPF1 passes all bands and outputs the raw myoelectric signal. BPF2 is a low-pass filter and BPF3 a high-pass filter with a cutoff frequency of $fc1$. BPF4 is a sub low-pass filter with a cutoff frequency of $fc2$. Because MAX260 by MAXIM is used for the filter IC, cutoff frequencies, $fc1$ and $fc2$, can be regulated to absorb changes of myoelectric signals caused by minute slippage of electrode positions and the physical condition of the subject. It should be noted that each filter used is a second order butterworth filter.

3.4. Prosthetic Hand Control

Figure 7 shows a block diagram of prosthetic hand control. EMG signals measured at electrodes are converted to eight signals in signal processing and input to the neural network. Motion discrimination is done at the main MPU by the LLGMN. The discrimination result obtained is sent to prosthetic hand control, where the motor to be operated is chosen by the sub MPU, and drives the ultrasonic motor, the prosthetic hand actuator. This system uses SH-1 (SH7032, Hitachi) as the main MPU and PIC16C74A (Microchip Technology) as the sub MPU. The blue sensor (MEDICOEST), which is a wet disposable electrode, is adopted as the electrode. For the amputee to wear the system, the signal processor is made of a flexible circuit in the prosthetic hand socket. Other circuits are kept in a waist pouch. The power source is a series of three lithium ion batteries yielding an electromotive force of about 25[V]. **Fig.8** shows the amputee wearing the system.

4. Experiments

4.1. Motion Discrimination Experiment by Normal Subjects

Using the prototype system, it is shown to conduct a discrimination experiment of left forearm motion by three normal males aged 25, 37, and 35. One pair of two disposable electrodes was used to get the signal by differential input and the two electrodes were positioned so they extend over plural muscles. This enables the use of EMG cross-talk from many muscles for discrimination. The electric ground was set by using a disposable electrode on the portion of the elbow without muscle.

Given the influence on wrist flection and extention, the cross-talk signal is measured at electrodes attached to flexor carpi radialis and flexor carpi ulnaris for flexion, where the electrode location is near the top of the muscle, and extensor carpi radialis and extensor carpi ulnaris for extension. The cutoff frequencies, $fc1$ and $fc2$, of the frequency characteristics extraction part were set to 120[Hz] and 150[Hz]. The experiment was conducted for four motions (wrist flection and extention, forearm pronation

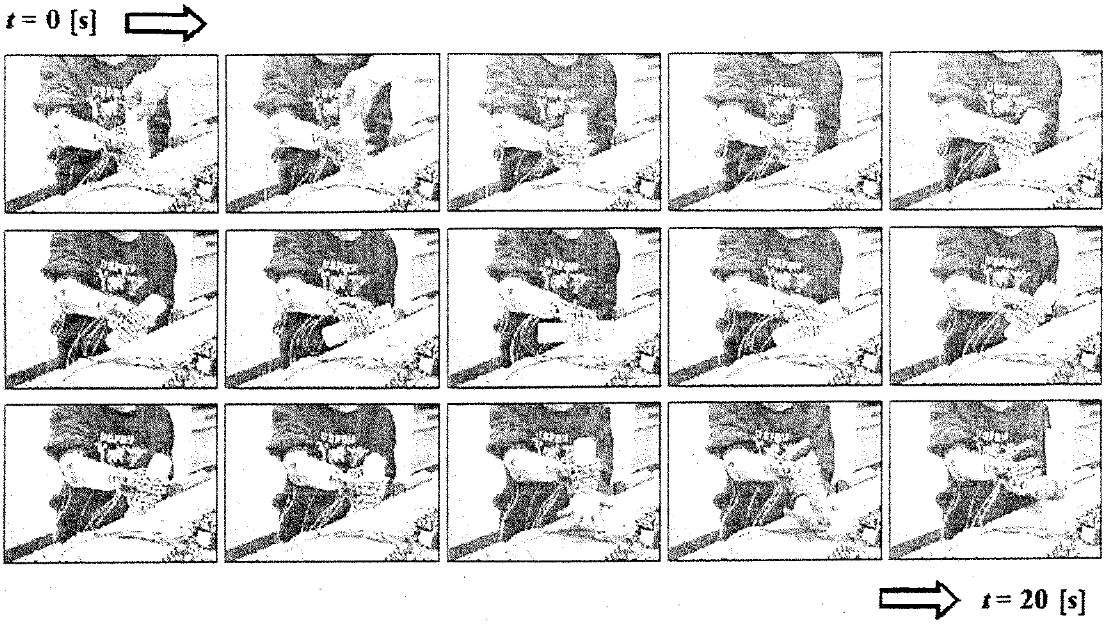

Fig. 9. Operation experiment by amputee.

Table 1. The results of the four motion discrimination.

(a) Normal A

		Intended motions				
		Flection	Extention	Grasping	Hand-opening	Total
Estimated motions	Flection	50	0	0	0	
	Extention	0	50	0	0	
	Grasping	0	0	50	0	
	Hand-opening	0	0	0	50	
Discrimination ratio(%)		100	100	100	100	100.0

(b) Normal B

		Intended motions				
		Flection	Extention	Grasping	Hand-opening	Total
Estimated motions	Flection	49	0	0	0	
	Extention	0	49	0	6	
	Grasping	0	0	50	0	
	Hand-opening	1	1	0	44	
Discrimination ratio(%)		98	98	100	88	96.0

(c) Normal C

		Intended motions				
		Flection	Extention	Grasping	Hand-opening	Total
Estimated motions	Flection	50	0	0	0	
	Extention	0	50	0	1	
	Grasping	0	0	50	0	
	Hand-opening	0	0	0	49	
Discrimination ratio(%)		100	100	100	98	99.5

Table 2. The results of the six motion discrimination.

(a) Normal A

		Intended motions						
		Flection	Extention	Pronation	Supination	Grasping	Hand-opening	Total
Estimated motions	Flection	50	0	4	0	0	0	
	Extention	0	50	0	0	0	0	
	Pronation	0	0	40	6	0	0	
	Supination	0	0	0	42	0	0	
	Grasping	0	0	0	0	50	0	
	Hand-opening	0	0	6	2	0	50	
Discrimination ratio(%)		100	100	80	84	100	100	94.0

(b) Normal B

		Intended motions						
		Flection	Extention	Pronation	Supination	Grasping	Hand-opening	Total
Estimated motions	Flection	50	0	7	0	17	0	
	Extention	0	50	0	0	0	0	
	Pronation	0	0	41	0	1	0	
	Supination	0	0	0	50	0	0	
	Grasping	0	0	0	0	32	0	
	Hand-opening	0	0	2	0	0	50	
Discrimination ratio(%)		100	100	82	100	64	100	91.0

(c) Normal C

		Intended motions						
		Flection	Extention	Pronation	Supination	Grasping	Hand-opening	Total
Estimated motions	Flection	50	0	0	0	0	0	
	Extention	0	50	0	0	0	20	
	Pronation	0	0	49	0	1	0	
	Supination	0	0	0	17	0	C	
	Grasping	0	0	1	28	49	1	
	Hand-opening	0	0	0	5	0	29	
Discrimination ratio(%)		100	100	98	34	98	58	81.3

and supination) and six motions (wrist flection and extension, forearm pronation and supination and hand grasping and opening). Prior to the experiment, teaching was done by getting 7 sets of teacher signals for each motion. The time needed for teaching was 4 minutes and 55 seconds for the four motion discrimination, and 11 minutes and 10 seconds for the six motion discrimination. After teaching, the subject conducted 50 repetitions of each motion at random and discrimination results were recorded. Preprocessing such as wiping the skin with alcohol was not done.

Table 1 shows the results of the four motion discrimination, and **Table 2**, the six motion discrimination. Subject A does the experiment of four motion discrimination frequently, but the six motion discrimination was the first time for him. Subject B had experience of both the four motion and the six motion experiments, but after an interval of about one year. For subject C, both four motion and six motion were the first experience, and no exercise was done. Considering results taking into consideration the particulars, as seen from the fact that for the four motion discrimination subject C demonstrates high discrimination of 99.5[%], the system can be readily and effectively used without special training. As seen from the fact that subject A demonstrates 100[%] and subject B shows lower discrimination than other subjects, better four motion discrimination is realized by practice.

For six motion discrimination, subject A made errors only for pronation and supination, which were new motion, but the number of errors is not so large. Subjects B and C repeated erroneous discrimination for specific motions (pronation and grasping as for B, and supination and opening as for C), and specially the number of erroneous discrimination of subject C is large, so subject A could flexibly meet new motions because he is already accustomed to the system. For subjects B and C, improvement of discrimination is expected by training in six motion discrimination.

4.2. Operation Experiment by Amputee

Then, an experiment is conducted, in which an amputee - a man in his 40s whose right forearm was amputated about 12[cm] from the elbow joint about 2 years ago. The location of two electrodes were determined in a way that four motion discrimination is possible with the prosthetic hand, and after LLGMN learning, we examined whether the amputee is possible or not to perform a motion instructed. The prosthetic hand used two axes of hand grasping-opening and forearm pronation-supination, and the number of motion discriminated was four.

The amputee was instructed to pour water from a cylindrical object into another vessel in a series of motions of (1) gripping the cylindrical object and lifting it (grasping), (2) pouring water into another vessel (pronation), (3) returning the hand to its previous position (supination), and (4) putting the object in the starting position (opening). Cutoff frequencies $fc1$ and $fc2$ for frequency characteristics extraction part are 120[Hz] and 150[Hz] for two electrodes.

The experiment confirmed that the amputee could perrform the series of motions after several repetitions of exercises (**Fig.9**). When the experiment was continued too long, discrimination dropped due to fatigue and pain at the amputated edge. It is necessary to make the prosthetic lighter and give it a more proper socket.

5. Conclusion

This paper proposed a five-finger EMG prosthetic hand using ultrasonic motor. The proposed mechanism made it possible to securely grasp an object with an irregular shape. This mechanism realizes flexibility (compliance) of fingertips and reduction of the influence of external force on the object.

This paper confirmed forearm motion discrimination by the LLGMN using cross-talk of myoelectric signals between muscles and frequency characteristics information with only two electrodes. As a result, as for four motion discrimination, exact discrimination results were obtained with only short training. This is very significant advantage compared to commercially available prosthetic hands, which require operations such as switching modes and whose four motions are realized by introducing complicated operations. For six motions, training was necessary to improve discrimination, but if six motion discrimination is possible, one more joint axis can be added, bringing the EMG prosthetic hand closer to the movement of a natural hand.

In an experiment of four motions by an amputee using the proposed prosthetic hand, the motions of pouring water, which is needed for every day activities, was realized by four motions. As a result, it was comfirmed that the proposed system can be effectively operated by an amputee.

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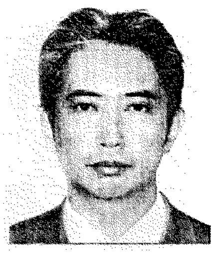

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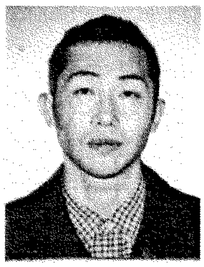
- Society of Biomechanisms Japan



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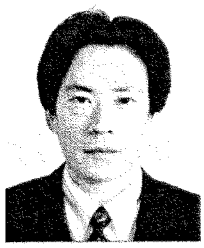
- The Society of Materials Science, Japan



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- Biological motor control

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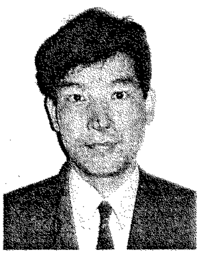
- The Robotics Society of Japan
- The Japanese Society of Instrumentation and Control Engineers



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