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Development of an Internally Powered Functional Prosthetic Hand

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Abstract

The purpose of this paper is to develop an internally powered functional prosthetic hand. First, the mechanical properties of commercialized functional prosthetic hands are examined. From the measurements of hand forces and finger motion, it is concluded that a patient needs quite large force to manipulate the prosthetic hands, so that the delicate control of the grasping movement is very difficult. Then, the effects of the movement of the thumb in human grasping actions are analyzed. The experimental results show that the movements of the thumb play an important kinematic role in human grasping movements. Finally, these results have brought about the development of a new type of internally powered functional prosthetic hand.

1 Introduction

Upper extremity prostheses which have been developed so far can be divided into four types: (1) a cosmetic type used to cover the lost limb; (2) an arm capable of performing tasks; (3) a functional prosthesis; and (4) an externally powered prosthesis.

The functional prosthesis is actuated by the remaining function in the limb, such as the movements of the shoulder and the shoulder girdle. This is called an internally powered prosthesis.

The hand of the internally powered prosthesis have either a voluntary opening or voluntary closing function. The former type involves a cable to open the thumb and other fingers that are supported by a rubber band or spring. The latter type involves the similar function to close the hand [1].

This study is intended to develop a hybrid type functional upper-extremity prosthesis for the patient with a below-elbow amputation. The hybrid type is characterized by an internally powered voluntary opening and closing of the prosthetic hand and an externally powered forearm for controlling forearm pronation and supination. With the use of a cable from the harness to the hand, the patient may receive sensory feedback while using an internally powered prosthetic hand. In this paper, we focus on the development of this prosthetic hand.

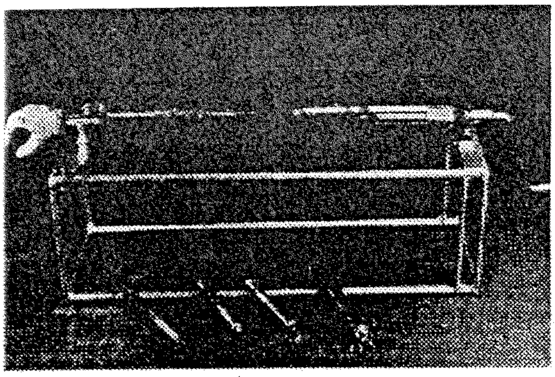
Through analyses on the mechanical properties of commercialized functional prosthetic hands and the effects of the movement of the thumb in human grasping actions, two problems are found in the internally powered functional prosthetic hands. The first problem is that the voluntary opening or voluntary closing is resisted by a spring or rubber band, so that the patient has to work against it. The second problem is the restricted movements of the thumb and the wrist joint in the opening and closing movements of the prosthetic hand. During movements, the thumb only moves in an opposite direction of the index finger and middle finger, and the wrist joint is fixed. The first problem leads to excessive force to control the hand, and the second problem leads to an unnatural posture to manipulate the prosthetic hand. Therefore, we need to introduce a new type of prosthetic hand.

2 Methods

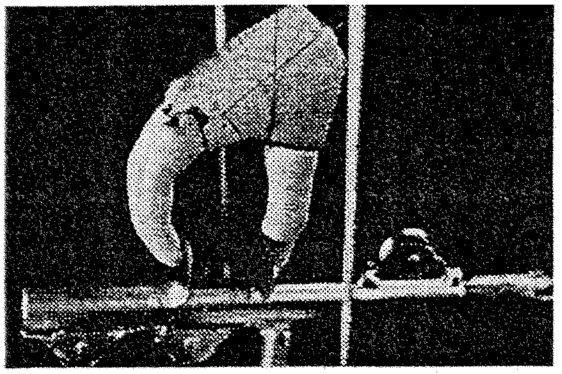
2.1 Analysis of the commercialized functional prosthetic hands

For ten kinds of internally powered functional prosthetic hands, nine voluntary opening hands and one voluntary closing hand, we measured a traction force with the control cable, a distance between the fingertips of the thumb and the index finger, and a pinch force. We removed the cosmetic glove when we measured the forces and the distance.

The equipment used for measuring the traction force of the control cable is comprised of a part that fixes the hand and a handle for the control of a traction force as shown in Fig. 1 (a). A spring scale is inserted between a cable attached to the hand and the handle



(a) Equipment to measure the traction force.



(b) Equipment to measure the pinch force.

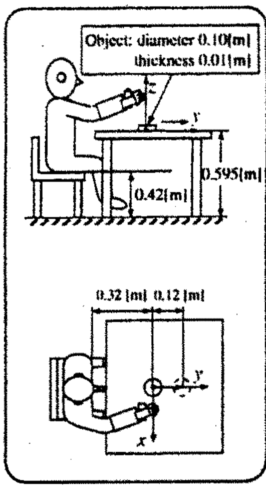
Figure 1: Equipments for measurement of the traction force of the control cable and the pinch force of functional prosthetic hands.

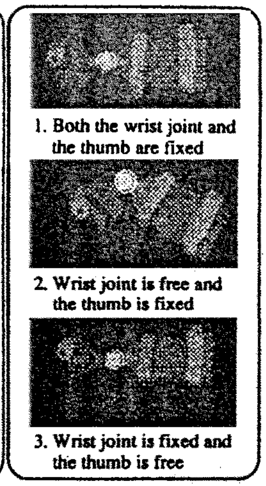
to measure a force. The distance between fingertips is measured with calipers.

By gradually increasing the traction force by the handle, we measured the force for every 5 mm the distance between fingertips changed, until the distance reached the longest. Then, we gradually decreased the traction force, and observed the relationship between the force and the distance.

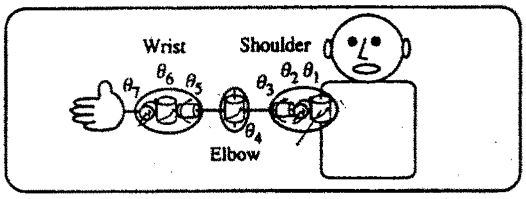
Next, the pinch force was measured by two vertical tabs on a pipe attached to the spring scale as shown in Fig. 1 (b). A pulley was used to reduce the friction between the pipe and vertical tabs.

When the hand pinched the two tabs, the pinch force were measured for every 5 mm the distance between the fingers changed.





(a) Experimental apparatus (b) Three experimental conditions



(c) The upper limb model with 7 d. o. f

Figure 2: Analysis of human grasping movements.

2.2 Analysis of human grasping movements

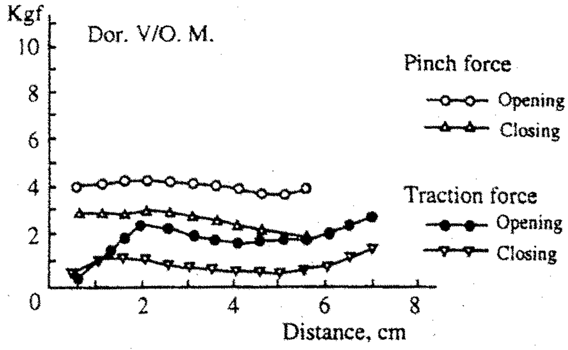
In this experiment, one subject, male, aged 48 years, performed the required tasks three times. A long opponens splint was applied to his right hand. Then, electromyographical analysis and three-dimensional motion analysis were performed according to the following procedures.

Figure 2 (a) shows the subject and the object to be grasped. The subject was instructed to sit at a designated table, pick up the object, and transfer the object as indicated. The object was placed 0.32 m in front of the subject, and moved 0.12 m forward. In order to analyze the effects of the constraints on the wrist and thumb movements, the following three experimental conditions were used (Fig. 2 (b)):

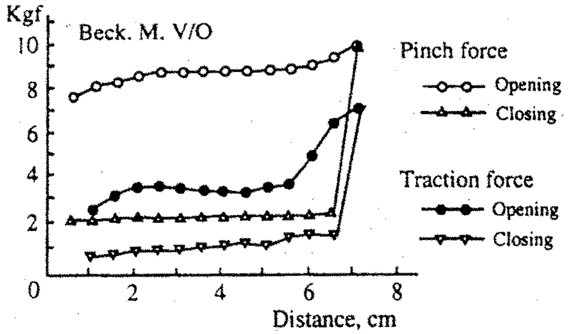
1. Both the thumb and the wrist joint were fixed.
2. The wrist was able to move freely, and the thumb was fixed.
3. The wrist joint was fixed, and the thumb was free.

Table 1: The measured traction force and pinch force for ten commercialized prosthetic hands.

			Traction force			Pinch force		
			Fingertips distance			Fingertips distance		
No.	Hand	Status	1cm	3cm	5cm	1cm	3cm	5cm
1	Dor. S	Opening	2.1Kgf	2.2Kgf	3.3Kgf	1.2Kgf	1.0Kgf	1.5Kgf
	V/O	Closing	1.1Kgf	1.4Kgf	2.2Kgf	0.3Kgf	0.3Kgf	0.5Kgf
2	Dor. M	Opening	1.1Kgf	2.1Kgf	1.9Kgf	4.2Kgf	4.3Kgf	3.7Kgf
	V/O	Closing	1.1Kgf	0.7Kgf	0.5Kgf	3.0Kgf	2.8Kgf	2.0Kgf
3	Dor. L	Opening	5.7Kgf	7.3Kgf	7.0Kgf	9.0Kgf	4.9Kgf	3.8Kgf
	V/O	Closing	3.4Kgf	4.5Kgf	4.6Kgf	3.0Kgf	2.1Kgf	2.0Kgf
4	Rob. soft	Opening	6.0Kgf	8.0Kgf	9.5Kgf	7.1Kgf	6.0Kgf	7.5Kgf
	V/O	Closing	2.8Kgf	3.3Kgf	3.0Kgf	0.6Kgf	1.6Kgf	2.9Kgf
5	Rob. M	Opening	4.9Kgf	7.8Kgf	9.5Kgf	/	/	/
	V/O	Closing	3.0Kgf	4.2Kgf	3.2Kgf			
6	Otto. S	Opening	1.9Kgf	2.8Kgf	4.0Kgf	1.5Kgf	2.0Kgf	2.8Kgf
	V/O	Closing	0.2Kgf	0.3Kgf	1.2Kgf	0.6Kgf	0.8Kgf	1.0Kgf
7	Pass.	Opening	2.4Kgf	3.3Kgf	4.4Kgf	1.4Kgf	2.0Kgf	3.3Kgf
	V/O	Closing	1.7Kgf	2.2Kgf	2.6Kgf	0.6Kgf	0.8Kgf	1.0Kgf
8	Beck.M	Opening	8.3Kgf	8.8Kgf	8.9Kgf	2.7Kgf	3.5Kgf	3.6Kgf
	V/O	Closing	1.7Kgf	2.4Kgf	2.3Kgf	0.6Kgf	1.0Kgf	1.2Kgf
9	Beck.P	Opening	4.4Kgf	6.5Kgf	8.8Kgf	1.4Kgf	2.0Kgf	3.3Kgf
	V/O	Closing	1.8Kgf	2.5Kgf	3.4Kgf	0.6Kgf	1.4Kgf	1.9Kgf
10	Sier.	Opening	2.7Kgf	2.8Kgf	/	Lock	Lock	/
	V/C	Closing	2.4Kgf	2.2Kgf		Lock	Lock	



(a) Hand No. 2



(b) Hand No. 8

Figure 3: Changes of the measured traction and pinch forces depending on the distance between fingertips.

The long opponens splint was adjusted to conform to the different conditions by using a dial lock at the wrist joint and a removable thumb rest.

When the subject performed the tasks requested, electromyographical (EMG) signals and three-dimensional arm movements were measured. The EMG data were measured from seven muscles: 1ch, trapezius (upper fibers); 2ch, deltoid (anterior fibers); 3ch, deltoid (middle fibers); 4ch, biceps brachii; 5ch, triceps brachii; 6ch, wrist extensors; and 7ch, wrist flexors.

The joint angles were calculated from the coordinates of the markers used for the three-dimensional video analysis by using a 7 degrees of freedom model with three links (Fig. 2 (c)). Markers were attached at upper sternum, acromion, lateral epicondyle process, radial styloid process, ulnar styloid process, and metaphalangeal joint of the index finger. When the subject completely straightens his arm, all the joint angles are at zero, and the counter-clockwise direction is defined as the positive rotational direction.

3 Results

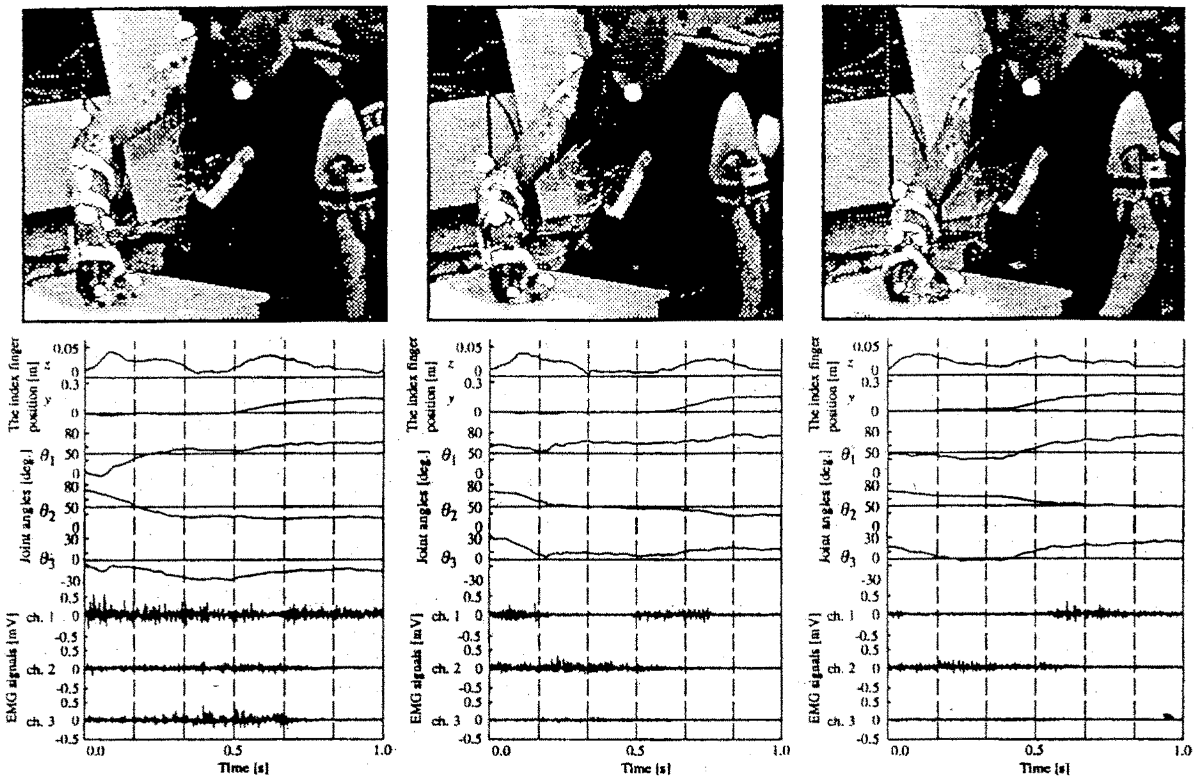
3.1 Mechanical properties of the commercialized functional prosthetic hands

Table 1 shows the results of the measured traction and pinch forces for ten kinds of the commercialized prosthetic hands. Figure 3 (a) indicates the characteristics of the hand No. 2. The pinch force is always maintained above 2 kgf and higher than the corresponding traction force. The distance between the fingertips is highly affected by subtle changes in traction force, so that it is very difficult to control the distance accurately. Also the pinch force decreases when the distance between the fingertips is more than 50 mm. This means that grasping larger objects tends to be more difficult.

The results of the hand No. 8 are also shown in Fig. 3 (b). It should be noted that the pinch forces of the hands numbered 3, 4, 5, 8 and 9 are smaller than the traction force. Also, it has been found that the pinch force is smaller during hand closing than the one during hand opening.

3.2 Human grasping movements

Figure 4 shows examples of the experimental results, where y and z coordinates of the marker on



(a) Both the wrist joint and the thumb are fixed

(b) Wrist joint is free and the thumb is fixed

(C) Wrist joint is fixed and the thumb is free

Figure 4: Examples of experimental results of the human grasping movements.

the index finger, the shoulder joint angles ($\theta_1, \theta_2, \theta_3$ as shown in Fig. 2 (c)), and the EMG signals (channels 1, 2, 3) are plotted.

When both the wrist joint and thumb are fixed, the shoulder joint angle θ_2 shows little movement during grasping movements (from $t = 0.3$ [s] to $t = 1.0$ [s] in Fig. 4 (a)), and shoulder elevation is obviously observed. Also the EMG of the channels 1 and 3 show large amplitudes. Considerably high muscle activity is necessary for the grasping movements. This can be also confirmed by the photo of the subject during the experiment as shown in Fig. 4 (a). The compensatory shoulder and elbow movements are observed under this constraint, which make the use of this simulated prosthetic hand difficult.

In order to examine the muscle activity during manipulation, the EMG signals were measured, and they were rectified and integrated. Table 2 shows the mean and the standard deviation of the integrated EMG during grasping movements under three different constraints.

The averages of the mean integrated EMG for all channels were also computed, and it can be seen that the average EMG was the highest when the wrist joint and thumb were fixed. In particular, the mean values corresponding to the channels 1 and 3 were much bigger than others. This was caused by the shoulder elevation and abduction movements.

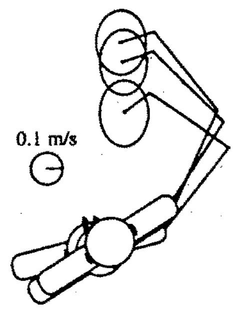
Next, the manipulability ellipses, the manipulability measure, and the condition number were calculated for the three-link model [2], [3], [4]. Figure 5 shows the manipulability ellipses, and Table 3 shows the manipulability measure and the condition number.

The long axis of the ellipse shows the direction in which the velocity of the end-point of the arm is easily produced by the joint velocity. The manipulability measure is in proportion to the area of the ellipse, and the condition number is the ratio between the long and short axes of the ellipse. The closer the ratio is to one, the closer the ellipse is to a circle.

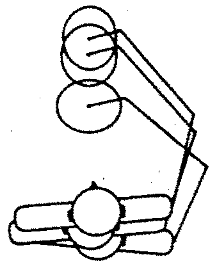
As seen in Fig. 5 (a), when both the wrist and thumb are fixed, the manipulability ellipses elongates

Table 2: Mean values and standard deviations of the integrated EMG during grasping movements

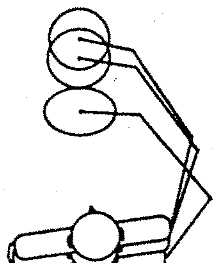
Conditions	Electrodes	ch1	ch2	ch3	ch4	ch5	ch6	ch7	Average
Fixed wrist joint and fixed thumb movement	Mean [mVsec]	89.7	36.0	44.2	35.4	8.4	12.6	23.5	35.7
	Standard deviation	4.0	3.5	8.6	3.9	0.7	0.1	1.6	1.8
Free wrist joint and fixed thumb movement	Mean [mVsec]	32.0	45.6	19.0	27.0	8.6	15.5	21.2	24.1
	Standard deviation	15.9	4.8	0.6	2.7	1.2	2.8	1.3	2.1
Fixed wrist joint and free thumb movement	Mean [mVsec]	35.8	40.7	16.8	34.5	7.9	8.3	17.7	23.1
	Standard deviation	5.2	0.9	0.4	1.2	0.7	0.1	1.4	0.6



(a) Both the wrist joint and the thumb are fixed



(b) Wrist joint is free and the thumb is fixed



(c) Wrist joint is fixed and the thumb is free

Figure 5: Manipulability ellipses during the grasping movements.

Table 3: Evaluation of manipulability during grasping movements.

Conditions	Indeces	Manipulability measure	Condition number
Fixed wrist joint and fixed thumb movement	Mean value	0.108476	0.721523
	Standard deviation	0.000891	0.017900
Free wrist joint and fixed thumb movement	Mean value	0.113141	0.872659
	Standard deviation	0.000075	0.007486
Fixed wrist joint and free thumb movement	Mean value	0.111615	0.850339
	Standard deviation	0.002237	0.083422

Table 4: Trunk motion during grasping movements.

Conditions	Indeces	d [m]	θ [deg.]
Fixed wrist joint and fixed thumb movement	Mean [mVsec]	0.2810	37.300
	Standard deviation	0.0335	5.6862
Free wrist joint and fixed thumb movement	Mean [mVsec]	0.1510	14.700
	Standard deviation	0.0055	0.5774
Fixed wrist joint and free thumb movement	Mean [mVsec]	0.1290	13.700
	Standard deviation	0.0139	2.5166

d: Moving distance of the shoulder joint
θ: Accumulative angle of the rotation of the trunk

along y axis, and the manipulability measure is smaller than the ones under the other two conditions.

Forward shoulder movements and trunk rotation, which were estimated from markers on the shoulder and sternum, are also shown in Table 4. These movements become large when the wrist and thumb are fixed.

4 Discussion

First, we have analyzed the mechanical properties of the conventional voluntary opening and closing

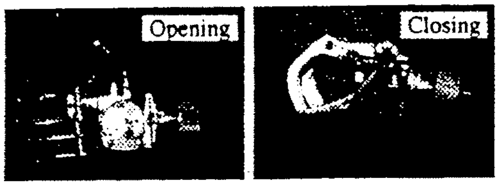


Figure 6: The developped voluntary opening and closing hand.

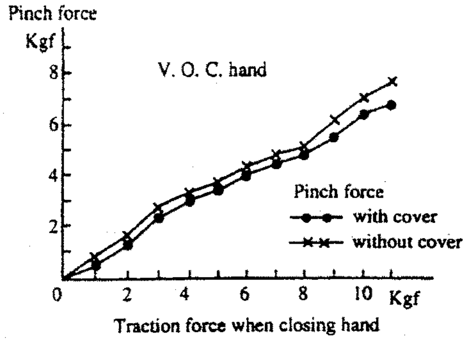


Figure 7: The relation between the traction force and the pinch force of the voluntary opening and closing hand.

prosthetic hands, and shown that some difficulties in the control of the hands exist. For example, in order to change the distance between the thumb and the index finger, a large force of the shoulder is necessary. Also with the voluntary opening prosthetic hands, the pinch force is weak when closing the hand to grasp. Mechanical stiffness caused by the spring, the rubber and the cosmetic-cover also make the hand difficult to be used. Therefore, we decide to develop a new voluntary opening and closing prosthetic hand.

From the analysis of human grasping movements, it has been shown that the free movement of either the thumb or the wrist joint makes the grasping movements easier. Because it is difficult to control the wrist joint through a cable, the thumb mechanism that is free to abduct is adopted for the new prosthetic hand.

Figure 6 shows the voluntary opening and closing prosthetic hand developed [5], the thumb of which can move in a diagonal direction between palmar abduction and radial abduction.

This internally powered hand is controlled by a pair of cables which alternately control a disk contained in the palm of the hand, and a link connected to the rotating disk opens and closes the fingers. It should be noted that there is no stiffness about the rotation of the disk.

Figure 7 shows the relation between the traction force and the pinch force when closing hand. It can be seen from figure that the relation is almost linear. It can be expected that this hand is superior in function as compared to the conventional ones.

5 Summary

In this paper, first, the commercialized functional prosthetic hands have been analyzed. Problems of the conventional prosthetic hands such as large force required in grasping motion and high stiffness of hand movements have been pointed out. Then, from the electromyographic and three-dimensional analyses of the human grasping movements, we found that if the wrist joint is fixed and the thumb moves in a diagonal direction, the compensating movement of lifting the shoulder and elbow joint decreases. Finally, a new voluntary opening and closing prosthetic hand has been developed, which has a diagonally moving thumb.

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