PROCEEDINGS

9th IEEE International Workshop on ROBOT AND HUMAN INTERACTIVE COMMUNICATION

IEEE RO-MAN 2000

September 27–29, 2000
Osaka Institute of Technology, Osaka, Japan

IEEE Catalog Number: 00TH8499
Library of Congress: 00-00155
ISBN: 0-7803-6273-X

Co-organized by

IEEE Industrial Electronics Society
The Robotics Society of Japan
The Society of Instrument and Control Engineers
The Japan Society of Mechanical Engineers
The Virtual Reality Society of Japan
New Technology Foundation
Osaka Institute of Technology

In Association with

Japanese Society of Precision Engineers
The Institute of Systems, Control and Information Engineers
Information Processing Society of Japan
Intelligent Manufacturing Systems Promotion Center
Manufacturing Science and Technology Center
Ninety-Nine Asian Student Scholarship Foundation
Sunahara Memorial Foundation

Proceedings of the 2000 IEEE International Workshop
on Robot and Human Interactive Communication
Osaka, Japan - September 27-29 2000

Development of an internally powered functional prosthetic hand with a voluntary closing system and thumb flexion and radial abduction
~ based on normal human grasping action ~

Akira OTSUKA† Toshio TSUJI†† Osamu FUKUDA†††
Michele EISEMANN SHIMIZU† Masatoshi SAKAWA††

†Department of Physical Therapy, Hiroshma Prefectural College Health Science, Mihara, JAPAN
††Industrial and Systems Engineering, Hiroshma University, Higashi-Hiroshima, JAPAN
†††Mechanical Engineering Laboratory, Agency of Industrial Science and Technology, Ministry of International Trade and Industry, Tsukuba, JAPAN

Abstract

The purpose of this paper was to introduce an internally powered functional prosthetic hand with a voluntary closing function, which was developed by using robot manipulator technology. From electromyographic and three dimensional analyses of human grasping movements, we found that, if the wrist joint is fixed and the thumb moves in a diagonal direction, the compensation of lifting the shoulder and elbow joints decreases. The experimental results demonstrate that the thumb movements of flexion and radial abduction play an important kinematic role in human grasping movements. Machinery for an internally powered functional prosthetic hand that can drive four fingers with two joints by a single cable is proposed. Tendon transmission in the machinery is useful for the hand to drive the finger joints. We suggest the following results ; (1) the hand we developed has passive compliance, (2) and can grasp objects with a cross section of different diameters.

1 Introduction

Upper extremity prostheses 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 [1].

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

The hand of the internally powered prosthesis has 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 a similar function to close the hand.

This study was under taken to develop an internally powered functional prosthetic hand with a voluntary closing system. With the use of a cable from the harness to the hand, the amputee patient may receive sensory feed-back while using an internally powered prosthetic hand.

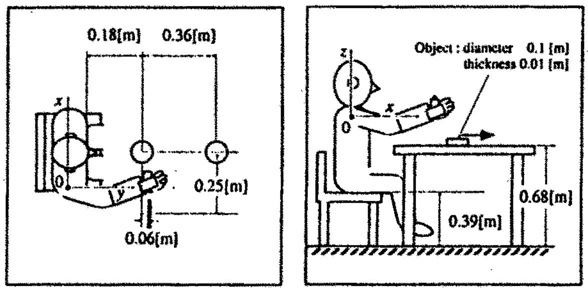


Fig. 1: Experimental design

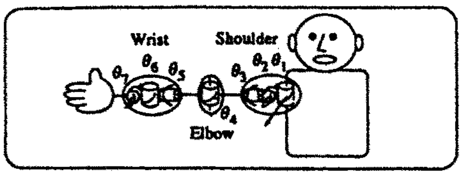
Therefore, an internally powered functional prosthetic hand with a voluntary closing function, was developed by using robot manipulator technology and electromyographic (EMG) and three dimensional video (3D) analyses of human grasping movements.

2 Methods

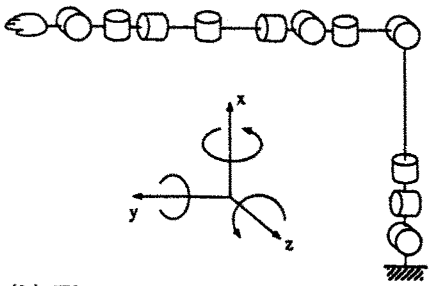
In this experiment, three male subjects performed the required tasks 12 times. A long opponens splint was applied to the right hand. Then, EMG analyses and 3D analyses were performed according to the following procedures.

Figure 1 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 0.18 meter in front of the subject, and the object was to be move 0.36 meter forward. In order to analyze the effects of the constraints on the wrist and thumb movements, the following four experimental conditions were used: C1) Free wrist joint and free thumb movement = human like, C2) Fixed wrist joint and free thumb movement, C3) Free wrist joint and fixed thumb movement = as with an ex-

0-7803-6273-X/00/$10.00©2000 IEEE



(a) The upper limb model 7 d.o.f.



(b) The upper limb model 11 d.o.f.

Fig. 2: The link model

ternally powered functional prosthetic hand, C4) Fixed wrist joint and fixed thumb movement = as with the old internally powered functional prosthetic hand.

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

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

The joint angles were calculated from the coordinates of the markers used for the 3D analysis by using one model with seven degrees of freedom and three links and one model with 11 degrees of freedom and five links (Fig. 2). Markers were attached to the upper sternum, acromion, lateral epicondyle process, posterior wrist between the radial styloid process and ulnar styloid process, metacarpophalangeal (MP) joint of the index finger, and nail of the thumb and index finger. A marker was also suspended from the ceiling to just above the top of head.

When the subject completely straightened his arm, all the joint angles were at zero, and the counter-clockwise direction was the postive rotation direction.

3 Results

3.1 An example of an experiment (Fig. 3)

The photograph shows the subject and the typical six marker points. At the right of the photograph is a stick picture of the x and z axes of the hand movements. The changes in joint angle positions for eight of the nine joints (excluding the wrist joint) is shown. The EMG results for the upper trapezius, middle deltoid, and anterior deltoid muscles are also shown. It can be seen from the joint angle results that the shoulder girdle and shoulder joint movements are large. The EMG results

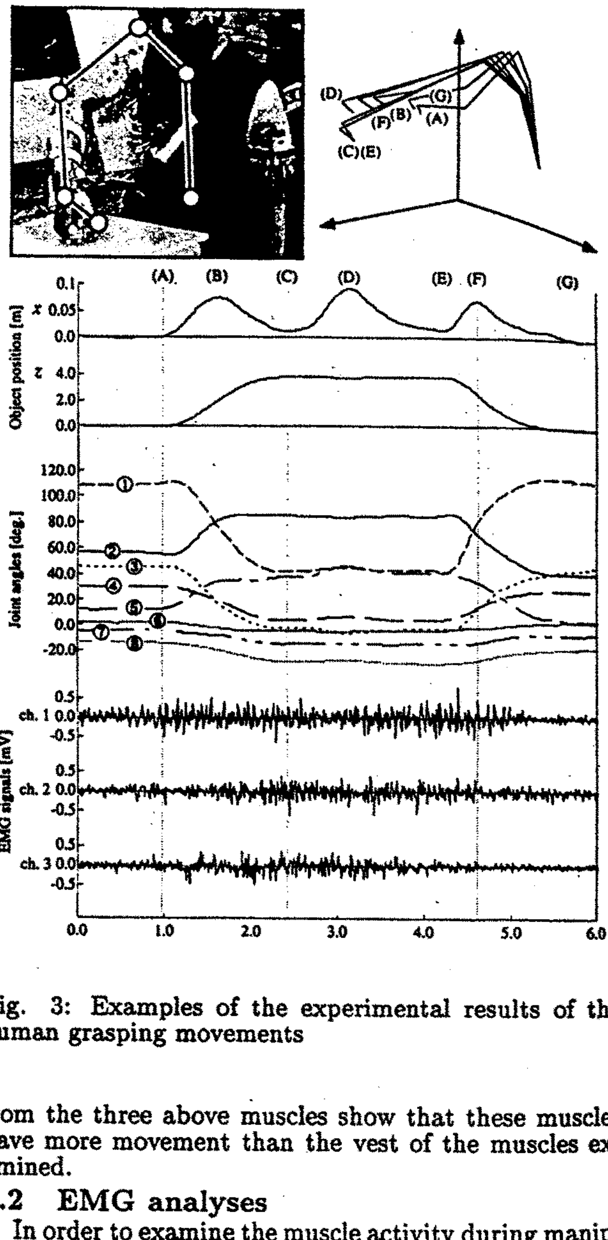


Fig. 3: Examples of the experimental results of the human grasping movements

from the three above muscles show that these muscles have more movement than the vest of the muscles examined.

3.2 EMG analyses

In order to examine the muscle activity during manipulation, the EMG signals were measured, and they were rectified and integrated. Table 1 shows the mean and the standard deviation of the integrated EMGs during grasping movements under the four different constraints.

As can be seen in the mean results from all yhe channels, müscle activity in C4 is great, which most likely means that the subject uses an exaggerated position to produce a movement. Comparing C2 and C3, C2 is generally smaller than C3, because a free thumb probably makes it easier to move the hand than does a free wrist.

3.3 Motion analyses (posture)

We examined what posture a subject assumes when lifting an object. Eight angles above the wrist joint were tested (Table 2). The eight angles include the following : θ_1 Lateral trunk bending to the right, θ_2 Trunk hyperextension, θ_3 Trunk rotation to the left, θ_4 Right shoulder girdle depression, θ_5 Shoulder girdle elevation, θ_6 Shoulder abduction, θ_7, Shoulder internal rotation, θ_8 Elbow flexion.

Table 1: Mean values and standard deviations of the integrated EMG during grasping movements

Electrodes	Subjects	A				B				C			
	Condions	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
Ch. 1	Mean[mVmsec]	58.3	57.6	70.8	84.0	51.4	105.2	99.8	99.9	49.1	92.3	91.3	120.2
	Standarddeviation	3.3	4.9	5.2	14.3	5.0	8.4	9.5	9.0	4.5	7.8	9.1	12.2
Ch. 2	Mean[mVmsec]	31.4	34.4	42.6	68.3	42.3	43.8	65.4	88.2	22.8	30.5	31.9	38.9
	Standarddeviation	2.9	2.1	4.9	6.0	3.8	4.8	4.6	6.5	1.4	1.6	2.0	5.2
Ch. 3	Mean[mVmsec]	29.4	30.6	38.3	62.7	36.0	34.7	40.7	50.7	58.1	63.0	65.1	67.8
	Standarddeviation	2.7	2.5	4.3	3.9	3.2	3.0	2.9	2.7	3.1	5.6	3.5	3.4
Ch. 4	Mean[mVmsec]	23.6	18.2	21.5	26.8	22.4	25.3	25.1	24.7	17.4	29.7	19.8	27.2
	Standarddeviation	3.0	1.2	1.1	2.3	1.8	1.7	2.6	2.4	2.3	1.9	1.9	3.1
Ch. 5	Mean[mVmsec]	39.8	23.9	22.7	29.4	11.5	8.6	11.8	17.8	10.5	14.8	16.6	16.8
	Standarddeviation	9.5	5.7	2.7	4.5	1.3	0.8	0.6	1.1	0.5	1.5	2.3	6.4
Ch. 6	Mean[mVmsec]	9.8	10.0	9.8	17.5	10.6	9.0	18.1	20.8	28.2	17.2	28.0	18.5
	Standarddeviation	1.2	0.9	1.0	1.8	1.1	0.4	2.3	3.1	2.9	3.0	3.0	3.1
Ch. 7	Mean[mVmsec]	9.9	8.9	10.4	11.3	14.8	11.7	16.5	17.0	11.5	23.2	14.2	26.8
	Standarddeviation	1.2	1.1	1.1	1.9	1.3	0.7	1.7	1.2	1.5	4.1	2.8	5.3
Total	Mean[mVmsec]	202.2	183.5	216.1	299.9	189.1	238.4	277.4	319.1	197.6	270.8	266.9	316.2
	Standarddeviation	23.8	18.4	20.3	34.8	17.4	19.7	24.2	26.0	16.2	25.5	24.6	38.7

Conditions:

C1. Free wrist joint and free thumb movement
C2. Fixed wrist joint and free thumb movement
C3. Free wrist joint and fixed thumb movement
C4. Fixed wrist joint and fixed thumb movement

Table 2: Joint angles when lifting objects

Joints	Subjects	A				B				C			
	Conditions	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
θ_1	Mean[deg.]	-12.7	-16.1	-14.7	-16.5	-12.1	-12.5	-14.0	-14.6	-7.4	-9.8	-9.4	-14.7
	Standarddeviation	1.8	2.4	0.9	2.3	1.2	1.6	2.0	1.6	0.8	2.1	1.9	3.9
θ_2	Mean[deg.]	-17.1	-24.7	-37.3	-38.9	-27.9	-31.7	-38.5	-41.0	-20.8	-24.9	-27.1	-30.6
	Standarddeviation	1.4	1.8	3.2	1.7	2.4	1.9	2.0	3.6	2.1	3.4	3.4	4.9
θ_3	Mean[deg.]	-2.6	-4.2	5.4	13.3	7.2	15.7	15.4	22.0	-8.3	6.2	8.2	12.5
	Standarddeviation	2.1	1.4	1.5	1.5	1.5	1.4	2.3	2.1	1.4	1.7	2.1	2.4
θ_4	Mean[deg.]	-14.3	-14.4	-17.9	-26.5	-4.8	-9.5	-15.5	-21.2	2.3	-9.5	-7.9	-13.7
	Standarddeviation	1.8	1.8	1.3	1.7	1.3	0.5	2.2	3.7	0.8	1.5	1.4	1.3
θ_5	Mean[deg.]	78.9	72.3	67.7	66.1	84.1	92.9	82.0	79.0	91.7	92.8	93.4	90.0
	Standarddeviation	1.7	2.2	1.4	1.6	0.8	1.6	3.7	5.0	1.6	2.1	1.9	3.7
θ_6	Mean[deg.]	20.5	18.7	5.2	1.8	-6.7	-13.1	-20.1	-22.3	8.2	-4.3	-11.0	-11.9
	Standarddeviation	2.0	2.7	1.8	2.4	3.3	1.4	2.1	2.1	3.3	3.8	2.1	2.9
θ_7	Mean[deg.]	40.4	40.2	47.6	29.4	44.9	28.4	29.4	16.6	29.8	23.7	27.1	15.9
	Standarddeviation	4.2	5.2	2.9	3.0	1.6	1.9	3.3	2.4	3.0	4.8	3.5	3.5
θ_8	Mean[deg.]	50.9	56.1	76.7	78.6	45.5	37.7	49.2	55.9	45.0	36.3	36.6	43.4
	Standarddeviation	3.6	2.9	4.3	2.4	1.9	2.9	4.3	7.1	3.3	4.5	4.2	5.7

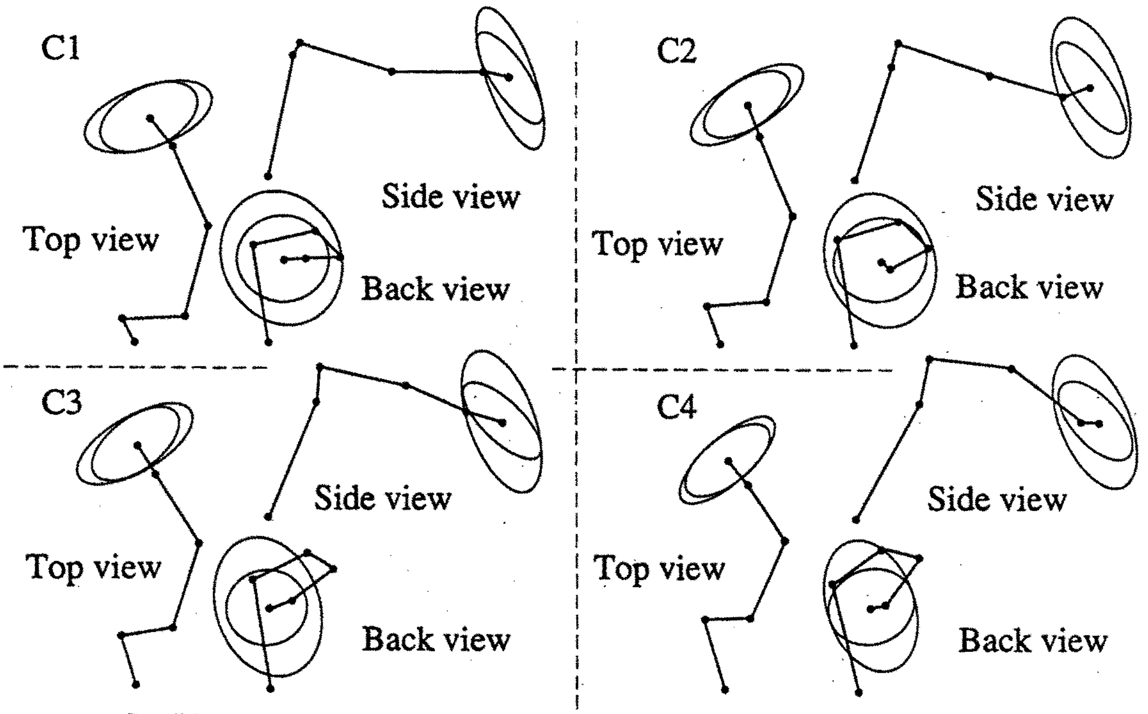
Conditions:

C1. Free wrist joint and free thumb movement
C2. Fixed wrist joint and free thumb movement
C3. Free wrist joint and fixed thumb movement
C4. Fixed wrist joint and fixed thumb movement

A similar change was noted in the θ_1, θ_2, θ_3, θ_4, and θ_6, angles in all three of the subjects. The change gets larger with each condition of fixation, respectively (C1-C4).

3.4 Analysis of the manipulability ellipses and manipulability

We computed the manipulability ellipses and manipulability [2]-[4] to determine from a kinesiological viewpoint the degree of ease of movement of the hand. We viewed the movements from the top, back, and side. The ellipses are shown in Fig. 4, and the differences in the diameters express the difference in ease of movement. The longer the diameter is the easier it is to move. On the contrary, the shorter diameter shows that the movement is more difficult. The smaller ellipse was computed with the seven degrees of freedom and three links model. The larger ellipse was computed with the 11 degrees of freedom and five links model. According to our calculations, the more joint freedom available produces a more easily moveable hand.



Conditions:

C1. Free wrist joint and free thumb movement
C2. Fixed wrist joint and free thumb movement
C3. Free wrist joint and fixed thumb movement
C4. Fixed wrist joint and fixed thumb movement

Fig. 4: Manipulability ellipses during the grasping movements

Table 3: Evaluation of manipulability during the grasping

Link Models	Subjects	A				B				C			
	Conditions	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
M1	Mean	0.354	0.357	0.317	0.275	0.319	0.301	0.3	0.286	0.293	0.332	0.333	0.327
	Standarddeviation	0.011	0.017	0.018	0.010	0.009	0.008	0.01	0.114	0.007	0.013	0.014	0.019
M2	Mean	0.065	0.059	0.067	0.059	0.059	0.043	0.053	0.051	0.061	0.043	0.045	0.046
	Standarddeviation	0.002	0.003	0.001	0.002	0.001	0.002	0.002	0.003	0.002	0.005	0.004	0.005

Conditions:

C1. Free wrist joint and free thumb movement
C2. Fixed wrist joint and free thumb movement
C3. Free wrist joint and fixed thumb movement
C4. Fixed wrist joint and fixed thumb movement

Link models:

M1. 5 links and 11 joints model(for C1 and C3) or 4 links and 9 joints model(for C2 and C4)
M2. 3 links and 7 joints model(for C1 and C3) or 2 links and 5 joints model(for C2 and C4)

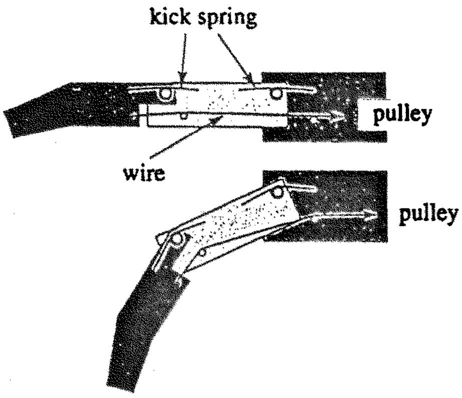


Fig. 5: Prosthetic hand model : control of two joints

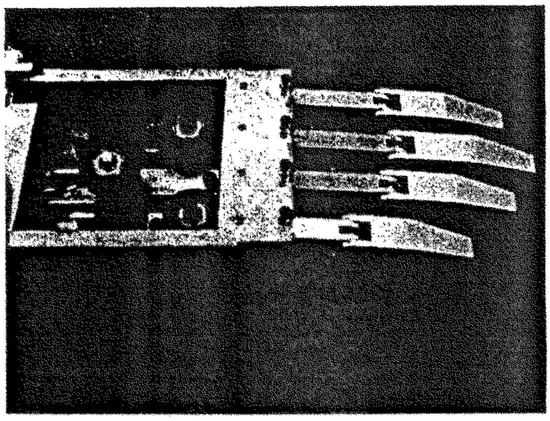


Fig. 7: Prosthetic hand model : control of four fingers

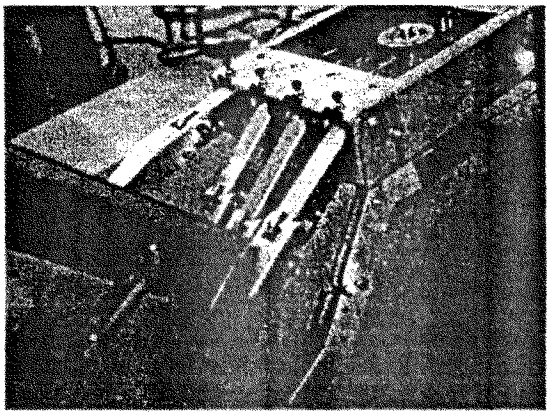


Fig. 6: Pliant prosthetic hand

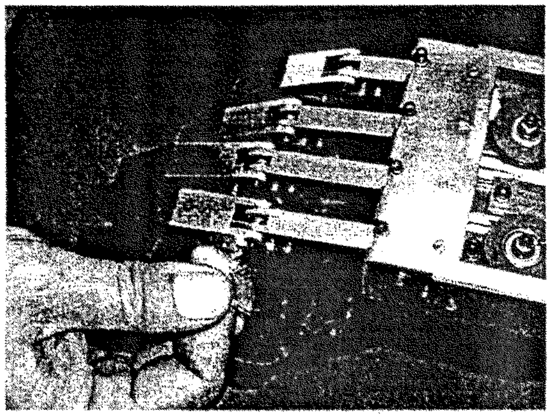


Fig. 8: Grasping ability for various sizes and shapes

When comparing C1 to C2, C3, and C4, it can be seen that C1 (free wrist joint and free thumb movement) affords the easist hand mobility. C4 is the hardest.

Next, we calculated the manipulability (Table 3), and this shows the volumes of the ellipses, which shows the capability of movement. All three subjects showed no common movements with the 11 degrees of freedom and five links model. However, with the seven degrees of freedom and three links model, manipulability decreased when the wrist is fixed (C2 and C4).

4 Discussion

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

4.1 Machinery for driving two joints

The commercialized internally powered functional prosthetic hand given to most patients is controlled by a cable that moves the links. This structure is very reliable. However, the proximal interphalangeal (PIP) joints can not be moved. That is why the authors decided to use a wire-pulley type. As seen in Fig. 5, we made a model in which the MP and PIP joints could both be moved.

Flexion is produced by a cable, and extension is produced through a spring, which made the fingers compliant (Fig. 6).

4.2 Machinery for driving four fingers

We developed a system which moves four fingers at the same time (Fig. 7). Pulleys are placed between the second and third fingers and between the fourth and fifth fingers. The wire is wrapped around the pulley twice. Another pulley is placed a little more proximally, and a wire, that goes from the center of one distal pulley to the center of the other, is also wrapped around the proximal pulley twice. The proximal pulley is attached to the cable by a wire.

Through this mechanism, even if one finger is stable, the other fingers can still move. Consequently, a wine glass can be held in this hand (Fig. 8).

4.3 The concept of a design for a new prosthetic hand

As seen in Fig. 9, we designed a new prosthetic hand that has the ability to move the MP and PIP joints, four fingers at the same time, and a thumb which can move

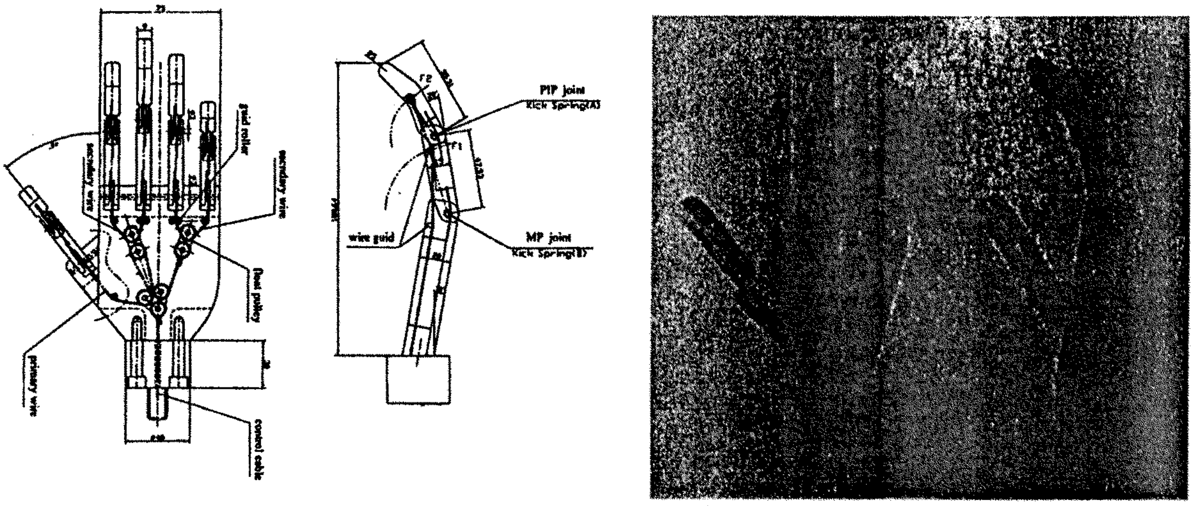


Fig. 9: The concept of a design for a new prosthetic hand

in a diagonal direction between palmar abduction and radial abduction.

The control is a voluntary-close type prosthetic hand. This is a totally new type of prosthetic hand.

5 Summary

In this paper, from the electromyograhic and three-dimensional video analyses of human grasping movements under different conditions, we found that, if the wrist joint is fixed and the thumb movees in a diagonal direction, the compensating movement of lifting the shoulder girdle, shoulder and elbow joints decreases.

Finally a new voluntary closing functional prosthetic hand, with a diagonally moving thumb was developed. This hand has passive compliance and can grasp objects of a cross section of different diameters.

References

[1] A. Esquenazi : Upper Amputee Rehabilitation and Prosthetic Restoration, PHYSICAL MEDICIN REHABILITATION, pp.275-288, W.B. SAUNDERS COMPANY, Philadelphia, 1996.

[2] T. Yoshikawa : Analysis and Control of Manipulators with Redundancy, Robotic Research, Yhe First International Symposium, eds. M. Brady and R. Paul, MIT Press, Cambridge, Mass. pp.735-747, 1984.

[3] T. Yoshikawa : Manipulability, Foundation of Robot Control, pp.108-131, CORONA PUBLISHING CO.,LTD. Tokyo, 1988.(in Japanese)

[4] A. Otsuka. et al. : Development of an Internally Powered Prosthetic Hand, Proceedings of 7th IEEE International Workshop on Robot and Human Communication, pp.201-206, 1998.