B2

COLLOQUES IRIA

textes des communications

conférence internationale sur les télémanipulateurs pour handicapés physiques

international conference on telemanipulators for the physically handicapped

IRIA

INSTITUT DE RECHERCHE D'INFORMATIQUE ET D'AUTOMATIQUE

DOMAINE DE VOLUCEAU - ROCQUENCOURT — B.P. 105 - 78150 LE CHESNAY — Tél : 954 90 20

International Conference on Telemanipulators
for the Physically Handicapped
IRIA, France, September 4-6, 1978

DEVELOPMENT OF WHOLE ARM PROTHESIS
(PROTOTYPE II)

Minoru ABE, Yuji MAEDA, Kazuo TANIE, Akio FUJIKAWA
Takefusa OHNO, Kazuo TANI, Susumu TACHI, Kiyoshi KOMORIYA
Mechanical Engineering Laboratory, MITI, Tokyo

1. Introduction

According to the statistic survey carried out by Tokyo Metropolitan Prosthetic and Orthotic Reseach Institute in 1970 [1], there is a survey result that no more than 25% of those who carry supplementary implements for their lost upper limb use them effectively and successfully, while the others of no less than 75% fail to do so. Most users complain about the low availability, heavy weight and unpleasant appearance of the prosthetic arm and stiffness around the shoulder they feel when they use it.

In view of such problems with the prosthetic arms as mentioned above, the authors have engaged in development of powered whole arm prosthesis for high-level amputees. In previous paper a hydraulically powered prosthetic arm with seven degrees of freedom (Prototype-I) was reported [2,3], which was preliminarily designed and manufactured as the first stage of the project. Its purpose was to replicate the functions of human arm as correctly as possible and look for the easily controlled arrangement of degrees of freedom and the problems that may encounter in the course of development activities.

In this project of Prototype-II, a specially designed compound type rotary servo actuator has been developed to be used at shoulder part, which can actuate two degrees of freedom, while coreless motors are used over the extent from upper arm to wrist. The prosthetic arm is designed and constructed in shell structures which are made of light and strong carbon fiber. Now the hardware of the prosthetic arm will be described below.

2. Basic design concept

2.1 Degrees of freedom and their arrangement

Prosthetic arm might be required to have as many degrees of freedom as natural arm when it is to function in the same manner as natural arm. Due to weight, controllability, and restriction of space to be occupied, it is difficult to realize so many degrees of freedom in accordance with the current technology. It is practical, therefore, to decrease the degrees of freedom to the minimum so long as the user with them can spend his daily life without any particular inconvenience. It seems that movement of the extent from shoulder to elbow serves mainly for positioning of the wrist, while orientating hand is undertaken by the forearm and wrist. In determining the minimum necessary degrees of freedom of the prosthetic arm, therefore, it is almost impossible to omit any of them over the extent from shoulder to wrist. Since increase in the number of degrees of freedom of the extreme part leads to increase in the weight of actuators, especially shoulder joint and elbow joint actuators, it is necessary to simplify the construction of the arm and the arrangement of degrees of freedom. Prototype-II is provided with seven degrees of freedom comprizing the upper elevation-depression, extension-flexion and rotation, elbow flexion-extension, supination-pronation, wrist flexion-extension and prehension.

The arrangement of degrees of freedom is illustrated in Fig. 1. Particulary the two degrees of freedom of the shoulder joint, i.e. the upper elevation-depression and extension-flexion are actuated by means of a single specially designed compound type rotary servo actuator and bevel gearing mchanism. The arrangement of degrees of freedom over the extent from elbow to wrist is the same as for Prototype-I.

2.2 Arrangement of actuators

It is necessary that an actuator for prosthetic arms is designed and constructed in a small size and light weight and at the same time with high output performance and controllability. For the shoulder part, a hydraulic system is adopted because of high torque required, while for the extent from upper arm to wrist, coreless motors are adopted because of relatively low torques required. It would be most preferable for the shoulder joint to have such an actuator that could by itself actuate three degrees of freedom . As an approach to the ideal actuator, a special designed compound type rotory servo actuator (SD-RSA) which can achieve operation of two degrees of freedom is developed.

(a) Specially designed compound type rotory servo actuator

A rotary servo actuator (RSA) is a kind of hydraulic servo torque amplifier which comprizes a combination of oscillating type high performance hydraulic actuator and precise rotary spool valve. In prototype-I, seven RSAs were used to actuate the degrees of freedom independently.

For Prototype-II, SD-RSA is developed which, fundamentally, contains two single type actuators integrally assembled in back-to-back fashion to operate two degrees of freedom. Fig. 2 shows the SD-RSA used for Prototype-II. As seen in Fig. 2, there are three ports on the housing. The center one is a drain port and the other two pressure and return ports. They are all common to both actuating servos of the SD-RSA. But inside the housing each servo has its respective channel, through which the pressurized hydraulic oil flows into the chamber by the volume corresponding to rotation of the input shaft to rotate the output shaft. The bevel gearing mechanism allows the SD-RSA to actuate the two degrees of freedom of the shoulder part. The bevel gearing mechanism is constructed with three pieces of bevel gears as illustrated in Fig. 3. If the gears a and b are rotated in same direction, then the third gear c is rotated around the SD-RSA without turning around its own axle (upper arm elevation-depression). If the bevel gears a and b are rotated in the opposite direction, the bevel gear c turns around its own axle (upper arm extension-flexion). Thus by controlling the direction of rotation and the angular velocity of the bevel gears a and b in such a manner as mentioned above, it is possible to control two degrees of freedom. The principle of performance of RSA is shown in Fig. 4.

(b) Coreless Motor

In Prototype-II, coreless motors with reduction gearing are employed (as shown in Fig. 5). They show high efficiency, being considerably light in weight and generating high torques. They are used for upper arm rotation, elbow flexion-extension, forearm supination-pronation wrist flexion-extension and prehension. Three types of motors are used as shown in Fig. 5. Each assembly shown in

Fig. 5 has reduction gearing section with output shaft on the front side, coreless motor section on the rear side, and shaft encoder between them.

(c) Location of actuators

In Prototype-II each actuator is located as close to the shoulder part as possible to reduce the torques required for the upper actuators. Such location permits lower output actuators to be employed for the shoulder and elbow parts, resulting lighter weight and smaller size of the prosthetic arm.

2.3 Control of actuators

In order to control the input shafts of the SD-RSA employed for the shoulder part, the DC motors are mounted on the housing of SD-RSA. In order to detect the shaft positions, trimmer potentiometers are used similar to those for Prototype-I. The angular position of each joint other than the shoulder is detected by the shaft encoder in the motor assemblies.

It is to be added that the present prosthetic arm is controlled by way of myoelectric signal, which will be reported in other paper later.

2.4 Structural material for the prosthetic arm

It is necessary to select light structual material for the prosthetic arm so as to reduce its weight. In Prototype-II duralumin is employed for the members such as the shoulder part which supports most of the weight of the arm. On the other hand FRP or Delrin is applied to the other parts. The upper arm and forearm construction are covered with carbon fiber shells as shown Fig.6. The shells are 1 mm thick, of six plies, and weight 117.4 g in total.

3. Description of the hardware

Fig.7 shows the prosthetic arm with seven dgrees of freedom (Prototype-II), which was designed and manufactured. Fig.7(a) shows the interior of the prosthetic arm with the carbon fiber shells removed, while Fig.7(b) shows the prosthetic arm with the shells mounted thereon. The shown prosthetic arm is designed to fit a person who lost his right arm.

3.1 Shoulder part

The shoulder part is constructed as illustrated in Fig.8. Particularly owing to the development of the specially designed compound type rotary servo actuator the two degrees of freedom have been achieved with the use of signal actuator and bevel gearing mechanism.

The manifold secured to the housing of SD-RSA is connected to the user's body. Each of the two output shafts of the SD-RSA is rotated in proportion to the angular displacement of the respective input shaft which is in turn controlled by a DC motor via pulley and spring belt, as shown Fig.8. Then the bevel gearing mechanism, actuated by the two output shafts of SD-RSA, as previously described, operates the two degrees of freedom of the shoulder part. All of the gears are made of Delrin, while the beam is of duralumin. The specifications of the SD-RSA and the DC motors are shown in Table 1 and Table 2.

3.2 Upper arm and elbow parts

The upper arm and elbow parts are shown in Fig.9. The shaft,around which the upper arm rotates, is fixed to the beam extending down from the shoulder. The shaft and beam are made of duralumin, while the bearing of Delrin. The upper arm beams, made of FRP, has a coreless motor mounted on them as shown on the upper left side of Fig.9. The motor, performing a planetary movement around the fixed shaft via pinion and gear, rotates the upper arm. The actuator seen on the right side of the Fig.9 is a coreless motor which serves elbow flexion-extension via spur gears and bevel gears. All of the beams supporting the actuators are made of

Delrin. Furthermore the shell made of carbon fibers is mounted over the beams. Three beams made of Delrin are fastened with two flat plates made of FRP. The shaft for the elbow flexion-extension is disposed on the lower end of the FRP plates. The actuators for the rotation of upper arm and for the elbow flexion-extension are located possibely close to the shoulder so as to reduce the moment of inertia.

3.3 Forearm part

As shown in Fig. 9, the actuator for the forearm spination-pronnation is fixedly arranged on the beam mounted on the shaft for the elbow flexion-extension. On the shaft of the actuator is connected a spur gear made of Delrin which rotates the forearm. The actuator, a coreless motor, is located near the elbow so as to reduce the moment of inertia.

3.4 Wrist and hand parts

The wrist and hand parts are shown in Fig. 10. The forearm is supported from the elbow side with the aid of two flat plates made of FRP. The actuators serving the wrist flexion-extension and finger operation are located near the elbow part to reduce the moment of inertia. As illustrated in Fig. 10, the wrist flexion-extension is carried out via wire transmission. The finger operation is also carried out by pulling the wire connected to finger link via the pulley fixed on the actuator shaft. It is the same way as in Prototype-I. The shaft and bearings of the wrist part are made of Delrin. The hand part is manufactured from the flat plate material of duralumin and all of the bearings thereof are miniature ball bearings. The specification of actuators that are used for the arm prosthesis are shown in Table 1.

4. Results of trial manufacture

4.1 Evaluation of Prototype-II hardware

Evaluation of the hardware of Prototype-II is described below.
(a) The weight of the individual parts and the total weight of the prosthetic arm are shown in Table 3. It is to be noted that the parts of the prosthetic arm are designed and constructed in a light weight, and that the actuators are located possibly close to the shoulder so as to reduce the required torques of the upper actuators. Owing to a fact that low torque is required for the actuators of the shoulder and elbow parts due to arrangement in that way, it has become possible to employ smaller and lighter models, resulting in substantial reduction of the total weight of the prosthetic arm and improved apperance thereof. The total weight of the prosthetic arm amounts to 2.5 Kg in case of Prototype-II, which means are remarkable reduction of 1.5 Kg in weight in comparision with the total weight of 4 Kg with Prototype-I.
(b) Owing to the development of the SD-RSA substantial weight reduction and simplification of the shoulder part have been accomplished.
(c) Owing to the arrangement of the shells made of carbon fiber it has become possible to reduce substantialy the weight of the arm parts without any loss in their mechanical strength. Moreover satisfactory results are obtained also in respect of appearance of prosthetic arm.
(d) The use of screws made of plastic material instead of metal ones has resulted in appreciable reduction of the weight of the prosthetic arm.

4.2 Evaluation of Prototype-II operation

It has been found out with Prototype-II that the movement of the degrees of freedom caused by the respective actuators is smoothly effected, that the shoulder part responds excellently to SD-RSA and that the mechanism including the bevel gearing carries out the movement as predetermined. The experiment for the dynamic characteristics of SD-RSA was conducted. Fig. 11 shows the frequency responses of both servos in SD-RSA with no load and driven independently. It shows that for frequencies under 1 Hz both servos have similar characteristics, while over 1 Hz they do not. The fact suggests that the two output axes of the bevel gearing mechanism cannot be driven independently by the nominal input over 1 Hz, as they can under 1 Hz. For the practical purpose, however, since the output rotations follow the input rotations without any noticeable gain attenuation or phase delay under 1 Hz, the SD-RSA has quite satisfactory characteristics for a shoulder of the prosthetic arms. Fig.12 shows the result of the experiment of SD-RSA attached to the bevel gearing mechanism and loaded with arm-equivalent weight. Note that, with the nominal input that should rotate only of the output axes, the SD-RSA and bevel gearing mechanism have nealy perfect output characteristics at the frequency of 1 Hz. Mounting of miniature ball bearings in the bearing portions of the hand part has removed the play of fingers and thereby made finger motion smoothly. The noise generated by the motors and reduction gearing is felt uneasy only when they are loaded a certain extent.

5. Conclusions

The main aim of this study has been stressed on lightening of the Prototype-II and this study has been worked out to attain the initially scheduled performance by various possibilities such as

1 development of compound type RSA,
2 consideration for part arrangement, and
3 selection of materials, in paticular, by use of carbon fiber.

The final evaluation on prosthetic arms should, however, be carried out systematically from the viewpoint of weight, appearance,maneuverability, controllability, reliability, cost and others of the total system including driving power supplies. From this viewpoint, the development of prosthetic arms with better performance is being undertaken now.

Acknowledgement

We would like to acknowledge our thanks to Dr. Honda, Director of Mechanical ngineering Laboratory, for supervising this project and encouraging us, to Professor Masuda, Kohgakuin University, and Mr. Mitsuoka, Mechanical Engineering Laboratory, for their technical advice, and to Mr. Minamide and Mr. Suzaki, the students of Kohgakuin University, for their technical assistance.

Thanks are also due to Dr. Saida and Mr. Imanaga, Mitsubishi Metal corporation, for their technical sevices for manufacturing SD-RSA, to Mr. Kondo, Toray Co. Ltd., for offering us carbon fiber shells, and to Mr. Aoki, Cannon Seiki Co. Ltd., for the technical advice concerning the coreless motors.

References

[1] Shuichi Kakurai: Current state of the physically handicapped; they need supplementary implements: Precision Machinery, Vol 40, No. 1, 1974, (in Japanese)

[2] Akio Fujikawa et al : A hydraulically powered prosthetic arm with seven degrees of freedom (Prototype-I), Proc. of 5th ETAN Belgrade, 341/350 (1975)

[3] Yuji Maeda et al: A hydraulically powered prosthetic arm with seven degree of freedom (Prototype-I), Bulletin of Mechanical Engineering Laboratory No. 27 1977

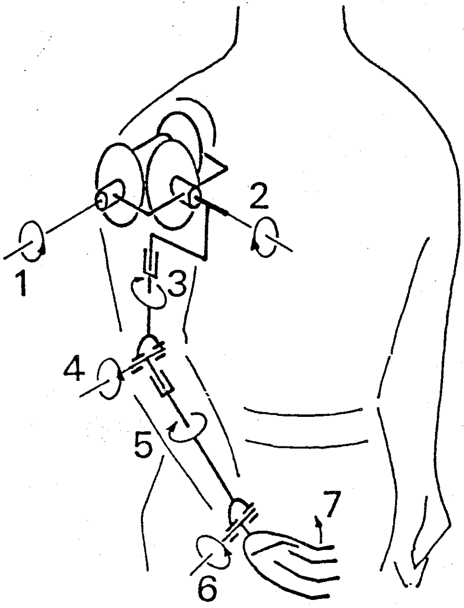


Fig. 1 Arrangement of degrees of freedom

(1) elevation-depression of arm
(2) extension-flexion of arm
(3) rotation of upper arm
(4) elbow flexion-extension
(5) supination-pronation
(6) wrist flexion-extension
(7) prehension

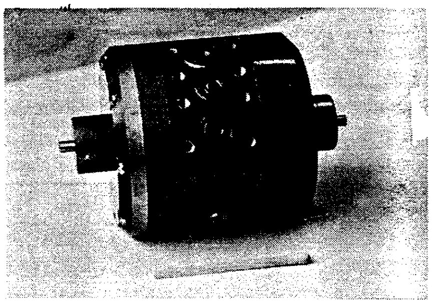


Fig. 2 SD-RSA

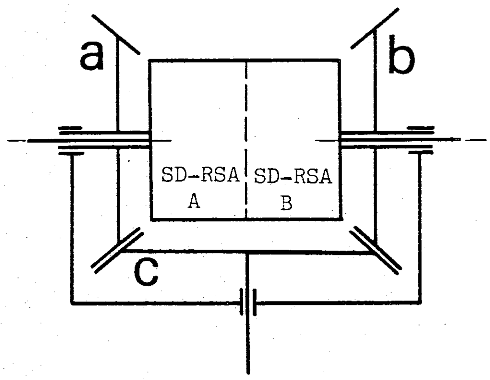
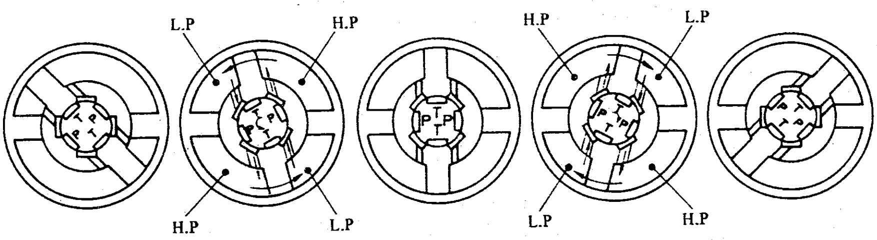


Fig. 3 Compound type RSA (SD-RSA) and bevel gear system



Neutral position after rotating leftward	Input shaft rotating leftward	Neutral position	Input shaft rotating rightward	Neutral position after rotating rightward

counter-clockwise — clockwise

Fig. 4 Principle of performance of RSA

Table 1

Specification of the actuators

movements	actuator	type	output torque (kg.cm)	rated speed (rpm)	gear ratio	dia. max. (mm)	weight (g)
elevation-depression of arm extension-flexion of arm	SD-RSA	C-SD0008B	120 ($30 kg/cm^2$)	—	—	66	700
rotation of upper arm	coreless motor	LA28-J31	5 max.10	60 (50)	1/125	36	189
elbow flexion-extension	"	LA28-J31	5 max.10	60 (50)	1/125	36	189
supination-pronation	"	LA22-P21	4	40	1/150	30	120
wrist flexion-extension	"	LA20-L21	0.5 max.2	30 (25)	1/250	20	64
prehension	"	LA20-L21	0.5 max.2	30 (25)	1/250	20	64

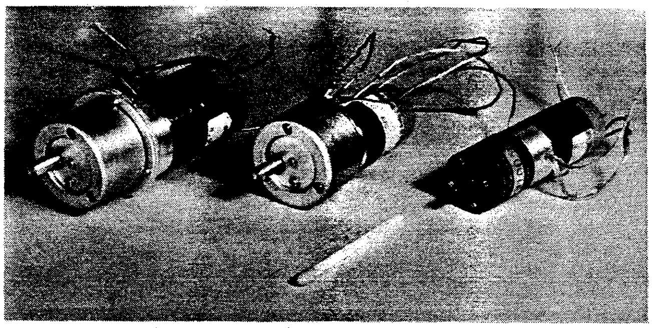


Table 2

Specification of DC motors

rated voltage	4.5 v
torque	3.0 g.cm
motor speed	7500 rpm
input	max. 0.4 W
current	max. 90 mA
output	max. 0.3 W

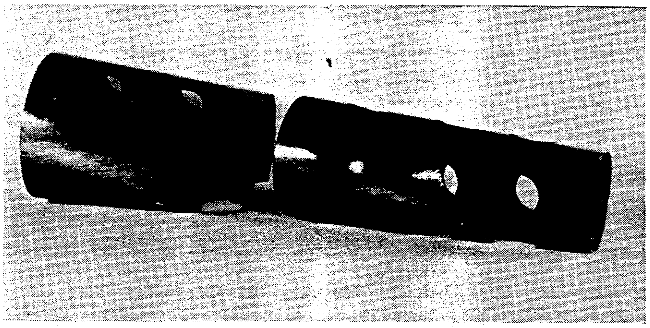
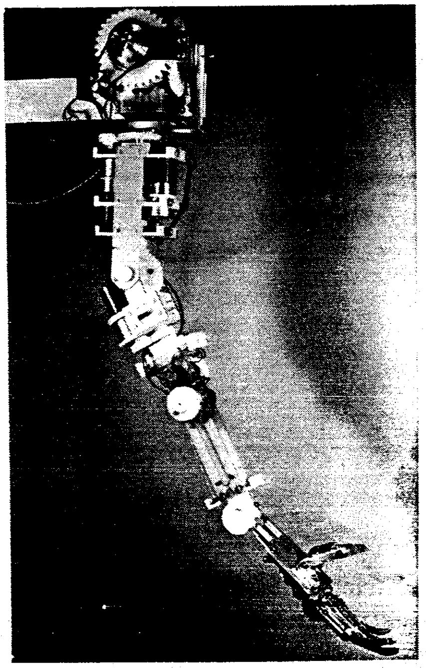
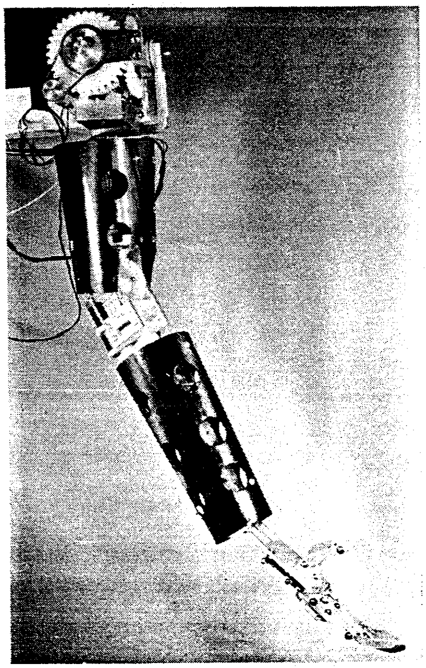


Fig. 6 Shells for upper arm and forearm made of carbon fiber



(a) Shells are removed



(b) Shells are attached

Fig. 7 Prototype II prosthetic arm

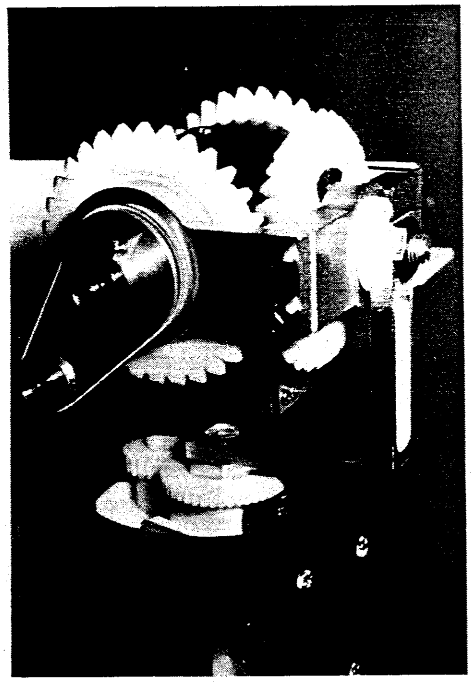


Fig. 8 Shoulder part

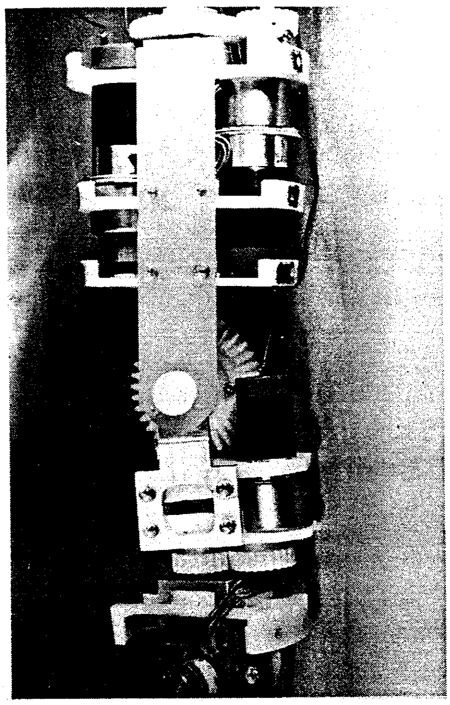


Fig. 9 Elbow part

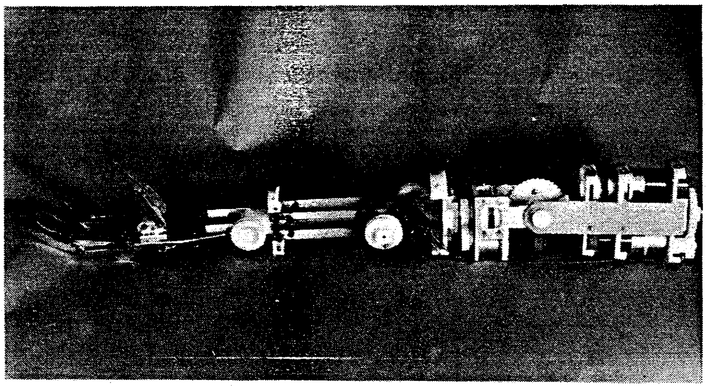


Fig. 10
Forearm and wrist

Table 3
Weight of main parts

location of part	part name	weight (g)	
shoulder	L-shaped beam	70	1130
	bevel gear support beam	168	
	bevel gears (3 pieces)	137	
	SD-RSA manifold	55	
	SD-RSA	700	
upper arm	inside beam (including elbow parts)	333	781
	shell made of carbon fiber	70	
	2 motors	378	
forearm	inside beam	141	457
	shell made of carbon fiber	68	
	motor	120	
	2 motors	128	
hand			116
	grand total		2484

* The weight of screws, gears, shafts, pulleys, etc. is included in the weight of the beams they are attached to.

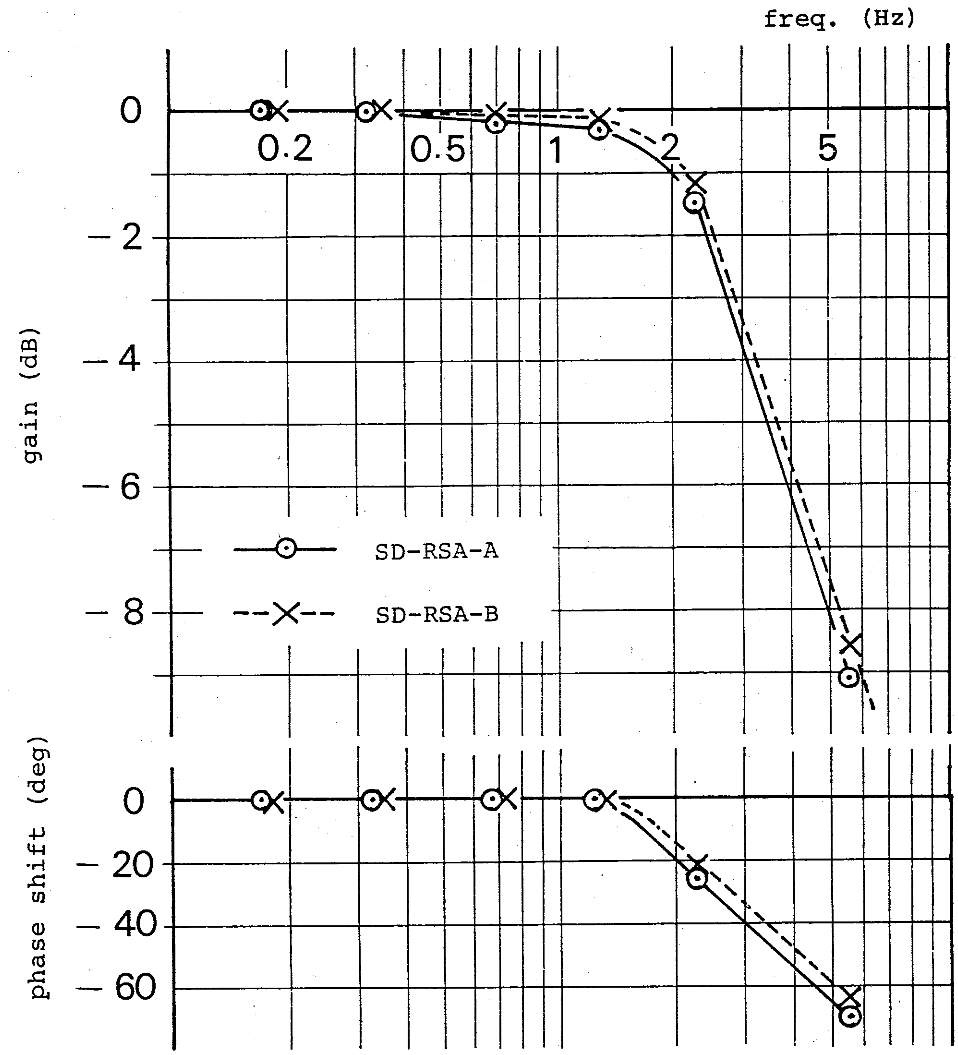
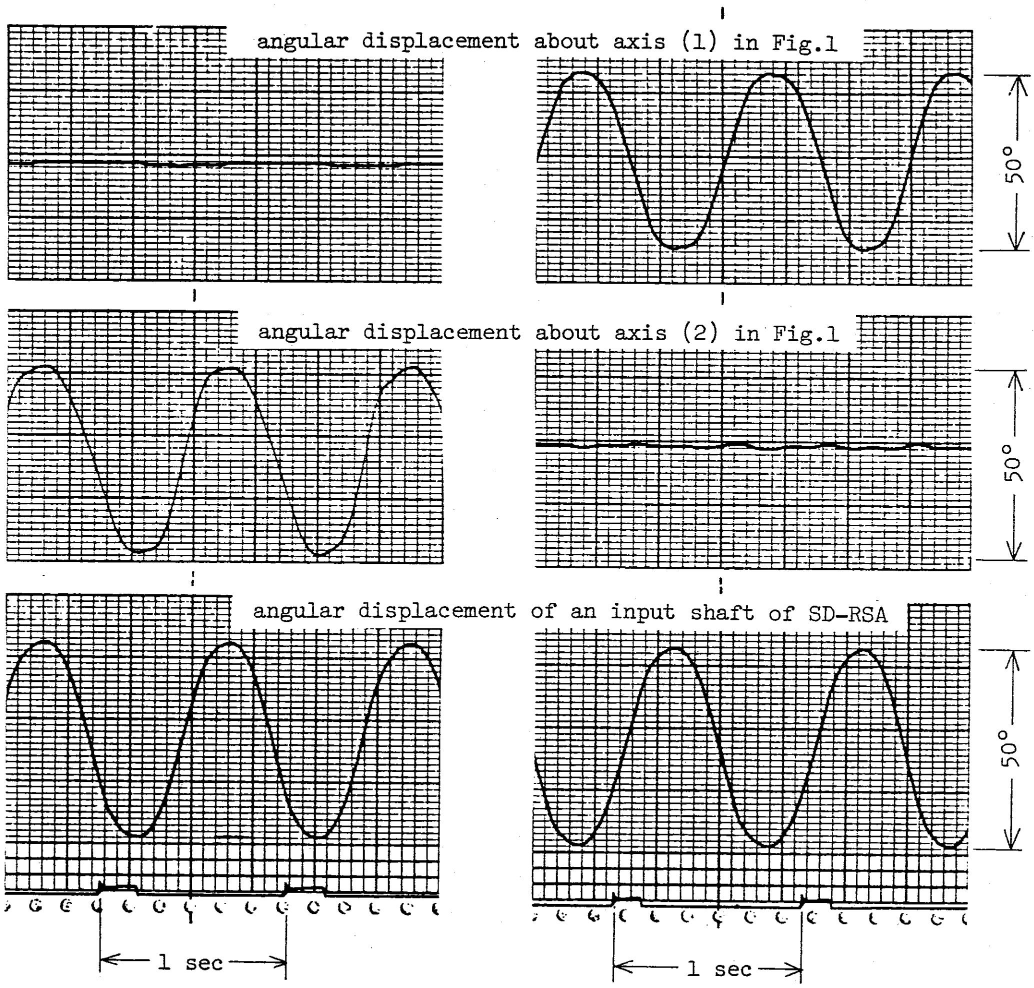


Fig.11 Frequecy response of both servos in SD-RSA with no load



(a)the other input shaft has the same displacement to the same direction.

(b)the other input shaft has the same displacement to the opposite direction.

Fig.12 SD-RSA response
(equivalent weight of prosthetic arm is applied)