MULTIFUNCTIONAL MYOELECTRIC HAND PROSTHESIS WITH PRESSURE SENSORY FEEDBACK SYSTEM — WASEDA HAND 4P

I. Kato, S. Yamakawa, K. Ichikawa, and M. Sano

Summary

As a preliminary stage for an extensive clinical use of the myoelectric hand prosthesis, a special type suited to forearm amputees was manufactured on a limited basis. In designing this artificial hand, chief aim was to equip the hand prosthesis with the most functions within the practical limits of the equipment, and this particular model is definitely characterized by the use of PNM electric stimulation signals for pressure sensory feedback to the user.

The artificial hand has two pairs of antagonist myoelectric potentials coupled with two microswitches to emit the control signals, outfitted with two DC micromotors which are driven to produce mobile functions of grasping, pinching, and wrist rotation. The electric stimulus feedback system comprises a system in which the voltage can be kept constant between 25 and 50 volts and the grasping between 5 and 50 Hz. As a matter of fact, the experimental use of the device on persons deprived of their forearms has demonstrated the practical value of this myoelectric hand.

Preliminary Stage of the Myoelectric Hand

A study group centering around Professor Kato of Waseda University launched its research work on the development of an artificial hand in the spring of 1964. This research was started with the valuable suggestions contained in a report by Professor Tomović of Yugoslavia. In the frist year, we put emphasis on the development of the soft pressure sensitive element to detect sensory pressure, and tentatively produced the element by impregnating urethanefoam with an electro-conductive paint for converting the pressure into the resistance (Fig. 1). The first model which was produced on trial by using this pressure sensitive resistor as the sensory element of the finger will grasp objects automatically when the elements of the palm and fingers touch an object.

The second model, which was produced in 1965, uses a method for storing memory of the action of hand by using a rotary disk for the command signal (Fig. 2) comprising a negative feedback loop from the pressure sensitive element to the driving motor. That is, when a strong pressure is added to the pressure sensitive element, the torque of the motor which drives the finger is reduced,

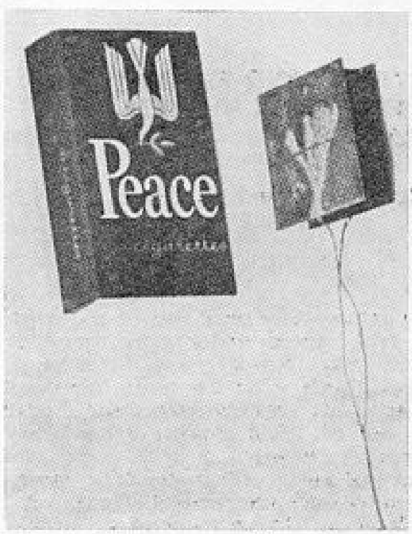

Fig. 1. Pressure sensitive element

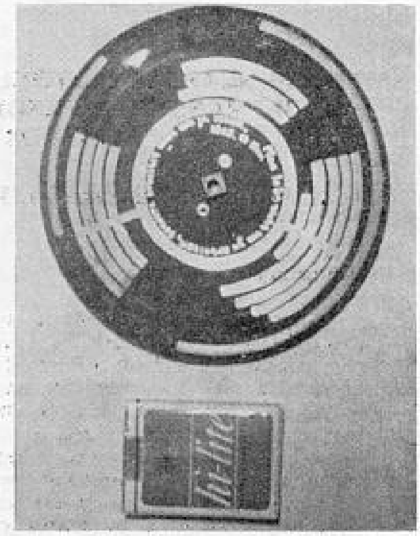

Fig. 2. Command disk

enabling the prosthetic hand to hold the object without crushing (Fig. 3). Driven by six micro servomotors, this model was capable of operating the rotation of forearm and bending every finger inde-

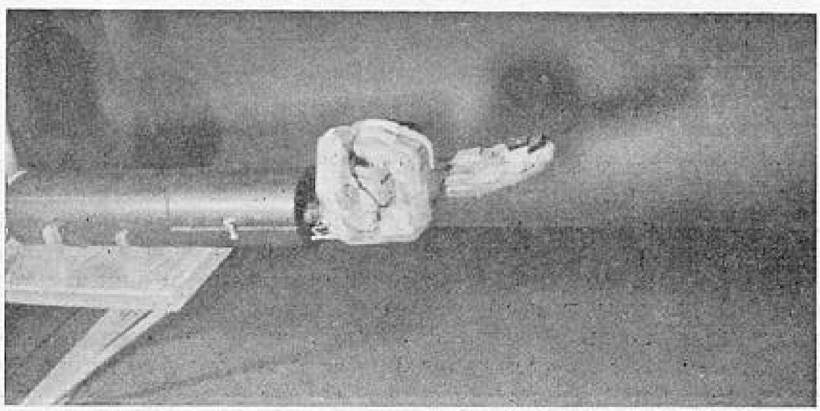

Fig. 3. An action of the model 2

pendently. We tried to operate these actions with the myoelectric potential of human forearm.

Then we produced a third model controlled by a multichannel system (Fig. 4). The third model is a multifunctional artificial hand which includes not only the independent motion of five fingers but also the bending of the wrist, and various combinations of such movements. Four muscles in the forearm are selected in order to record myoelectric potentials which present different patterns in

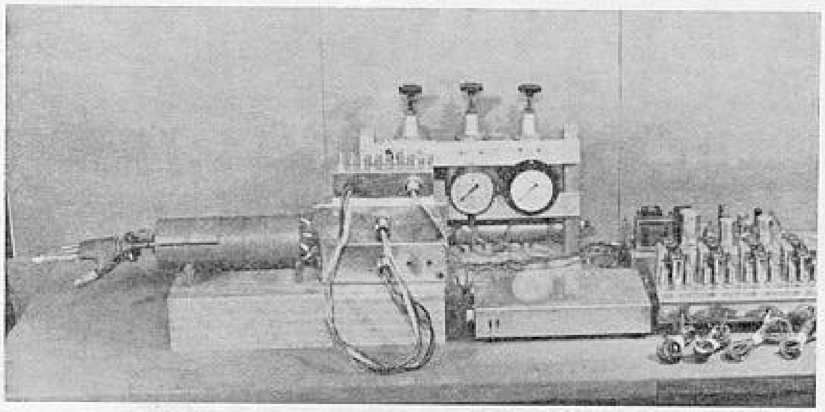

Fig. 4. Whole view of the model 3

keeping with eight-direction movement of the wrist. Thus recognition is achieved with the Schmitt and logic circuit in order to produce many driving signals. Acceleration of the action of the prosthe-

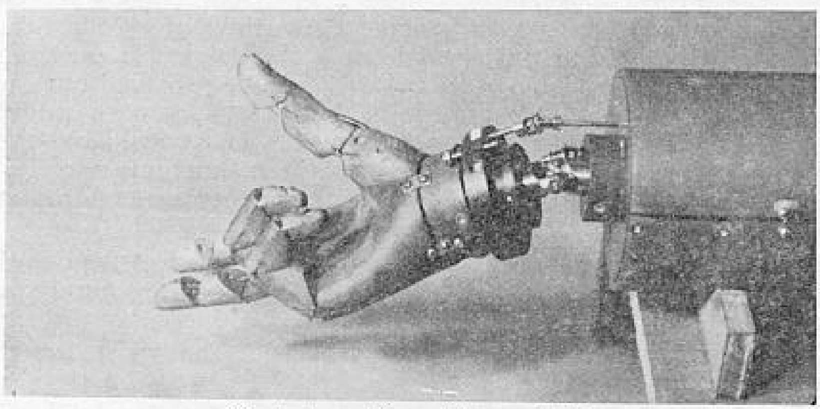

Fig. 5. An action of the model 3

sis is achieved by using a pneumatic bellofram cylinder so as to have a better simulated function of man's hand. Figures 5 and 6 are examples of the actions.

Specification of Myoelectric Hand Prosthesis

Almost all the hand prostheses now being used by many amputees in Japan are either a cosmetic artifical hand or a hook. The active hand prosthesis with external power is not used at all. Under the circumstances, it appears very worthwhile to try to promote the rehabilitation of amputees by practical use of hand prosthesis employing the myoelectric potential as a signal for control.

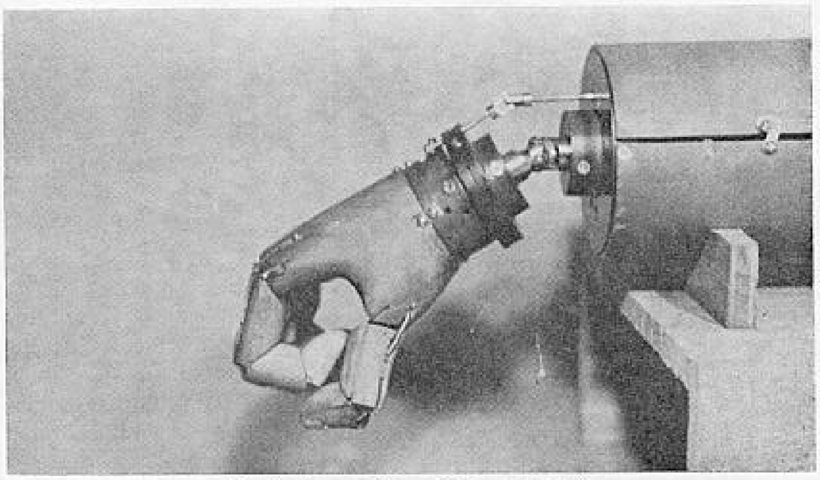

Fig. 6. An action of the model 3

The biggest problem encountered in manufacturing the electrically powered hand, is its weight. The weight of a human arm which is amputated at the elbow joint is about 1 kg, so the weight of the hand prosthesis must be below 1 kg. We provided our hand prosthesis with a limited number of motions based on a study of activities of daily living. Many researchers had considered these basic motions, but we limited them to three functions namely, to grasp, pinch, and hook in view of the frequency of such motions in actual life.

As a result of considering, moreover, the myoelectric potential, driving unit, and control system, we decided on the general specification of the hand prosthesis as follows:

(1) Able to grasp, pinch, and operate the wrist for prosupination.

(2) Use the myoelectric potential as a driving signal, adopting a proportional control system based on the myoelectric amplitude.

(3) Equipped with a feedback system for pressure from the hand prosthesis to human body.

(4) Use DC micromotors for driving.

(5) Weight of the hand prosthesis is less than 1 kg.

(6) High durability.

(7) Same shape and same size as man's hand.

(8) Inexpensiveness

Model No. 4

We manufactured Model No. 4 in 1967 as the prototype myoelectric hand prosthesis to fill this specification. This machine uses two-channel antagonistic myoelectric potential as command signals, which are proportionally controlled by myoelectric amplitude. Two DC micromotors are used, one for the wrist, the other

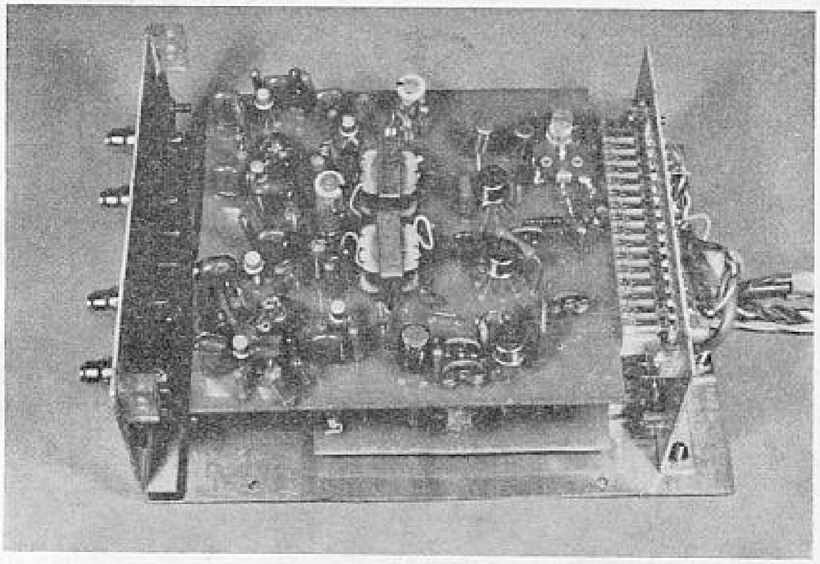

Fig. 7. Control circuit

for the fingers. The possible motions are pro-supination of the forearm and grasping and pinching of the hand. Pro-supination is achieved by use of a reversible motor and two microswitches mounted on the forearm. Grasping and pinching are achieved with one motor by using the phase lag of two bevel gears with the myoelectric potential of the two channels.

The feedback function is achieved by modulating the resistance variation of the pressure transducer attached at the tip of the forefinger into the amplitude of 100 Hz sine waves, which is transmitted to human skin as mechanical vibration.

The complete circuit for the control of Model No. 4 is shown in Figure 7. It is composed of two pieces of printed board. We will miniaturize this circuit by means of IC (Integrated Circuit).

Figures 8 and 9 are example of actions of Model No. 4 and each motion uses the pressure sensitive element of forefinger effectively.

Model No. 4, however, did not prove to be satisfactory, so we did not fit it to amputees. Not only were there problems of stur-

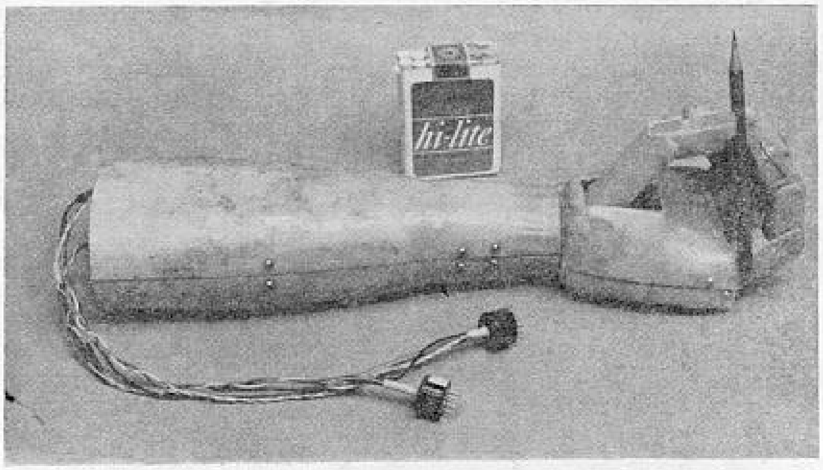

Fig. 8. An action of the model 4

diness and durability, but also there was shortage of driving power and a deterioration of mechanical vibration feedback function due to the adaptation of skin sensation.

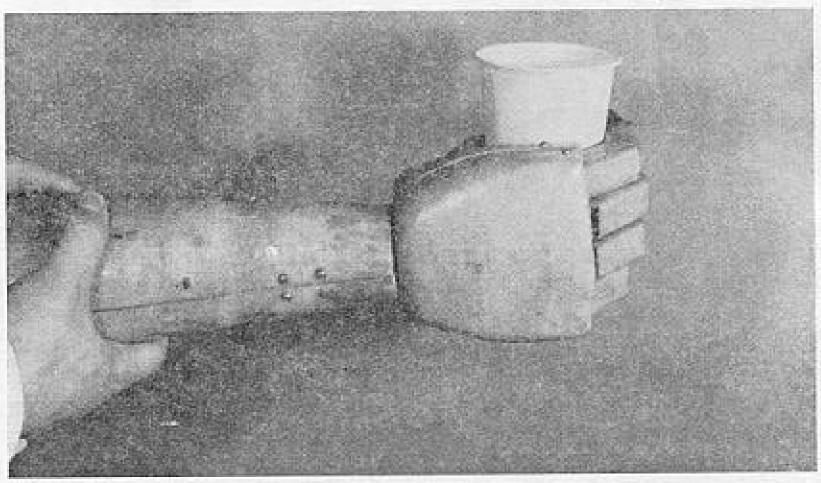

Fig. 9. An action of the model 4

Waseda Hand No. 4P

Based on Model No. 4, Model No. 4P was manufactured in 1968 for the purpose of performing clinical experience by mounting it to the amputees. P stands for "practical".

Functions

The functions of Model No. 4P are three-point pinching, grasping with five fingers, and supination and pronation of the forearm. The speeds of pinching and grasping were controlled in proportion to the amplitude of the myoelectric signal, while supination and pronation were controlled by an on-off single-contact switch.

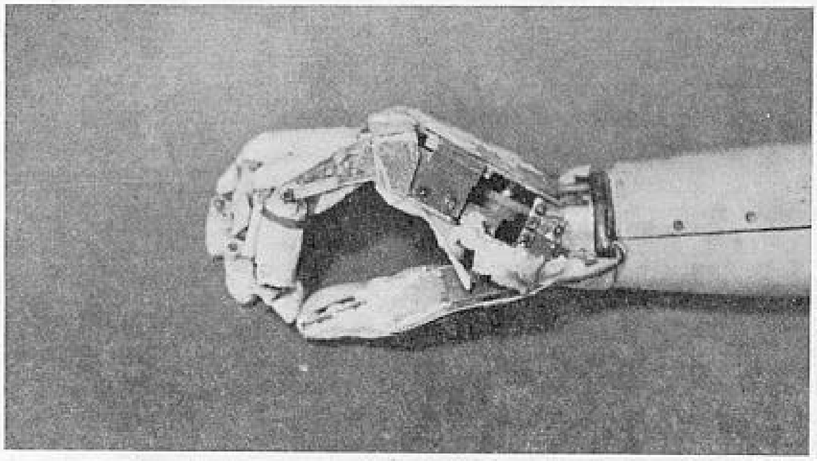

Fig. 10. Three-point pinching

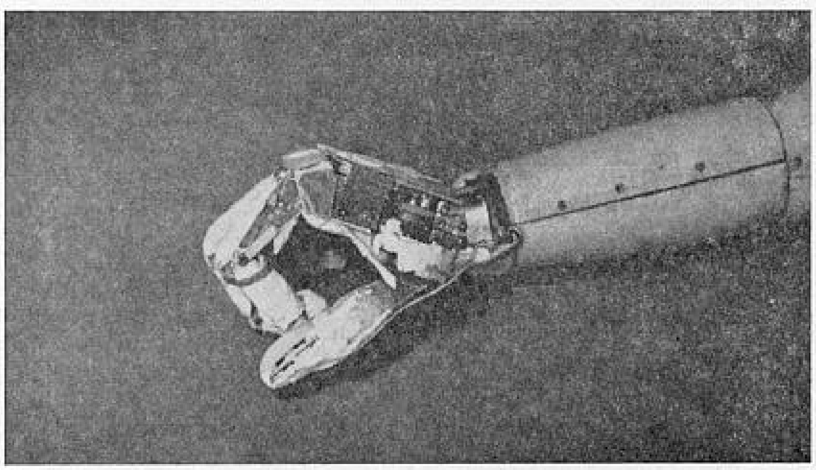

Fig. 11. Grasping with five fingers

Generally in the hand prosthesis which utilizes external power, when we increase the kinds of motion, we must increase the size of the actuator, involving the heavier weight of the hand prosthesis, so it becomes very difficult to put the actuator in the limited space.

Accordingly in Model No. 4P, we decided to use the myoelectric potential of two channels taken out from the stump as the control signal, providing the two motions, i.e., three-point pinching shown in Figure 10 and grasping with five fingers shown in Figure 11, with the variation of rotary direction of one micro DC motor. The hand thus can hook as in raising and lowering a bag by these two motions. In this type of action, the reversing by overload is prevented because of using a worm gear in the gear train, and the artificial hand does not loose hold of weighty goods.

The switch for control of supination and pronation of the wrist is installed on *trigonum colli laterale*, and pushing the switch by laying down the neck slightly controls the rotary direction of the wrist.

Mechanism

In the hand prosthesis where pinching is the principal function, a single joint finger is enough for practice, but as many finger joints as possible are desirable if grasping is also intended. Because a larger number of joints provide a closer grip on the object with the fingers, many joints are needed for natural performance of the hand. For this reason, we provided each finger with three joints, except the thumb which has a single joint. A link mechanism was used to bend the fingers. The finger was prevented from bending unnaturally or as in a fracture by installing a stopper in part of the link mechanism.

It is desirable that the thumb has a mechanism to permit rotation around its basal joint, but the mechanism involves such difficult problems as the need for an extra driving motor and an additional channel for control signals. So we made the angle between the thumb and the palm 45 deg. to keep the thumb from facing the other four fingers completely while the former is opened. As the result, the thumb is rotated inward 45 deg.

In order to feed back the grasp pressure to the human body, we installed a pressure sensory zone which covered all the area from the second joint to the thumb on its inner side to the tip of the finger (Fig. 12). For this pressure sensory zone, we used silicon rubber in part B in Figure 12. Thus the power is transmitted to the pressure transducer when any part of the pressure sensory zone is pushed.

The finger composed of a skeletal structure of duralumin covered with polyurethane. So the elasticity of the finger is close to that of the human finger.

The mechanism which performs the two motions of grasping and pinching by the reversible motor is one of salient features of Model No. 4P. The phase of thumb closing is selected by use of a gear train. That is, the phase of thumb gear is advanced for pinching and the phase of thumb gear is made to lag for grasping. We can change the phase angle of the thumb by shifting the rotary direction of the motor if we adjust the position of the thumb's link. If the amputee generates two-channel myoelectric potential independently, the polarity of the voltage applied to the motor by means of the electronic circuit, which will be described later, is changed so that the motor can be rotated in either direction. Then the amputee can voluntarily choose the motion of grasping or pinching. The inside of the palm is illustrated in Figure 13.

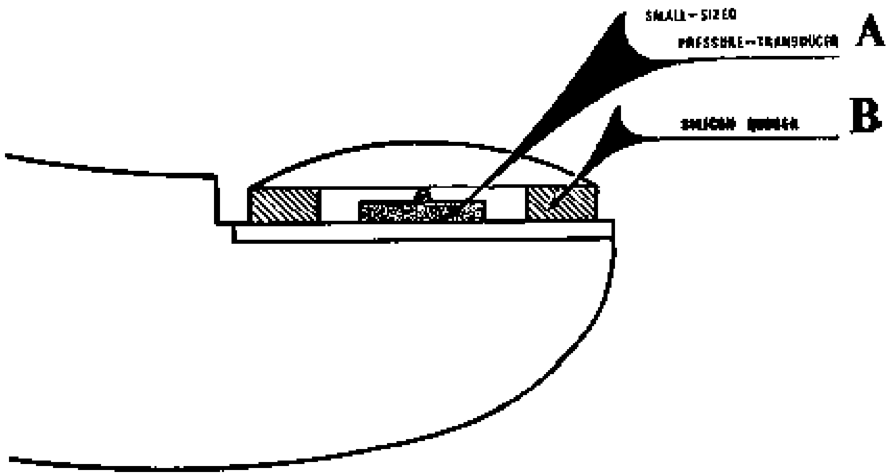

Fig. 12. Pressure sensory zone

We could not give the palm the skeletal structure as with the finger because the gear train was installed in it with needle bearings so we adopted a shell structure. However, nearly the same figure and the same elasticity as man's hand can be realized by bonding polyurethane on the outer face of the shell which was made of duralumin and aluminium.

Model No. 4P is not equipped with the bending function of the wrist. Instead of it, the hand is dorsiflexion of the wrist at 25 deg. in the proximal-distal direction. Obviously there are frequent needs of operating the arm while the wrist is bent. Therefore, a bent wrist looks more natural. The condition of the dorsiflexion of the wrist is shown in Figure 14.

The forearm portion of the prosthesis is made of polyester laminate and is small and light to present a similarity to the normal arm. The forearm is very slender because the model is fitted for a woman. The wrist forms an ellipse of 48.40 mm by 56 mm. Inside the arm are installed two DC micromotors, one for driving fingers (2.2 W) and the other for rotating the forearm (0.75 W), (Fig. 15).

The wrist is designed to rotate about the long axis of the forearm, with a stop installed at a rotary angle of about 250 deg.

A cosmetic glove covers the region from the rotary part to the end of the fingers.

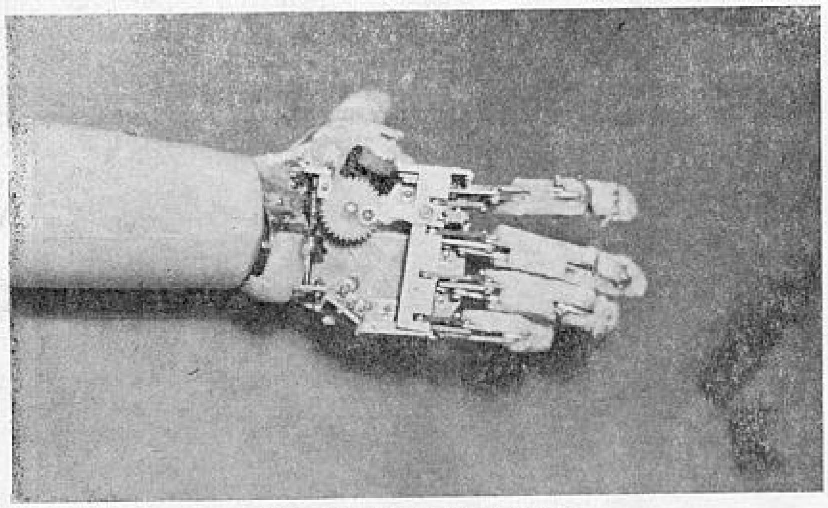

Fig. 13. Inside of the palm

The socket is a total contact Münster type, mode of air-permeable ligolac.

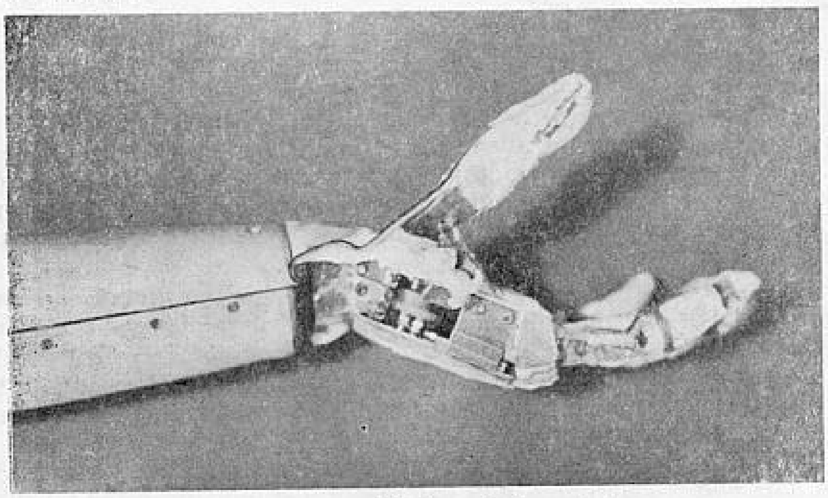

Fig. 14. Dorsiflexion of the wrist

Driving Circuit

The block diagram of the electronic circuit for driving the fingers of Model No. 4P is shown in Figure 16.

The two-channel myoelectric potential obtained through the skin electrode is amplified, and the two-channel myoelectric potential is subtracted by a subtracter so that the output of the subtracter may be changed into plus or minus depending upon the absolute value. Two direction of rotation of the motor is determined by the positive or negative output. Thus two motions, grasping and pinching, are controlled.

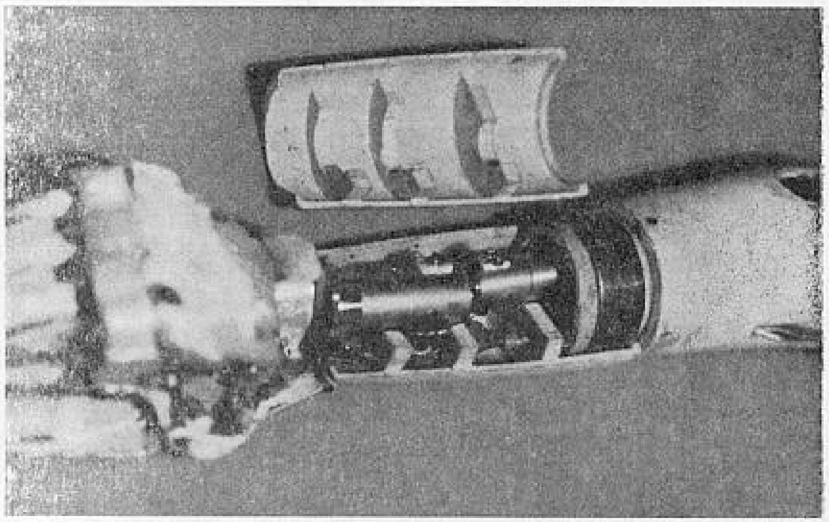

Fig. 15. Inside of the forearm

Noise induced by the human body or lead wire is apt to interfere because the myoelectric potential derived from the stump was at a very low level. But this circuit is useful to reduce the noise by subtracting the noise of two channels with the subtracter.

The electronic circuit used in Model No. 4P is designed on the basis of the circuit of Model No. 4, and the circuit was constructed with introduction of integrated circuits to make the product small and light, for the clinical use of the myoelectric hand prosthesis was intended.

The rechargeable nickel-cadmium battery supplying 12.5 V and 17.5 V is used for the power source. This battery can produce constant voltage during most of the operation time with a sufficient capacity to last all day.

Sensory Feedback

In Model No. 4, the grasped pressure is fed back to the human body as mechanical vibrations. However, mechanical vibration has the following weak points: it is liable to be adapted readily by the human body; its power consumption rate is high; and its ability to distinguish stimulation is low. So we feed back, in Model No. 4P, the grasped pressure to the human body as the frequency variation of electric pulse (PNM waves). As we explained before, the pressure sensitive region covers all the field from the second joint of the thumb on its inner side to the end of the finger, which is in closest contact with the grasped object.

The merits of using electric stimulation for the sensory feedback in the hand prosthesis are considered:

1. Adaptation to the human body is low.
2. Distinguishing ability is excellent.
3. It is possible to transmit two kinds of information separately with one electrode (voltage and frequency).
4. Not accompanied with noise as in the case of mechanical stimulation.
5. The design of the circuit is complex, but it is easy to install and remove the electrode, which is made small.

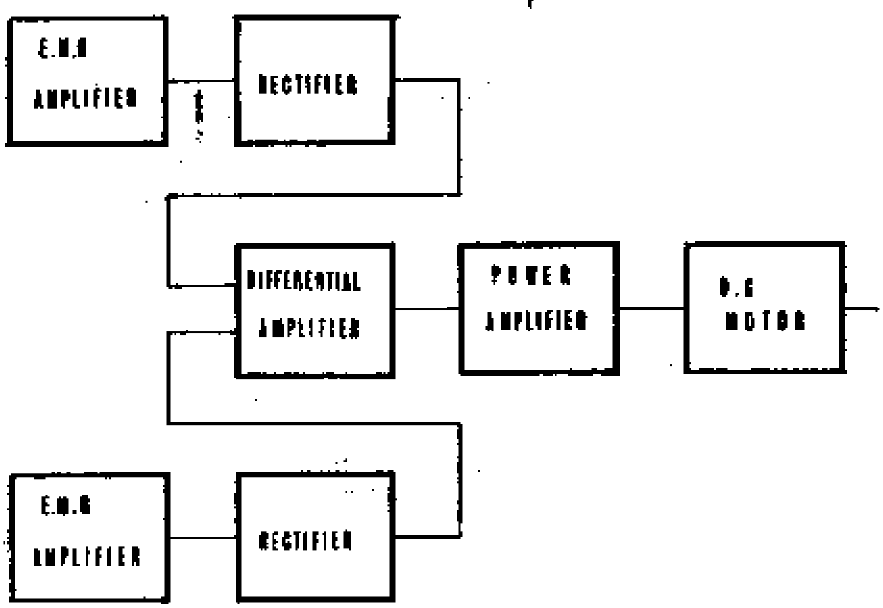

Fig. 16. Block diagram of the electric circuit for driving fingers

The stimulation electrode is made of conductive rubber and its stimulation comes from the forearm. The pulse width is 0.1 ms, and the user can select a proper voltage which gives him pleasant feeling from the range of 25 to 50 volts, because the threshold value of voltage depends upon individuals. Besides, the muscle of the stimulated point never shrinks by the electric stimulation. The frequency band is 5—100 Hz, changing in proportion to the force (0—1 kg) applied to the pressure transducer.

The block diagram of the electric stimulation circuit is given in Figure 17 but the electric stimulation circuit can also be used for mechanical stimulation.

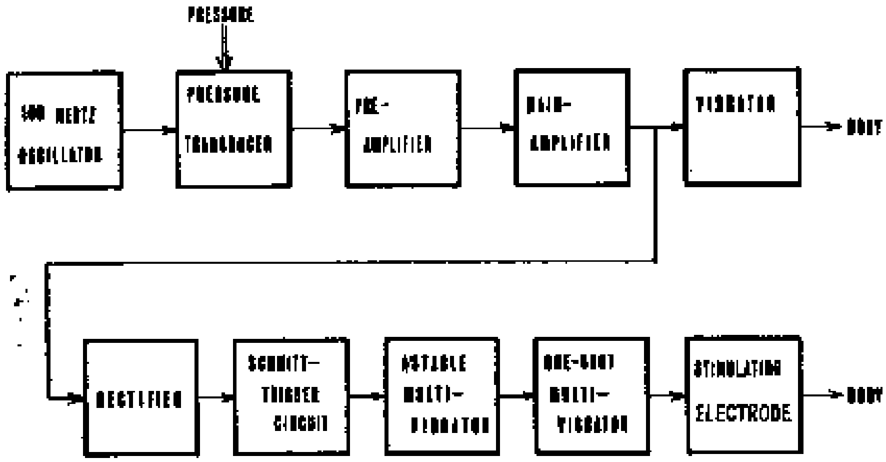

Fig. 17. Block diagram of the electric stimulation circuit

Conclusion

The weight of Model No. 4P breaks down as follows;

(1) Body of the hand prosthesis	830 g
(2) Myoelectric amplifier	335 g
(3) Myoelectric amplifier battery	665 g
(4) Sensory amplifier	230 g
(5) Frequency converter and its battery	470 g

Items (2), (3), (4) and (5) are attached to the waist with a belt. The weight of the cosmetic hand prosthesis, which the subject has been using daily is 385 g. So the weight of Model No. 4P (830 g), is more than double that of the cosmetic hand. Because the subject is a woman, this seems to be a little too heavy.

As the subject was a unilateral case, she could dow the prosthesis and related equipment by herself in about seven minutes.

We tested the following motions with Model No. 4P fitted to the patient:

(1) Raise and carry a glass containing water. (Fig. 18)
(2) Raise and carry a bottle of Coca Cola (600 g).
(3) Hand a handbag.
(4) Pinch a steel ball of 11 mm in diameter. (Fig. 19)
(5) Hold a baseball.
(6) Pour Coca Cola into a glass.
(7) Draw a picture. (Fig. 20)
(8) Hold a paper cup without crushing it.
(9) Stack up wooden blocks.

Fig. 18. Cup holding.

Fig. 19. Steel ball pinching.

While wearing the hand prosthesis, the subject tried to do all these motions without preparatory training, and she could perform almost all of them. This was one of the important reasons for utilizing myoelectric power for the signal source of Model No. 4P.

The experiments from (1) to (3) were intended to check the grasping power, which was found to be enough to hold a Coca Cola bottle with ease. When hanging something as in (3), the user can hold anything as heavy as the weight required to crush the equipment, thanks to the lock mechanism provided.

Experiment (4) relates to pinching a small thing. It was found that the wearer could pinch a fairly small thing because of the elasticity of the finger and the rubber glove worn. There is no fear of snapping it off.

Experiment (6) is the work using the rotation of wrist. In this series of experiments, number (6) was the only one in which we could not get good result. The rotary speed of the wrist was too fast (15 rpm), and the subject was not accustomed to the use of the switch. But this trouble can be eliminated by training the subject and lowering the rotary speed.

Fig. 20. Drawing.

Fig. 21. Stacking up.

The subject could draw a picture wery skillfully in experiment (7). The hand prosthesis could be used to draw in a manner comparable to the normal arm.

Experiment (8) is for checking the effect of feedback. As for the user, catching the feedback due to electric stimulation, to stop the revolution of the motor. Therefore, it often happened that the motor had turned excessively when the subject stopped it. Because the problem of sensation relates to the feeling of using the hand prosthesis, it appears necessary to train the user to some extent.

Epilogue

Because the equipment was to be used by a woman, we designed it to be as small and light as possible, and almost satisfactory results were obtained. It is possible to carry out activities of daily living satisfactorily with this hand prosthesis, except for some special actions.

For the first time, electric stimulation has been used for the sensory feedback in the hand prosthesis, but the model did not feel bad while using it, and no paralysis of skin sensation occurred even when it was used for a long time. The distinguishing ability was superior and did not need preparatory training.

We manufactured Model No. 4P wholly by hand in the laboratory of our university. Now we are confident that this model, if made industrially, will completely meet practical requirements.

Acknowledgements

We thank Mr. Unokichi Iida, chief, Prosthetics Services, National Rehabilitation Center for Physically Handicapped, for his cooperation.