# HYDRAULICALLY POWERED FOREARM PROSTHESIS - WASEDA HAND-9H3

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## Summary

Hydraulically powered prosthesis has been developed and worn by a forearm amputee inorder to evaluate its function ability.

This prosthesis has three degrees of freedom; adaptable grasping, pro-supination and dorsal volar flexion. These degrees of freedom are driven by new type hydraulic rotary actuator-- Rotary Servo Actuator. Its features are light in weight, compact, and highly precise. The weight of this prosthesis without socket is about 550g.

The pump as a power source is driven by a mini d.c. motor, and its total weight is about 850g.This pump unit is contained in a case with oil reservoir and a pressure switch.

This prosthesis is controlled by EMG pattern signals of remaining six stump muscles. The EMG pattern is recognized by a micro computer. The circuit of the micro computer is constructed of three cards, and the program of the micro computer is stored into Random Access Memories.

The EMG pattern can be generated by moving amputee's phantom limb, and the phantom limb movements of the amputee are cooperated with the prosthetic movements. So even if this prosthesis has many degrees of freedom the control training can be accomplished in a very short time. Using this control computer, the amputee can get both individual movements of each degree offreedom and synergical movements of two modes by using two degrees of freedom.

Using this prosthesis various activities have been more natural, and the amputee can use this prostheiss skillfully even if he is hardly trained.

## 1. Introduction

As the electrically powered forearm prosthesis with one degree of freedom has been clinically valued and come into wide use, a prosthesis with multi degrees of freedom and multi function has been strongly aimed-at. This can be true not only of the prosthesis for a high degree amputee like a above elbow amputee or amputee without the shoulder joint but also of the forearm prosthesis, because the forearm amputee who has once used the prosthesis with one degree of freedom desires more functional one. Consequently several powered prosthesis with multi degrees of freedom have been investigated and developed, but there are few which can be put to practical use. In order to develop a light and small prosthesis with the multi degrees of freedom as well as the large output power in each degree of freedom, there need to be a total re-examination not only of the power source and the actuator but also of the development of the signal source for the control of the multi degrees of freedom and the control method which will lighten the amputee's burden to the minimum[1]. Accordingly we have tried to develop a miniaturized portable hydraulic pump driven by a small d.c. motor as a power source and investigated to miniaturize the rotary servo actuator (RSA) for the prosthesis which is the hydraulically oscillating motor in which the control value is inclose[2][3]. On the other hand, we have analyzed the EMG detected from the remaining muscle groups of the forearm stumps and try to use the EMG pattern accompanying the volantary movement of the phantom limb as the control signal for a prostheisis with multi degrees of freedom[4].

On the basis of the said studies we have developed a prosthesis with three degrees of freedom for a forearm amputee so as to make it available in his daily life.

In the case of forearm amputee he has on advantage in that there remain many parts of the forearm muscles which drove the lost part after the amputation, but in giving multi degrees of freedom the space in which to fix the mechanisms is very small. So we have developed a composite type rotary servo actuator. The oil piping is inclosed in its structure to make the prosthesis as small as possible[5], and usable for amputees exclusive of these with long stump. And the control system has been discriminated EMG pattern, which accompanies the volantary movement of the phantom limb of the amputee, and the training for the operation of the prosthesis has been lessened by making the movement of the prosthesis correspond with that of the phantom limb [6]. The control circuit has been miniaturized and made portable by utilizing the micro computer chips.

## 2. Hydraulic source

The hydraulic pump should have the following conditions as the power source for the prostheis :

a) the small size and the light weight
b) the high power and high efficiency
c) slightoscillation and low noise
d) no oil leakage
e) maintenance free and ease of check

Considering these conditions and comparing the many types of pump, we have selected the rotary piston pump of orbit type. This rotary piston pump works with the piston reciprocating by means of the eccentric cam in the rotating rotor. How it works is shown in Fig.1. As shown in the figure, the single piston of this pump reverses the two processes of suction and exhaust in one cycle.

### 2.1 General view of the pump unit

In developing the portable pump unit for the forearm prosthesis with 3 degrees of freedom, the design standard of the design of the pump unit has been decided as follows:

a) pressure---25[kg/cm$^2$]
b) flow rate---over260[cm$^3$/min]
c) smallsize,light weight, and portability
d) low noise level
e) slight temperature rise
f) operating fluid must be colorless, odorless, and pollutionless

The outlook of the pump which has been designed by these standard is shown in Fig.2 This pump unit is broadly divided into the following parts

a) pump proper and relief valve
b) power transfer parts (motor,timing belt etc.)
c) case (serving as a resevoir)

The pump proper and relief valve are lighten in weight by using the aluminum alloy mainly. Because of the restriction of the size, the pump and relief valve are inclosed in the case to simplify the oil piping and the dorain of the relief valve. The pump and relief valve is shown in Fig.3.

The power transmission mechanism is composed of the motor, sheave, and belt. Power is transmitted by the sheave through the timing belt to prevent noise. Battery is used as a power source, and d.c. motor is used as a driver for the pump.

To prevent noise, the abnormal rise of oil temperature and oil leakage, the pump is put in a case. The case also serves as a tank, the volume of which is about 170[cm$^3$]. It is a product formed of polypropylene. The top plate of the tank is used as a plate on which the motor, pump, and relief valve are mounted. As shown in Fig.2, all components are stored in this case. To prevent the intrusion of the extraneous matter (dust, mote, etc.) and the oil leakage, the unit is completely sealed by O ring between the plate and the case, and by packing between the plate, the pump and relief valve. And the pump is so shaped as to be conveniently fixed on the human body.

The specification of the pump is shown in table 1.

## 2.2 Performance and problems to be solved

The characteristics of the pump are shown in Fig.4. The pump unit is practically used with the setting pressure of the relief valve at 30[kg/$cm^2$]. The characteristics of the pump unit at this time is shown in Fig.5. Considering these, it fully satisfies the design standard of the pressure 25[kg/$cm^2$] and volume flow rate 260[$cm^3$/min].

This pump unit has reached the initial goal, but the following problems have to be solved in the future.

a) improvement of the pump unit efficiency by soaking it in the oil, etc.
b) lightening the weight by means of utilization of the carbon fiber etc,
c) reduction of the noise
d) reduction of the oscillation of the pipe
e) deciding the optimal condition of the system from the working condition (pressure, flow, and working frequency etc.) in order to improve the efficiency of the pump unit.

## 3. Prosthesis proper

The forearm prosthesis with multi degrees of freedom must have the necessary functions and the large output power within the restricted space and weight because of the constraint of the length of the stump. Considering this, we have developed a composite type RSA based on the one which was developed past and simplified the maintenance about the oil piping etc. and miniaturized the whole system.

The following are the intended performances in putting the forearm prosthesis to practical use, according to which the prosthesis have been designed and developed.

a) kinetic velocity---90[deg/sec] with each degree of freedom
b) handling weight---over 1[kg]
c) gripping force---over 5[kg]
d) internal leakage of the actuator---under 10[$cm^3$/min]
e) total weight ---under 600[kg]

## 3.1 Construction of the prosthesis

The prosthesis proper is shown in Fig.6 and Fig.7. It is constructed with actuator, control motor, bracket fixing the actuator, connecting link for prehention and fingers. Each part will be stated indetail below.

### 3.1.1 Actuator for the prosthesis

There occur the following disadvantages if we use one RSA for each degree of freedom of the prosthesis.

a) total weight of the volume are increased
b) oil piping which connect the oil line is needed
c) oil pipimg reduces the reachable range and increases the load torque

For these reason, we buried the oil piping in the structure and have developed the composite type rotary servo actuator. This is shown in Fig.8. There are only two oil pipings, inlet and outlet pipe, to connect the power unit. The specification of each actuator is shown in table 2.

In order to obtain high efficiency, the internal leakage of each actuator must be held as low as possible, and the square shape seal (made of fluorine rubber) has been used for the rotor vane of the output shaft and fixed guide vane and the seal made of Teflon or fluorine rubber has been used in the casing on both sides of the output shaft. To reduce the weight of prosthesis, all parts are made of the high-strength alminium except the guide vane.

### 3.1.2 Elecric-mechanical Interface

For the pilot motor which drives the input shaft of the RSA, a stepping motor has the following advantages over a d.c. motor.

a) there dose not need to be any detector for feedback
b) although step miss may occur in the over load, it is more stable and hunching dose not occur
c) long life is obtained because there is no area of contact like brush,etc.

The stepping motor for working has permanet magnet for the rotor and 4 phase coil (wound bifilar way) for the stator.

### 3.2 Result and problem to be solved

We have developed a prosthesis with 3 degrees of freedom of prehention, wrist flexion, and pro-spination according to the above mentioed configulation. And we have obtained the following result.

a) this prosthesis, which has 230[mm] in total length, can be applied to the wide range of forearm amputees exclusive of those with long stump.
b) adopting the internal seal broadly in the actuator, outer leakage is prevented and it dose not occur that the prosthesis proper soil the clothes
c) in driving the actuator, no noise is heard
d) adopting the internal seal, the internal leakage is reduced, and the synergical movement of the two degrees of freedom of the wrist can be obtained

The result of the performance test of the actuators are shown in table 3. From the frequency response test, it has been found that each degree of freedom can follow the input of 1[Hz].

The output power, with a cosmetic glove on, which is measured with for measuring apparatuses of limb ability is shown in table 4.

From these data, we have reached the initial goal as to the figure, size, weight and the performance.

The following are the subject to be studied in the future.

a) the change of the driving torque for the RSA input shaft with time elapsed must be lessened
b) torque efficiency must be improved more
c) responce performance of the system composed of the stepping motor and the reduction gear must be improved
d) mechanical links of the mechanism of the finger etc. must be lessened

## 4. Control system

The most important point in constructing the control system of the prosthesis with multi degrees of freedom is how to construct a system which requires learning no special control technique on part of the amputee. From this point of view it is better to use the upper limb neural muscle control system itself of the amputee which was constructed in the central nervous system before amputation. Here for the signal source we used the EMG which occurs in the muscle groups of the forearm stump accompanying the phantom limb movement which the amputee feels about the amputated part. Pattern-recognizing the EMG, we decided, not only to control individually the hand prehention, wrist flexion, forearm rotation which corresponds to the degrees of freedom of the prosthesis, but also to control the most synergical motion of the combination of wrist flection and forearm pronation. Total movements are 8.

### 4.1 EMG processing and pattern recognition

We detected EMG with the surface electrode, and got information from the time ratio that the amplitude of signal exceed a certain threshold level. This time ratio is expressed inthe following equation.

$$E_m = \frac{1}{\alpha}\int_0^{\alpha}[1/2+1/2\,\mathrm{sgn}[e_m(t) - \delta]]dt \qquad (1)$$

here, $Em(t)$ : EMG, $sgn(x)=1\ x\geq 0$, $sgn(x)=-1\ x<0$

$\delta$ : threshold level, $\alpha$ : counting time

We used parametric linear discrimination function for pattern recognition as shown below :

$$gi(X) = X^{t}\Sigma^{-1}\bar{M}^{1} + \log Pi - 1/2 M_i^{t}\Sigma^{-1}\bar{M}^{1} (i=1---\delta) \qquad (2)$$

her, $X = \begin{pmatrix} X1 \\ X2 \\ x6 \end{pmatrix}$ and X is patterns, M is vector of

X, $\Sigma$ is covarience matrix

pi is a prori probability of category i

The muscle groups used here are 6, that is (a) Extensor carpi ulnaris (b) Extensor digitorium communis (c) Extensor carpi radialis (6) Pronator teres (e) Flexor carpi ulnalis (f) Flexor digitorum profundus.

In the discrimination test with a computer, both the normal subject and the forearm amputee showed a satisfactory result.

### 4.2 Construction of the control system by using the threshold logic unit

Here we have constructed the control circuit by the logic units in order to confirm the practicability of this pattern recognition system. Concerning the the equation (2), we must find a discrimination function which gives the maximum value to decide on the category.

The logic unit cannot directly select the maximum value, so here we used the threshold logic unit (TLU) in order to discriminate the category. The outline of the control unit by TLU is shown in Fig.9. We made EMG into a pattern by the method mentioned in the previous paragraph. If the level of the input pattern is under a certain threshold level, the gate cuts the output and the prosthesis is held in a static state. There are 8 categorized movements, so there need to be 28 TLU and 196 weight factors. The pulse frequency which drives the stepping motor for control is constant, and the rotational angle of the rotary servo actuator, that is, the position of the angle of the prosthesis is controlled by the occuring time of EMG.

### 4.3 Construction of the control system by using a micro computer

TLU control device constructed by the analgue circuit is too large to carry, and the EMG processing method is suitable for the digital operation, so we miniaturized the control circuit by using the micro computer system. The outline of the control circuit is shown in Fig.10 and its photo is shown in Fig.11. We used dry electrodes in which was contained the impedance convertor of dual FET. EMG gose through the 200 times (46dB) amplifier and hum filter and is pulse-coded by the comparator, gates, and 80[kHz] oscillator. This pulse is counted for 100[ms] and the count value is the pattern. CPU is 12 bit type (IM6100)and has RAM(256) for programs and weight cooefficients. CPU calculates $G_i(X)=W_iX$ and the i category which give the maxmum value of $Gi(X)$ is latched and put out to the motor drivers.

The time delay of the total system which includes the count time of EMG and the cariculation time is about 0.2[s]. As shown in Fig.11, the total circuit is composed of three cards including the battery which works as a RAM backup and the total weight is about 1[kg].

### 5. Clinical testing

With the TLU control device, this prosthesis was brought to the simple motion testing of a forearm amputee. The subject was a man 26 years old who had lost the left forearm in an accident at the end of 1974 and had a standard stump length(15[cm]).

Test motion were :

a) to pour the content of a bottle into a glass

b) to drink with a grass
c) to write letters and clean the hair
d) to put a block on another changing its direction by 90 degrees

Hand prehension mechanism is the same as the WIME HAND which has already been put to practical use, so here the gripping ability test is omitted.

The above test motions can be done even by the forearm prosthesis with one degree of freedom (with only prehention), but there needs to use large compensating motion of the other region of the human body. In the motions a (to pour into a glass)(fig.12) and d (to build blocks), it requires not only an outer rotation of the shoulder to compensate for the forearm rotation but also a motion of incining the body. But this new prosthesis has a pro-spinating function. So the amputee can work like a normal subject without changing the elbow position. In the case of motion b ( to drink with glass), the amputee can use wrist flexion to bring a cup closer to his mouth and the compensating motion of the head is improved. However, this function of wrist flexion can not be utilized because when the normal subject drinks, the rotational center is at the edge of the glass but, when , the amputee utilized the pro-spination of this prosthesis, the rotation axis is on the apse line of the forearm.

In the motion of cleaning the hair, the direction of the comb cannot be fully controlled by this prosthesis. More degrees of freedom and wider reachable area are needed for it, but they are technically difficult now. For the present time this problem must be solved by utilizing some selfserving devices.

As in this case, there are some motions which cannot be improved by using this prosthesis, but, it has been ascertained that this prosthesis is useful for many other motions. There still remain several problems to be solved, but they are not insoluble, and we trust that our prosthesis deserves further study so that it will be so much improved as to be put to practical use.

## 6. Acknowledgments

We must express our hearty thanks to Mr. Hideo Oouchi, who was willing to test as a subject, and to Yooichi Saida, kojiro Imanaga, Kunio Kanda, Kazuhisa Ikenoya, Satoshi Sakoo, Giichi Kotani, who have cooperated with us for the development and production of the prosthesis.

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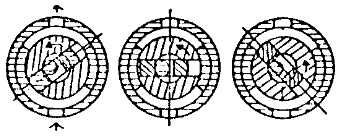

Fig.1 Principle of Piston Pump Operation

Fig.3 Dismantle Appearance of Pump and Relief Valve

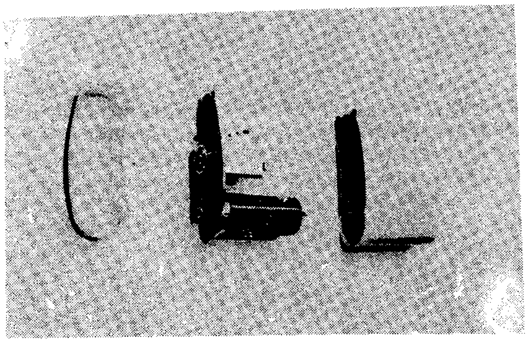

Fig.2 Dismantle Appearance of Pump Unit

| Item | | Specification | |
|---|---|---|---|
| Pump | Size | W32xL42xH48 | [mm] |
| | Weight | 150 | [g] |
| | Piston Dia. | φ7.5 | [mm] |
| | Piston Stroke | 2 | [mm] |
| | Piston Number | 2 | |
| | Exhaust Volume | 0.176 | [cm /rev] |
| Relief Valve | Size | W32xL15xH48 | [mm] |
| | Weight | 50 | [g] |
| | Setting Pressure | 30 | [kg/cm$^2$] |
| Driver | Input Voltage | d.c.24 | [V] |
| | Motor Weight | 340 | [g] |
| | Motor Type | CK38-HI(Canon S.) | |
| | Transmission | Timing Belt | |
| | Reduction Ratio | 3 | |
| Case | Size | W50xL136xH105 | [mm] |
| | Weight | 150 | [g] |
| | Material | Polypropylene | |
| Oil | Type | Sell HLP 25 | |
| | Volume | 170 | [cm$^3$] |
| Unit Total Weight | | 850 | [g] |

Table.1 Specification of Pump Unit

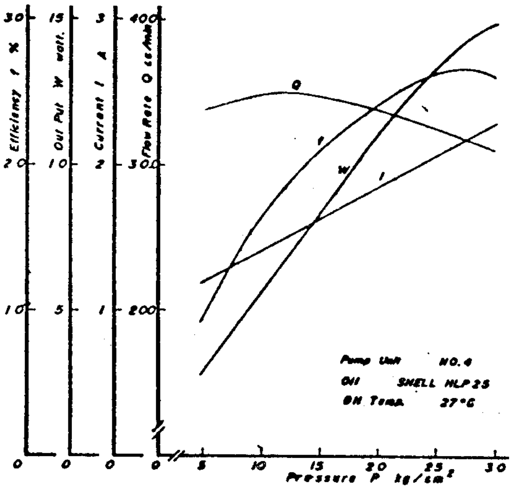


Fig.4 Pump Performance

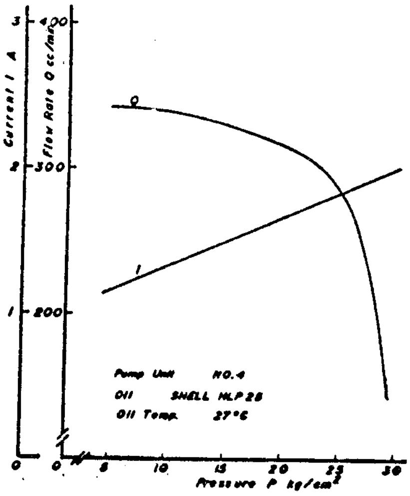


Fig.5 Pump Performance

settling presure of relief valve is at 30[kg/$cm^2$]

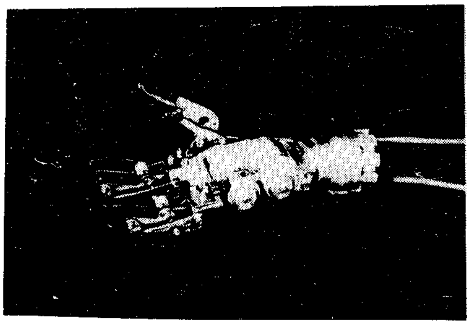

Fig.6 Dismantle Appearance of Prosthesis

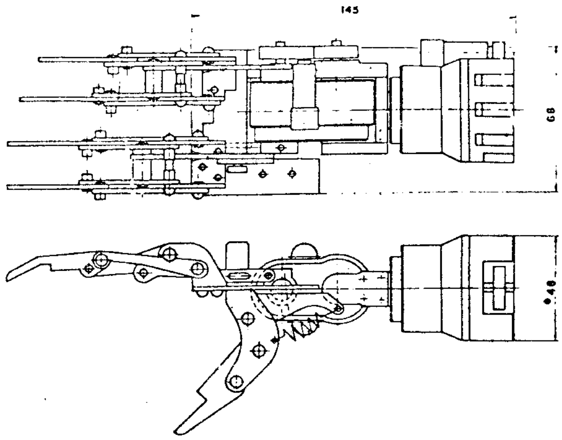


Fig.7 Dismantle Assembling of Prosthesis

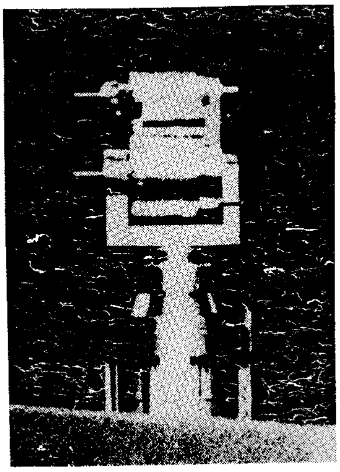

Fig.8 Composite Type RSA

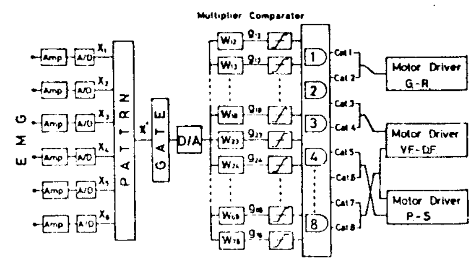


Fig.9 TLU Control System

| Item / Name | Working Pressure kg/cm² | Output Torque kg-cm | Oil Exhaust cm³/rad | Rotational Angle deg |
|---|---|---|---|---|
| Forearm Pro-spination | 25 | 25.0 | 1.1 | 90 |
| Wrist Flexion | | 15.0 | 0.6 | |
| Hand Prehension | | 10.0 | 0.4 | |

Table.2 Specification of each RSA

| Item / Name | pressure kg/cm² | Input Torque kg-cm | Output Torque kg-cm | Torque Efficiency % | Internal Leakage cm³/min | |
|---|---|---|---|---|---|---|
| | | | | | Neutral | Stool |
| Forearm pro-spination | 25 | 30 | 22 | 89 | 64 | 128 |
| Wrist Flexion | | 45 | 10 | 62 | | |
| Hand Prehension | | 25 | 5 | 46 | | |

Table.3 Performance of Actuator

| | | |
|---|---|---|
| Maximum Gripping Force | Pintch | 0.8 kg |
| | Grip | 1.6 kg |
| Wrist Flection | Flexion | 0.8 kg |
| | Extension | 0.8 kg |
| Forearm Rotation | Pronation | 13 kgcm |
| | Supination | 12 kgcm |

Table.4 Output Power of Proshtesis

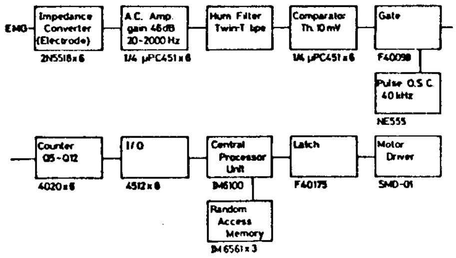


Fig.10 Micro Computer Control System

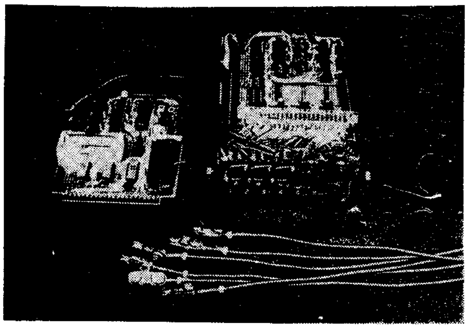

Fig.11 Appearance of Control Circuit

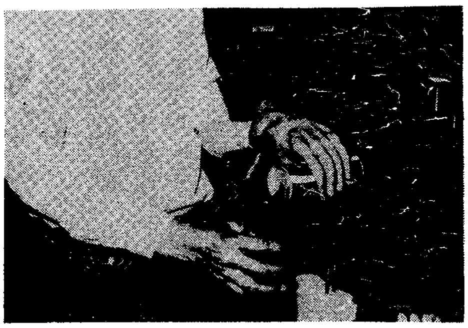

**Fig.12 Pouring into a glass**