DEVELOPMENT OF A POWERED UPPER-ARM PROSTHESIS FOR THALIDOMIDE CHILDREN

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Summary

Our main purpose is the development of an optimal control system for the disabled. As a starting point, we chose a children's upper arm prosthesis. Our research of the powered prosthesis for thalidomide children - especially for phocomelia - indicated the following specifications of a prototype model:

a) The pneumatic system was chosen for a power source because of weight factors.

b) Linkages of a model of an upper extremity limb are used to generate control signals to the prosthesis, and potentiometers are mounted at each joint. Thus synergistic movements of each joint can be obtained.

c) The prosthesis can provide seven degrees of freedom; that is, a terminal device opening and closing with five fingers (grasp), three points pinching, forearm pronation and supination, elbow flexion and extension, humeral outward and inward rotation, shoulder flexion and extension, and shoulder adduction and abduction.

d) Cylinder type actuators were not used because a rotation type actuator was required for this prosthesis.

e) The terminal device is the hand type, and each phalangeal joint can be moved.

We intend to use this prototype model in our experiments involving a prosthesis for children.

Introduction

Perhaps the most difficult problem in designing a multi-axis powered upper-limb prostheses intended for supra-aplasia reside in the control system.

A powered upper-limb prosthesis system that allows individual control of a multi-degree of freedom system is most challenging. Much labor and time is required if the user is to master its operation. For this reason, in the case of a prosthesis with a multi-degree of freedom system, such a control system allowing all the degrees of freedom synergistically for a single purpose without controlling each degree of freedom independently, is required. In other words, a control system in which the user gives only a command related to a certain purpose, directs his senses only towards the situation of attainment of the purpose, and can carry out control of each degree of freedom subconsciously is desirable.

Let us reflect briefly on motion control system of the normal extremity. A multi-degree of freedom system is operated synergistically by a hierarchial structure comprising various feedback loops which allow the intended action to be carried out effectively. To effectively perform such synergistic movements the following two factors are important /1/. These being a learning algorithm of movements and a body interior model. The learned algorithm of movements is an algorithm of synergistic movements learned in the process of individual growth. These are stored in the higher central nervous system, considered to be principally in the cerebellum. The body interior model is mapped in the higher central nervous system, which, on the basis of information from sensory systems such as proprioceptive and exteroceptive afferentation, etc., controls movements by modifying model characteristics at all times. That is, it carries out identification between a mapped model and actual movements of extremities, trying to effect an optimum of control. Owing to the existance of such learned algorithm of movements and body interior model, we can perform coordinated actions serving as a whole for a single purpose without being conscious of the movements of individual joints.

Losing an upper limb means not only losing the muscles as actuators but simultaneously losing the sensory systems such as proprioceptive and exteroceptive afferentation, etc. Accordingly, the body interior model mapped in the higher central nervous system and the learned algorithm of movements also becomes meaningless. Consequently as a basic design conception for the control system of a prosthesis, we should aim at constituting a control system under which the feedback systems corresponding to proprioceptive and exteroceptive afferentation are technologically substituted; thereby, forming a new body interior model and learned algorithm of movements. While such a concept is lacking, not only the function of the prosthesis will continue to be most limited, but also the mental and physical burdens on the user will continue, resulting, obviously, in non-use of the prosthesis.

When considering a control system of a prosthesis, one must inevitably take into account the handicap involved. Our efforts in this regard will be discussed later, but, first, let's review for a moment the functional aspects of the upper limb. The number of degrees of freedom required for positioning of the normal upper extremity are seven; three involve the shoulder, one the elbow, one the forearm and two the wrist. The major as well as the most complex functions of the upper limb are mostly performed by the hand. This is most obvious when considering the mechanical aspects which indicate that of the twenty seven different degrees of freedom in the entire upper limb and hand /2/, as many as eighteen are found in the hand alone. In view of these considerations our specifications for the control system of a powered upper-arm prosthesis took the following form:

1) Positioning of the terminal device

a) To provide a control system which utilizes the existing or a newly formed body interior model and the learned algorithm in the higher central nervous system.

b) Command signals for a powered upper prosthesis should be generated under a method identical with or at least similar to that which existed prior to limb loss.

c) Coordinated movements (synergistic movements) should be possible.

d) A feedback loop within the mechanism should provide output of each joint following input.

e) The position control system should have priority over the power control system.

f) As far as possible, the system should allow sensory feedback; that is, an artificial sensory system facilitating the formation of a body interior model.

2) Handling with the terminal device

a) A control system which utilizes the body interior model and learned algorithm presently or newly mapped in the higher central nervous system should be provided (same as 1-a).

b) Command signals for a powered upper-limb prosthesis should be generated under a method identical with or at least similar to that which existed prior to limb loss (same as 1-b).

c) Priority will be given to the power control system rather than the position or velocity control system.

d) Along with an enclosed feedback loop, an exteroceptive afferentation feedback should be provided in order to control delicate movements.

On the basis of these specifications, we approached our task to develop a powered upper arm prosthesis and its control system for "thalidomide" children.

Control System

Signal Source

Concerning the signal source of pneumatic upper-limb prostheses for phocomelic children, various options exist. For example, switching by the phocomelic extremity is perhaps the most common. Under this method, one of the switches, arranged correspondingly to individual actuators, is selectively pushed to drive a specific actuator and an intended action is performed. This method, however, does not utilize the body interior model nor the learned algorithm. Further it is not a method which either facilitates the formation of a body interior model or a learned algorithm. Moreover, to operate, let alone control, such a device in this fashion, visual feedback, effort, and learning is placed at a premium. Synergistic movements in a multi-degree of freedom system are difficult. Available as an alternative means is the system developed at Moss Rehabilitation Hospital /3/. This makes possible the synergistic movements by using a multi-channel E.M.G. and pattern recognition techniques. It is considerably effective in that proprioceptive afferentation and movements of the upper arm prosthesis can be coordinated when a proportional control system is used. At present, however, it is difficult to receive enough multi-channel E.M.G. signal from "thalidomide" cases to make possible the control of all degrees of freedom.

We are employing a model control system which makes the upper-arm prosthesis a reinforcing machine for the phocomelic extremities. Most of the phocomelic children are performing various routine movements in using their phocomelic extremities. Accordingly, their body interior model and learned algorithm concerning the phocomelic extremities seem to be mapped or are in the course of being mapped in the higher central nervous system. This point should not be overlooked when designing an upper-arm prosthesis.

It should be considered that when movements of the phocomelic extremities are converted into movements of the upper arm prosthesis, the body interior model and learned algorithm can be utilized and easily formed. In practice, the signal source model is operated by the phocomelic extremity, the model being coupled with the upper-arm prosthesis by means of a servo system. The function of the hand is divided into positioning and orientation of the hand and handling by the hand. With respect to the former, the wrist of the signal source model is brought to a desired position. Each joint angle of the signal source model is amplified as the input for each joint angle of the upper-arm prosthesis, thus positioning of the prosthesis is performed (Fig. 1). In this case, the range of joint motion of the signal source model is matched with that of the phocomelic extremity. The range of joint motion of the upper-arm prosthesis is made coincident with that of a normal extremity and a proportional control is performed within such range.

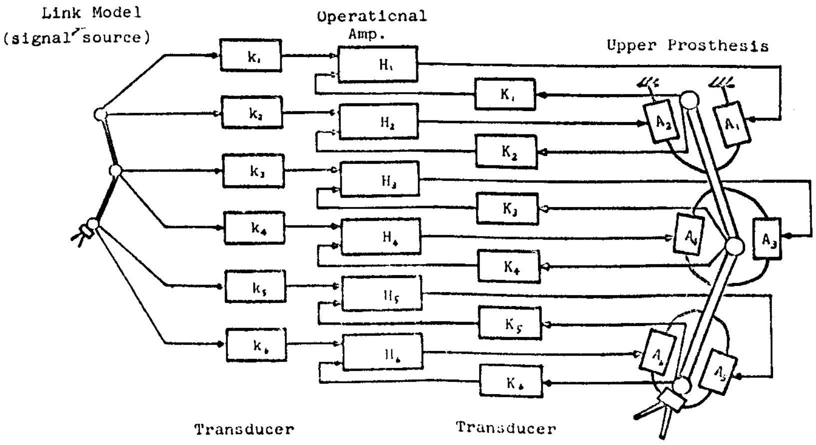


Fig. 1. Control system of prosthesis

The adaptibility of this control system to different degrees of freedom and ranges of joint motion of the phocomelic extremity is most encouraging. Such a control system may be called "a model control system".

The output of the signal source model is amplified (in terms of both power and displacement) to move the prosthesis. The phocomelic extremity and the prosthesis correspond to each other at a ratio of 1 to 1. The proprioceptive afferentation of the patient's phocomelic extremity and movements of the upper-arm prosthesis are connected closely, causing the body interior model and learned algorithm of the prosthesis to be easily mapped in the higher central nervous system of the user. Thus, the mental burden on the patient at the time of operation of the prosthesis in considered to be reduced considerably /4/.

It is advantageous to carry out the control of terminal device handling by means of the rudimentary digit as well. Although the handling control system should be a power control system, we utilized an open loop for control at this time. Also in our prototype model, no consideration was given to detection of the sense of pressure. For power control of output, in a system employing pneumatic pressure for the power source, pneumatic pressure supply should be controlled. However, it is difficult to use the phocomelic extremity for this purpose. An analogous power control is effected by control of the open time in a valve. In our control system, for better adaptation of a gripped object, a control of finger movements pattern is used; "grip" and "pinch". This was realized by shifting the thumb motion from the motions of the other four fingers. If the motions of the thumb and the other four fingers are made coincident with each other, the pattern "pinch" is obtainable and if the phase of thumb is delayed in relation to the other four fingers, the pattern "grip" can be obtained. The system for such phase shift is quite a simple one and is accomplished by two pneumatic flow lines for the thumb, with one line being designed for high resistance and the other, low. Higher resistance reduces flow rate, thus increases the lag time of movement and reduces the closing speed of the thumb. The reverse occurs when resistence is reduced. By selecting one of the switches for these two flow lines by means of phocomelic fingers, "gripping action" or "pinching action" can be obtained.

System

To enable a patient to freely position the upper-arm prosthesis, a position servo system has to be used at the muscle regulatory level between the movements of the prosthesis and the command signal. For the purpose of realizing such a position servo system, a small potentiometer to convert movements of the phocomelic extremity into an electrical signal is provided in each region corresponding to a joint of the signal source model, this signal serving as a command signal. Each joint of prosthesis is provided with a potentiometer to detect the joint angle as a feedback signal. Subtraction is made with respect to the command signal and feedback signal. The resultant error signal is fed to a comparator, in which it is subjected to a three-value processer. The width of the blind sector of the three-value processer is important. The three-value processed signal operates a relay and the relay output drives a solenoid valve to operate an actuator (Fig. 2).

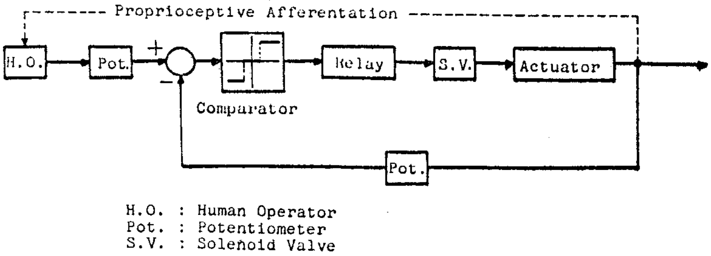


Fig. 2. Block diagram of servo-mechanism

Elements

Power Source

Commonly used power sources for upper-limb prostheses are of course electricity, electro-hydraulic pressure and pneumatic pressure. Each have their own characteristics. However, for children and in particular, for supra-amputated (or-aplastic) children, a pneumatic system is most effective owing to its light weight and ease in accumulating power. Further, the pneumatic system provides a prosthesis with "softness". Pneumatic pressure has not been employed thus far in Japan despite its advantages. Only electrically driven systems are being made on a trial basis. Our decision was to employ pneumatic pressure (CO_2) as the power source.

Actuator

Various actuators for pneumatic upper-arm prostheses have been developed. For example, there are artificial rubber muscles of the McKibben type and the Warsaw type /5/, the pouch actuator /6/, and piston cylinders, etc. Of grestest interest to us is the pouch actuator. Not only does the pouch actuator make it possible to obtain rotary movements directly (being therefore high in energy transmission efficiency) but it is simple to fit to an upper prosthesis. Its greatest advantage is that a joint, requiring a multi-degree of freedom (such as a shoulder joint), can be realized without accompanying mechanical complexity. Considering these merits, we decided in principle to employ the pouch actuator. As the antagonist to this actuator, the elastic energy of rubber is utilized in the prototype model for simplicity. The natural length of the rubber is 30 mm, a width of 10 mm and an elastic constant (k) of 38 mm/kg.

Solenoid Valve

A commercially available 2-port valve was employed as the solenoid valve as a clinical test was still premature. In preparation for the clinical test, we are attempting to develop an ultra-small solenoid valve. A prototype has been completed, but it is not completly satisfactory relative to weight and other characteristics. We do intend to develop a perfected one by the time of the clinical test.

Gas Cylinder (Accumulator)

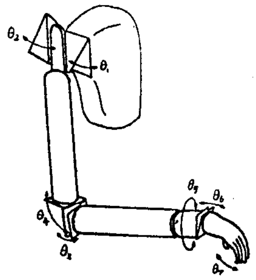
Japans lightest marketable cylinder presently weighs 290gr., inclusive of the weight of the CO_2 which is 60gr. This cylinder, besides being too heavy for the prosthesis, cannot be recharged thus has to be discarded after use. Furthermore, if one includes a regulator, etc., the total weight will exceed 500gr. In our prototype model, such a cylinder and regulator will be employed, thus we plan to develop a much lighter cylinder and regulator prior to the clinical test.

Mechanism

In this study, from the viewpoint of development of a control system, first the prototype model was designed instead of a model for testing on a patient.

Arm

As we have indicated earlier the number of movements, or let us say degrees of freedom, in the arm in the normal extremity is seven, comprising three at the shoulder, one at the elbow, one at the forearm and two at the wrist. As the principal role of the arm is hand-positioning the number of degrees of freedom basically required when designing an upper arm prosthesis is four; three at the shoulder (flexion-extension, adduction-abduction and humeral outward and inward rotation) and one at the elbow (flexion-extension). However, if one considers daily work activities, one will find that hand-orienting is one of the important roles of the arm. By adding one degree of freedom to the forearm (pronation-supination) and another to the wrist (flexion-extension), the function will be improved remarkably. Therefore, in the prototype model, we aimed at six degrees of freedom by adding the two degrees of freedom just mentioned. An example of this is shown in Figure 3. One of the degrees of freedom at the shoulder (humeral outward and inward rotation) was realized at the elbow. Power, corresponding to an antagonist is ofcourse required at each degree of freedom. For this, elastic energy of rubber was employed.



θ_1; adduction and abduction of shoulder
θ_2; flexion and extension of shoulder
θ_3; humeral rotation
θ_4; flexion and extension of elbow
θ_5; pronation and supination
θ_6; flexion and extension of wrist
θ_7; handling

Fig. 3. Degree of prosthesis

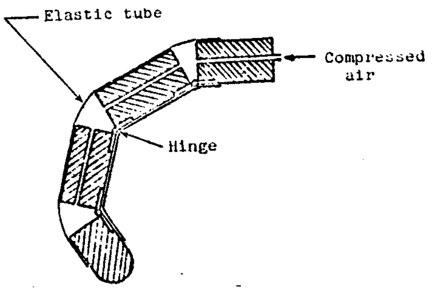


Fig. 4. Mechanism of artificial finger

Hand

Many of the terminal devices for the conventional upper arm prosthesis are of a hook type. Considering social-cultural factors in Japan, the hook possesses quite a heavy psychological burden on the user. Furthermore, because a major objective of our study is to exercise control over a control system similar to a normal hand, we made it an absolute requirement to use an anthropomorphical form.

To drive the phalangeal joint an operating principle similar to that of the pouch actuator was employed. That is, a method of utilizing the space to be produced by rotation of the phalanx as an actuator was employed. A series of blocks (phalanx) linked with fingers are covered with an elastic tube (rubber in this case) bound by yarn in the circumferential direction. Pneumatic pressure is applied to cause finger flexion (Fig. 4).

The advantage of such a mechanism is that it adapts itself to any objects regardless of shape. The weight will not increase even if the number of joints to be driven are increased. This makes it possible to realize the same shape and provides a major function of the hand. In this model there are two movable joints in the thumb and three movable joints in each of the four fingers.

Results

Characteristics of the Pouch Actuator

Characteristics of the puch actuator, which has an effective sectional area of 42 x 42 mm, are shown in Figures 5 and 6. Figure 5 shows the pressure-torque characteristic at a fixed rotation angle of the actuator, this is, the characteristic under isometric contraction. A torque of approximately 60 kg-cm can be

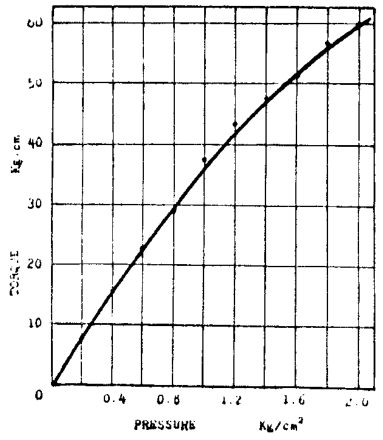


Fig. 5. Characteristic of pouch-actuator

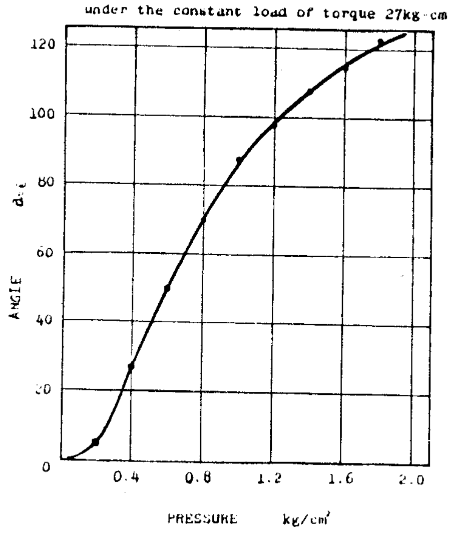


Fig. 6. Characteristic of pouch-actuator

obtained under a supply pressure of 2kg/cm^2, which, when considering an upper-arm prosthesis for children, is quite satisfactory in whatever region the actuator may be employed. As a matter of course, if a larger torque is required, it may be obtained by increasing either the sectional area of the pressure supply. However, if the latter course is chosen, due caution should be taken in the selection of the materal used in the pouch actuator. Figure 6 shows the pressure-angle of rotation characteristics when a load of 27 kg-cm is applied. The pouch actuator is made with different parameters according to the magnitude of the maximum angle of rotation. The one shown in Figure 6 has the maximum angle of rotation of 180°. Nearly similar results can be obtained with other types (90°, 120°), also. These characteristics satisfy the requirements for an actuator for a powered upper-limb prosthesis.

Characteristics of Control System

Figures 7 - 9 show some of the characteristics of the control system. Figure 7 demonstrates the response to a step input of 120° under a load of o.6 kg = 15 kg-cm (arm length: 25 cm) and supply pressure of 2.0 kg/cm^2. Figure 8 shows response to a step input of 120° when pressure of 2.6 kg/cm^2 was applied. As can be seen in comparing Figures 7 and 8, considerable improvement in response characteristics can be achieved by increasing pressure. Figure 9 shows the follow-up characteristics with respect to a random signal. It is recognized that these results are by far inferior to those of servo systems used industrially. They are satisfactory, however, if one takes into account that a user can compensate for this and for many tasks, movements at higher speeds are not required. Pressure supply and the elastic constant of rubber used in place of the antagonist provide the greatest influences on the response. Pressure supply can be increased by improving the material of the actuator.

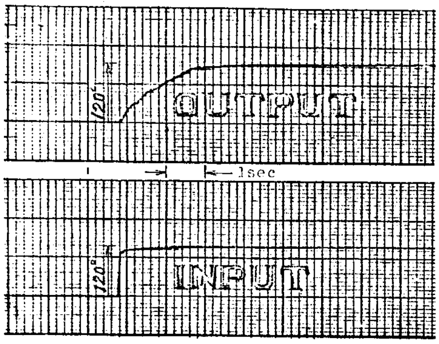


Fig. 7. Characteristic of servo-mechanism (step response)

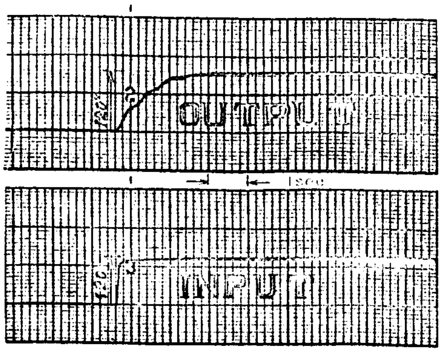
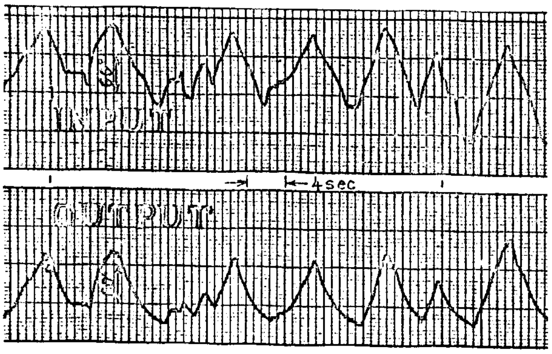


Fig. 8. Characteristic of servo-mechanism (step response)



working gas pressure; 2.0kg/cm
load; 0.6kg (length of arm; 25cm)

Fig. 9. Characteristic of servo-mechanism (response to a random input signal)

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