CLINICAL APPLICATION STUDY OF MULTIFUNCTIONAL PROSTHETIC HANDS

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A control system for a multifunctional hand prosthesis, which requires a minimum of training for the amputee, has been developed. The great advantage of the pattern recognition technique in making it possible to control as many as six prosthetic movements has prompted this study. The development of a complete miniaturised system has allowed a clinical trial on four patients. Two different tests have been employed to evaluate this system: an objective computer test and a test representing activities of daily living (ADL test). The computer test shows that a high rate of correct recognition is obtained immediately after the prosthesis is applied to the amputee. The ADL test shows that forearm rotation, and flexion and extension of the wrist are used in most activities, indicating that few compensatory movements are performed. It is suggested that this control system is feasible and that long periods of training are unnecessary.

A limited number of externally powered hand prostheses are commercially available today. For forearm amputees, myoelectric hands are the most widely used prostheses in Europe. They offer a single function—prehension—and have potential advantages over earlier body-powered prostheses (Herberts 1969; Soerjanto 1971; Childress, Holmes and Billock 1974; Kondraschin, Jakobsen and Voskobojnikova 1975). However, clinical experience has shown that they do not fulfil the requirements of many amputees. The limited function frequently results in the prosthesis not being used at all or being used only as a cosmetic replacement for the lost limb. Additional functions, controlled in a natural way, would considerably improve the utilisation of these devices.

The development of multifunctional prostheses, allowing grasp, forearm rotation and wrist flexion movements, has been in progress for several years (Lymark and Möhl 1967; Kato *et al.* 1970; Germans, Brekelmans and Wijkman 1970; Rakić 1975). The great and unsolved problem, however, has been how to control the many movements of such an advanced device. The fact that there are few places in the body where isolated control signals are available, reduces the possibilities for the amputee to communicate with his prosthesis. Isolated myoelectric signals cannot control more than three or possibly four movements, and implantable electrodes to optimise the control signals (Herberts *et al.* 1968) have not been the solution.

Ideas for solving the control problem have been presented, but very few have been developed into a

clinically available system. Hybrid systems, in which myoelectric and mechanical signal sources are used in conjunction for control of several functions, have been applied in a number of cases (Childress, Billock and Thompson 1974; Mann 1974; Näder 1976). Several methods based on the use of two myoelectric signals for controlling more than two functions have been suggested. Hägg (1973) proposed the use of two electrodes for control of four movements. Similar methods have been proposed by Docras and Scott (1966), Voskobojnikova (1970) and Brittain and Caldwell (1976). Multifunctional systems in which myoelectric signals are used exclusively have not so far become available to the amputee.

Finley and Wirta (1967) introduced an entirely new approach to the control of a multifunctional prosthetic arm. Their method makes use of pattern recognition to identify and discriminate synergistic muscle action in the back, chest and shoulder, and to provide simultaneous control of movements of the upper arm, the elbow, and the forearm (Wirta and Taylor 1970; Taylor and Finley 1974). In Sweden, this concept has been further explored and used to control a multifunctional hand prosthesis (Herberts *et al.* 1973; Lawrence, Herberts and Kedefors 1973). The patterns of myoelectric activity in the region of the stump were found to have considerable individual variations. These variations mainly arise from the fact that the anatomy of the stump has been changed as a result of the trauma and the subsequent operation. This implies that, in contrast to previous systems, a good pattern recognition system

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must conform to the individual characteristics of the amputee.

In the present project a complete portable control system, utilising the pattern recognition technique for control of six movements, has been developed. The multifunctional hand prosthesis used provides for grasp and for rotation, flexion and extension of the wrist (Hägg and Spets 1973).

The control system and the prosthesis have been applied to four amputees. The ability of the patients to

Electronic control circuits. An analogue electronic network implements the classification procedure. Since each discriminant function represents one movement, a complete control unit consists of six channels implementing the functions. The complete control unit, containing pattern recognition circuits and power circuits, is placed in a portable plastic box; the individually adapted part consists of a single plug-in circuit card.

Electrodes for signal processing. The signals forming the pattern consist of essentially direct current analogue signals, proportional to the contraction levels of the muscles. To detect the myoelectric signal in this way, one needs an electronic circuit providing amplifiers, filters and rectifiers. Furthermore, for optimal control of the prosthesis, it is

Fig. 1

Myoelectric signal patterns recorded when the patient performs phantom hand movements: finger flexion (FF), finger extension (FE), pronation (P), supination (S), wrist flexion (WF) and wrist extension (WE).

Fig. 2

Block diagram of the computer function in the training phase.

operate their prosthesis in various situations has been evaluated by two different tests. Objective information of the patient's ability to control the prosthesis was obtained by using a digital computer before and after training. The functional capability has been evaluated according to a standardised test of the activities of daily living.

METHOD

Theory. The myoelectric activities in the stump can be reproduced because of the phantom limb phenomenon, which appears to some extent in most amputees (Cronholm 1951). The phenomenon means that the amputee perceives his lost hand and that he can imagine various phantom movements. Such movements are accompanied by specific muscle contractions, which can be registered by a number of surface electrodes attached to the stump. The myoelectric signals are specific for each phantom hand movement. The signals constitute patterns, which are illustrated in Figure 1. Six electrodes are used, and the imagined movements are finger flexion, finger extension, pronation, supination, wrist flexion and wrist extension.

The various movements of the phantom hand can be identified by discriminant analysis of the signal patterns (Herberts *et al.* 1973; Lawrence *et al.* 1973; Lawrence and Kadefors 1974). The analysis is performed by a digital computer, which operates in two phases. In the first phase, the training phase (Fig. 2), patterns associated with known phantom hand movements are registered by the computer, which then classifies these patterns and calculates optimised weighting factors for the discriminant functions. In the second phase, the test phase, the computer uses the weighting factors in an analysis of unknown patterns for classification of the associated phantom hand movements (Fig. 3). The amputee can operate the prosthesis via the computer as an initial investigation of his ability to control the device (Fig. 4).

Fig. 3

Fig. 4

The prosthesis is operated on-line via the computer in the test phase. Figure 3—Block diagram. Figure 4—A patient operating the prosthesis.

important to suppress disturbing signals. No commercially available electrode complies with our requirements for signal processing. We have therefore developed an electrode of our own design. The electronic circuits, placed in the same unit as the pick-up electrode surfaces, include a differential amplifier, a band-pass filter, an active full-wave rectifier, and a low-pass filter. The amplifier features high input impedance, high suppression of common mode signals, and variable gain. It is moulded in Araldite, and the skin electrode surfaces are made of gold-covered brass buttons. The complete prosthetic system is illustrated in Figure 5. For further information about the electronic circuits, electrodes, and power source, see Almström (1977).

Fig. 5
Complete prosthetic system.

Application. The general procedure for providing a patient with this prosthetic system has several aspects, which mainly fall under the competence of three disciplines: medicine, electronics and bio-mechanics. The main tasks pertaining to medicine are the judgment of the ability of the individual patient to operate an advanced prosthesis, the location of sites for the electrodes and the inspection of the myoelectric signals. To electronics belong the adjustment of electrode amplifier gain, the operation of the computer and the adaption and adjustment of the electronic circuits for the individual patient. The biomechanical problems of the patient-appliance interface consist of the fabrication and fitting of the socket, for which the prosthetist is responsible. All the tasks are, of course, carried out in close collaboration.

The patient is first informed about the project and the multifunctional prosthetic system. The stump is carefully examined with respect to its muscles, skeleton and the level of amputation. The patient is asked to perform imagined movements with his phantom hand, and the muscles are palpated so that the electrode sites can be located. It is important to find sites where the muscle activities are directly related to the various phantom hand movements. For this purpose we use an electrode that can easily be moved. When six electrode sites have been located and marked, simple surface electrodes are fixed to the skin by double-sided adhesive tape. The signals are processed and registered on a paper recorder by Grass Polygraph 7 amplifiers (models 7P3B and 7DAD). The patient is asked to move his phantom hand, and the patterns are visually inspected: if considered good, they are recorded by the computer. The computer analysis is then performed, and if the separation of the training patterns is not satisfactory, the electrode positions are adjusted. This is repeated until satisfactory separation is attained. Then the test phase takes place.

Socket fabrication. The most important properties of the socket are the perfect fitting to the stump and a stable fixation to the elbow under normal dynamic circumstances. Furthermore, the electrodes mounted

Fig. 6
The prosthesis and the control system fitted to a patient.

in the socket must be accurately and stably located to yield an optimal pattern.

The manufacture of the socket is divided into two phases. In the first phase, a socket made of a transparent thermoplastic is fabricated by conventional technique, similar to that developed in Münster (Kay *et al.* 1965). The advantage of this method is that the fit can be checked visually; furthermore, it is the only way to transfer the electrode locations from the stump to the socket. In the second phase, the final socket, an exact copy of the transparent one, is manufactured from methylmethacrylate.

The complete system fitted to a patient is shown in Figure 6.

Training. An occupational therapist is responsible for the training of the patients. The training starts on a basic level: the patient sits with the prosthesis supported by the table, practising grasp and release activities. The difficulty of the tasks is gradually increased by making the patient work in different levels and pick up objects of varying shape, size and weight in order to train him in all the prosthetic movements. When the patient can operate his prosthesis, he is trained

in activities of daily living (ADL). In these activities, the patient is trained to co-ordinate the prosthetic movements with those of the normal hand.

Each training session lasts one to one and a half hours. Stump muscle fatigue has been observed after this time. The training procedure is performed twice a week for approximately two months.

CLINICAL MATERIAL

The complete prosthetic system was manufactured in a small series and applied to four patients. The patients were not selected for any specific characteristic except for the length of the stump, but they were all well able to operate complicated devices and to withstand the stress that inevitably occurs in a research project. All of them were amputated as young boys, as shown in Table I. Two of the men used conventional electric hand prosthesis daily, one of them used a cosmetic prosthesis, and one of them did not use prosthetic devices at all. All patients perceived the phantom hand distinctly, but the perceptions show considerable individual variations (Fig. 7).

Evaluation procedure. The patients were evaluated as to their ability to control each specific prosthetic movement as well as their ability to operate the prosthesis in activities of daily living (ADL). For this purpose, two different methods were employed for the evaluation: an objective computer test and an ADL test.

In the computer test the patient was asked to perform the basic prosthetic movements. The output signals from the pattern recognition unit to the prosthetic motors were recorded by the computer. Hence requested and inadvertent movements classified by the pattern recognition unit were registered. The patient was asked to start each movement on a specific command. The computer recording started at the same time as the command was given, and was stopped when the requested movement was completed. The computer calculated the fraction of the completion time in which requested and inadvertent movements were classified. The results yielded the rate of correct recognition of the myoelectric patterns.

All the patients were evaluated twice with this test. The first time was immediately after the application of the prosthesis. After the training period, the ADL test was performed on three of the patients, and then all the patients were evaluated with the computer test the second time. Case 4 was not evaluated with the ADL test, and he had just a short training period before the second computer test. The patients did not have the prostheses at home, which meant that they could use them only on the training and test occasions.

The purpose of the ADL test was to study how the patient uses the prosthesis in various tasks. The result was then used as a basis for an estimation of the functional benefit that each patient would obtain from the prosthesis.

The ADL test, which was developed by a group in Sweden

Fig. 7

Illustrations of the various phantom hand perceptions. Case 1 perceives his phantom hand as situated just distally to the end of the stump. He can distinguish between all movements of the hand, and he perceives that the fingers move. Case 2 perceives the phantom hand in the stump. He can distinguish between all the movements of the hand, and he perceives that the fingers move. Perception of the wrist is less clear than perception of the fingers. Case 3 perceives the whole forearm and the hand. Some of the finger movements are linked, and cannot be separated. He perceives no movements and can only produce force. Case 4 feels as though he were disarticulated at the wrist, with the phantom hand just distal to the end of the stump. He can distinguish between all movements of the hand, and he perceives that the fingers move.

Table I. Age, sex and stump length of the four patients and type of prosthesis they used before

Case number	Sex	Age (years)	Age at amputation (years)	Side of amputation	Stump length (cm)	Type of prosthesis used before
1	M	37	10	Left	18	—
2	M	37	10	Left	17	Otto Bock, electric
3	M	25	9	Left	15	Otto Bock, electric
4	M	33	11	Right	19	Cosmetic

Table II. Rate of correct recognition

Case number	Requested movement	Classified movements (<i>per cent</i>)*											
		FF		FE		P		S		WF		WE	
		B	A	B	A	B	A	B	A	B	A	B	A
1	FF	95	100	0	0	0	0	0	0	11	0	0	0
	FE	0	0	100	100	0	0	0	0	0	0	0	0
	P	0	0	11	0	88	90	9	8	0	3	0	0
	S	0	0	37	0	0	0	100	100	0	0	0	0
	WF	1	0	0	0	0	0	0	0	76	100	0	0
	WE	0	0	0	0	0	0	0	0	0	0	92	100
2	FF	86	100	7	0	0	0	0	0	0	0	0	0
	FE	0	0	100	100	0	0	0	0	0	0	0	0
	P	0	0	0	0	100	100	0	0	0	0	0	0
	S	0	0	18	39	0	0	94	90	0	0	0	97
	WF	0	95	8	0	0	0	0	0	61	88	0	0
	WE	0	0	0	0	2	9	0	0	0	0	88	90
3	FF	95	100	0	0	0	0	0	0	0	0	0	0
	FE	0	0	82	99	0	0	7	26	0	0	0	0
	P	0	0	21	0	94	100	6	0	0	0	0	0
	S	0	0	2	0	0	0	100	77	0	0	0	0
	WF	0	0	0	0	0	25	0	0	57	100	0	0
	WE	0	0	0	0	0	0	0	0	0	0	80	92
4	FF	100	100	0	0	0	0	4	0	27	0	63	0
	FE	0	0	89	88	0	0	4	29	0	0	100	0
	P	0	0	0	0	100	100	0	0	80	0	11	0
	S	7	0	0	0	0	0	98	98	2	0	96	0
	WF	0	0	0	0	0	17	0	0	100	100	0	0
	WE	0	0	0	0	9	0	0	0	0	0	100	100

*Since simultaneous movements can be performed, the sum of the fractions may exceed 100 per cent for a requested movement.

FF=finger flexion FE=finger extension P=pronation S=supination WF=wrists flexion WE=wrists extension B=before training A=after training

(Wärnberg, Andersson and Rydell 1973), included fifty activities from various fields, such as feeding, clerical work, housework, and light assembly work. The activities were constructed in such a way that both hands must be used simultaneously for the patient to achieve a normal pattern of working, without compensatory movements. The performance was carefully observed and registered, particularly with respect to the use of active prehension, pro-supination and flexion and extension of the wrist.

RESULTS

Computer test. The results from the computer tests are shown in Table II. Each movement was tested about fifty times.

Case 1. The patient already had a high rate of correct recognition before training. There were, however, some inadvertent movements identified by the pattern recognition circuit. After the training period the misclassification was almost completely eliminated and the patient operated all the prosthetic movements practically free from error. Figures 8 and 9 give the rates of correct recognition for Case 1. The dispersion is representative for all subjects.

Case 2. Erroneous classifications were few before training. After training, the rates of recognising the requested movements were increased, but classifications of inadvertent movements also increased. The performance of this patient showed considerable variations from one test occasion to another.

Case 3. The rates of correct recognition of the requested movements were increased after the training period, although the rotation movements were erroneously classified in some cases. The low rate for supination (77 per cent) indicated that the patient had some difficulty in reproducing the patterns for this movement; in the remaining fraction (23 per cent) no movement was recognised. The patient could, however, always complete the movement, but the prosthesis was moved at intervals.

Case 4. The patient operated the finger movements and the rotation movements very well before training. There were, however, erroneous classifications of the wrist movements in all of the requested movements. This patient was trained a shorter time (five occasions in one month), and he was not given the ADL test. The rate of correct recognition was considerably increased after training.

Table III. Result of the ADL test. Number of times the various functions were used

Number of	Case number		
	1	2	3
Activities performed	47	44	45
Active prehension	45	40	44
Flexion and extension of wrist	35	35	38
Pro-supination	37	35	39
Passive ulnar deviation	1	3	2
Compensatory movements	4	0	5
Times used as support	1	3	2

ADL test. Results from the ADL test are presented in Table III. None of the patients performed all of the fifty activities, since implements were not available to carry out some of the tasks. As illustrated in Table III, the prosthetic functions were frequently used. Besides the prehension, which was used in most of the activities, the

flexion and extension of the wrist and pronation and supination of the forearm were used in approximately 80 per cent of the tasks. Compensatory movements were few; the patient in Case 2 did not perform any such movement. The patient in Cases 1 and 2 were unable to perform one and two activities, respectively.

DISCUSSION

The major difficulty with respect to multifunctional arm prostheses is the problem of control. It is not possible to control several degrees of freedom with the corresponding number of isolated myoelectric signals. The muscles are in general not operating independently (Lyman, Groth and Weltman 1964), because the natural way of activating a muscle is within a complex pattern in a movement (Radonjic and Long 1970). The objectives in the design of a control system must be not to burden the amputee with tedious training before he can operate the prosthesis satisfactorily, but provide him with a control system where the prosthesis can be operated on a subconscious level after a short period of training. Therefore, the control system must be designed so that the amputee perceives the control of the artificial limb to be similar to the control of the limb he has lost, and uses the remaining muscles in the same way as they functioned before. The pattern recognition method used in this project complies with these objectives. The control system is individually adapted to the patient, in contrast to other systems where the patient has to learn how to operate the prosthetic movements.

In the application procedure, a digital computer is employed for the analysis of the myoelectric patterns and to simulate control. The analysis of the patterns must be performed carefully so that the frequency of recognition errors is minimised. At present, this requires a research centre with good basic resources in engineering and medicine. The interface between the patient and the prosthesis is of great importance for successful application. This socket can, however, be fabricated and fitted by any skilled orthopaedic workshop used to supply commercially available myoelectric hands. The fabrication procedure is time-consuming, and in general several sockets must be made before an acceptable fit and correct locations for the electrodes are obtained.

The high rate of correct recognition of requested movements even before training shows that the subjects can reproduce the patterns immediately after application. One of the patients felt that he was operating the prosthesis subconsciously when positioning the hand. In the training, the patients acquired patterns of movements such as flexing the wrist at the same time as grasping an object on the table, which appeared very natural. This is one of the reasons for the inadvertent movements that were observed during the computer tests. From a functional point of view, the inadvertent movements were non-detrimental.

During training, the patients are to some extent

Fig. 8

Fig. 9

Rates of correction recognition for Case 1. Figure 8—Before training. Figure 9—After training.

reanimating the perception of the phantom hand. One of the patients (Case 2) required a period of time to reanimate the perception of the phantom hand if the interval between training sessions exceeded ten days; daily use of the prosthesis would probably further improve his control. The considerable individual variations of the phantom limb perception have been well documented by Solonen (1962).

The purpose of the multifunctional hand prosthesis is to position the grasping device accurately in two-handed activities. This is not possible with prostheses available today, a problem which has been observed by Childress (1973a). During the ADL test it has been found that in the laboratory all patients frequently use all active functions. Remarkably few compensatory movements are used. Instead, active forearm rotation and flexion and extension of the wrist are used to position the hand. Compensatory movements are a severe problem for many amputees, since they often cause a bad working posture. Forearm rotation, and flexion and extension of the wrist thus provide more natural movements and also an improved cosmesis, which to many amputees are more important than functional benefits.

In the course of this investigation, only two prostheses which could be mounted on any of the individually adapted sockets were available for use in the project. Consequently, none of the patients has had the opportunity to use the prosthesis regularly at home. Five new prostheses have recently been manufactured and have become available to our laboratory. The patients are now fitted with these prostheses for daily use. A follow-up study of the prosthetic system in practice is in progress. The patient's opinion of his prosthetic system will be examined since the final acceptance of complicated technical aids is difficult to estimate (Höök *et al.* 1973). Event counters to measure active movement compliance will be mounted in the prostheses (Hägg *et al.* 1975).

The system developed gives on-off operation of the prosthesis. Neither the velocity of the movements nor the force developed in the prosthesis can be controlled by the operator. In a prosthesis providing a high-speed prehension mechanism, proportional control of the velocity is necessary for accurate positioning of the fingers (Childress 1973b). A clinical experiment indicates that the myoelectric signals forming the patterns are increasing with increasing force developed in the phantom hand as perceived by the amputee. This characteristic of the signals implies that proportional control is feasible with a pattern recognition control system. The possibilities of realising such a system are now under investigation. An alternative to the electronic circuit implementing the pattern recognition technique is to use a microcomputer (Almström 1977). Such a computer can be made small and reliable at a low cost, and it will facilitate the application procedure.

A great disadvantage of prosthetic systems available at present is the complete absence of sensibility in the prosthesis. To operate the prosthesis, the patient must use his eyes to be aware of the position of the hand. It is believed that sensory feedback will considerably improve the functional value and facilitate an accurate control of a complicated prosthesis. Promising efforts are being made to solve this great problem (Anani, Ikeda and Körner 1977a; Anani *et al.* 1977b; Solomonow, Lyman and Freedy 1977; Szeto 1977).

It is suggested that the pattern recognition system is a feasible solution to the control problems associated with a multifunctional hand. An advanced technical and medical organisation is needed for the individual adaption of the system. With this method, it is possible to control the prosthesis subconsciously and to exclude a long period of training for the patient. It is our belief that in a few years it will be possible for an amputee to operate the prosthetic movements proportionally, and that a form of sensory feedback will be incorporated in the prosthetic system.

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