EXPERIENCES WITH A MULTIFUNCTIONAL HAND PROSTHESIS CONTROLLED BY MYOELECTRIC PATTERNS

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Summary

In controlling a below-elbow powered prosthetic device with several degrees of freedom, it is difficult to find a unique control site for a particular movement. The reasons for this are firstly that some stump muscles are recruited together during different movements and secondly that certain muscles may show abnormal or weak myoelectric patterns due to the nature of the injury and the technique used in the surgery. One solution to this problem is to weight the simultaneous activity levels of several muscle signals in the decision-making process.

In the present work on five amputees, the myoelectric signal patterns of an individual subject were used to computer-design a unique control signal isolation system for him. The subject was then evaluated on his ability to control without training, a prosthesis with three bidirectional degrees of freedom. The results have shown that approximately 50% of the total number of control tasks investigated could be performed adequatly without training and a further 30% indicated that a slight amount of training would be required. All of the movements evaluated however, could be controlled to some degree.

Introduction

Externally powered hand prostheses have been developed and applied with considerable success. Several kinds of artificial hands, including EMG controlled electric devices and mechanically operated pneumatic systems, are now commercially available. It is almost likely that such assistive devices have come to stay.

However, these artificial hands are almost exclusively simple, one degree-of-freedom prehension devices with proportional control of velocity as the most exotic feature. Although multifunctional hands received a great deal of attention as a concept, they have not yet been put into widespread use. This fact is undoubtedly due to a number of reasons, but it is clear that some of the

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lack of success can be attributed to the control signal isolation problem: how to operate a number of movements without tedious training and with adequate reliability.

Control Signal Isolation

Several groups have previously made contributions in the field. Bousso and Ishai /1/ investigated the possibility of using separate myoelectric control sities for operation of an arm prosthesis for children. Four separate EMG sities on the stump were used by Germans et al. /2/ for proportional control of finger flexion / extension and thumb adduction / abduction by means of several signal comparators and gates. Different type of logic was employed in the Soviet two-function hand, were switching between modes of operation was attained by simultaneous contraction of the two stump muscles used as control sities /3/. Kato et al. /4/ used Schmitt and logic circuits to decode four-channel EMG patterns produced by combinations of eight movements of the wrist, for the operation of the independent movement of five fingers and wrist bending. A practical version which included grasp, pinch and wrist rotation required that myoelectric and mechanical control be combined.

Purely mechanical control of artificial arms has been considered by Klasson /5/, who used a joy-stick arrangement for the purpose, whereas Simpson /6/ developed a position servo system for control of an arm prosthesis applied to Thalidomide children.

Some of the systems briefly touched upon above have proved useful on a limited basis, and show great promise for further development. In the design of a control system for a multifunctional hand such as the Swedish hand /7/, none of the above system seems well suited for the purpose. This prosthesis active pronation / supination, wrist flexion / extension and grasp / release-3 biderectional degrees of freedom or six movements, and it contains built-in feedback of force and velocity.

There are a number of desirable features that the signal isolation system of such a prosthetic wrist/hand should have. Firstly, amputee acceptance of the device would be enhanced by reducing or if possible eliminating training requirements. This is especially true in unilateral amputees who in many cases can get along for most activities by using the passive prosthesis to support manipulation with a normal hand. Secondly, the concept of the self-contained and self-supported prosthesis /8/ is a goal that should be sought for this type of aid. Thirdly, the control technique must be selective enough that a sufficient number of hand movement signals can be isolated without resorting to time multiplexing, multi-level signals, mode switches and the like, all of which increase the learning and training time and decrease amputee acceptance. Finaly, the system should be flexible enough that it can accommodate a large proportion of the amputee problems and thus eliminate special constructions for individual amputees. Consideration of these features has led to a search for other possibilities for isolating control signals.

If a number of electrodes are applied to the stump and recordings of surface EMG are made while the amputee is asked to perform various movements of the phantom hand /9/, it is clear that there are different patterns of myoelectric activity produced for each movement. With current myoelectric control technique, it is not possible to make use of the information contained in these multi-channel patterns. However, the use of statistical pattern recognition techniques /10/ in the analysis of these data, and linear thereshold devices /11/ in the electronic implementation provides a possible solution to this problem.

This approach was proposed by Harrison /12/ at Philco-Ford. Since then the Krusen Engineering Center et Moss Rehabilitation Hospital in Philadelphia has taken over these developments and has produced a prototype device for the control of three bidirectional degrees of freedom in an above-elbow prosthesis /13/.

The prospects of using myoelectric patterns to control movements of a multifunctional below-elbow prosthesis are currently under investigation in the Dept. of Clinical Neurophysiology of the Sahlgren Hospital in Göteborg in conjuction with the Dept. of Applied Electronics at Chalmers University of Technology. A preliminary set of experiments on a small number of normals and amputees has recently been reported /14/. The outcome of those experiments indicated that stump myoelectric patterns produced during muscle contractions corresponding to hand movements were separable using pattern recognition techniques. The amputees could also reproduce these patterns.

The objective of the present set of experiments was to quantify the amputee's ability to control a multifunctional prosthesis without training, based on a set of preliminary, open-loop EMG recordings from the patient hiself, made prior to his operation of the device.

Pattern Recognition in Myoelectric Control

Essentially pattern recognition definies a rule for partitioning the multi-channel input EMG space into labelled regions. This rule can take the form of a discriminant function f(E) where $E = e_1, e_2, \ldots, e_n$ are the n rectified and smoothed EMG channels. If $f(E)>0$ the pattern belongs to one movement class, and if $f(E)<0$ it belongs to a second class. The decision surface is definied by $f(E)=0$.

For example consider the straight line $f(E)= \omega_1 e_1 + \omega_2 e_2 + \omega_0 = 0$ (with parameters ω_0, ω_1, ω_2) formed by plotting EMG activity e_1 on one channel against activity e_2 on a second channel. For control of the single prosthesis motor, any time the EMG levels produce a point on one side of the line ($f(E)>0$) the motor could be turned on, and when the point is on the other side of the line ($f(E)<0$) the motor could be turned off.

To be useful for prosthesis control using a larger number of EMG channels the discriminant function must be easily transformed into hardware. Fortunately, the simplest decision surface - a hyperplane in multi-channel EMG space is usualy adequate to separate the signal patterns considered here. A hyperplane (obtained by setting the discriminant function equal to zero) is simply the extension of the straight-line boundary to higher dimensions. Its mathematical representation is:

$$f(E) = \sum_{i=1}^{n} \omega_i e_i + \omega_0 = 0$$

where e_i = EMG activity on channel i
ω_i = weight factor associated with channel i
ω_0 = constant
n = number of input EMG channels

and an electrical equivalent is shown in Figure 1.

If each of the resistor values is made proportional to the inverse of its associated weight, then the voltage at the input of the zero detector is proportional to the analytic value of f(E).

Each of the discriminant functions can be used to separate

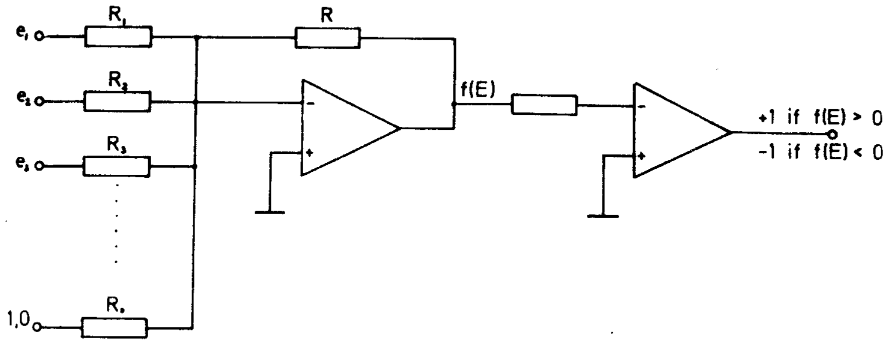


Fig. 1. Linear threshold device

patterns of one class from patterns of a second class. For each discriminant, the set of weights $W=(\omega_0, \omega_1, \omega_2, \ldots, \omega_n)$ can be derived using any of a number of different techniques /10/ given a set of sample patterns from each of the two classes. The techniques vary considerably in their success in different applications, depending on the statistical properties of the data and the assumptions used in the derivation of the technique.

Material

The myoelectric pattern investigations were carried out for a series of five male arm amputees, all aged between 26 and 32 years. The series consisted of below-elbow amputees only and no songenital defects were included. Three patients were amputated in childhood, at the age of 8, 10 and 11 years. The remaining two were 24 and 25 years old at the operation, respectively. The male sex and the age of the patients selected for this investigation were in accordance with several publications stating that arm amputations mainly strike young men /15/.

The cause of the arm amputations and the lengths of the stumps are shown in the Table. Traumatic lesion was the cause of amputation in four cases, a malignant tumour in one case. It is well known that the most common cause of arm amputations are traumatic injuries at work or in traffic /16/. Tumour is a rare cause of this operation, about six per cent in larger series. The lengths of the stumps were measured on the dorsal side of the forearm from the tip of the olecranon.

Table. Cause of amputations and stump length. Occupation and type of prosthesis used before by the five examined amputiees.

Patient	Age years	Stump length (cm)	Amputation cause	Prosthesis used before	Occupation
A	32	17	Blasting accident	None	Painter
B	28	19	Industrial accident	Passive hand	Industrial worker
C	27	13	Blasting accident	Myoelectric prosthesis	Administrator
D	31	16	Blasting accident	Active and passive hands	Industrial worker
E	26	10	Traffic accident	Myoelectric prosthesis	Hospital orderly

Information about the technique used in the operation was available in one case only. Thus, two patients were operated upon abroad many years ago and two at remotely situated hospitals in Sweden.

All five patients had a ramaining phantom limb perception of the lost hand /9/. This feeling is due to the fact that the anatomic representation of the limb within the brain is intact. No patient experienced phantom pain, however. The possibility of opening and closing of the phantom hand as well as extending and flexing the wrist was perceived distinctly by all patients. The resting position of their phantoms was usually a semi-closed hand.

In all patients, the myoelectric signals from both sides of the stump were evaluated according to conventional, clinical electromyographic methods. EMG signs of lower motoneuron lesion were found for one of the ten examined stump muscles only (Case D, flexor stump muscle). The EMG signs of that lesion were moderate with a reduced activity during maximum voluntary contraction. No spontaneous activity such as fibrillary action potentials, was observed.

Regarding the types of prosthesis used before, both active functional hand prostheses and passive cosmetic hands were mentioned. One patient never used any prosthesis (Case A). A myoelectric hand prosthesis was used for three years by one patient (Case D) and still another one (Case C) was recently applied with this type of functional prosthesis.

Methods

Clinical Description

All the patients were subjected to a careful, clinical exemination. This included inspection, palpation, assessment of range of motion and force, and testing of sensibility of the stump. The range of motion in the shoulder and the elbow joints and the remaining rotation of the forearm stump were measured with a goniometer. The physical strength of the arm was compared with that of the uninjured side. The sensibility of the stump was tested for pin prick and touch and was avaluated by Weber's two-point discrimination test.

From careful anatomical considerations it is possible to identify the exact position of several forearm muscles (Fig.2). This is true for forearm stumps not shorter than ten centimeters.

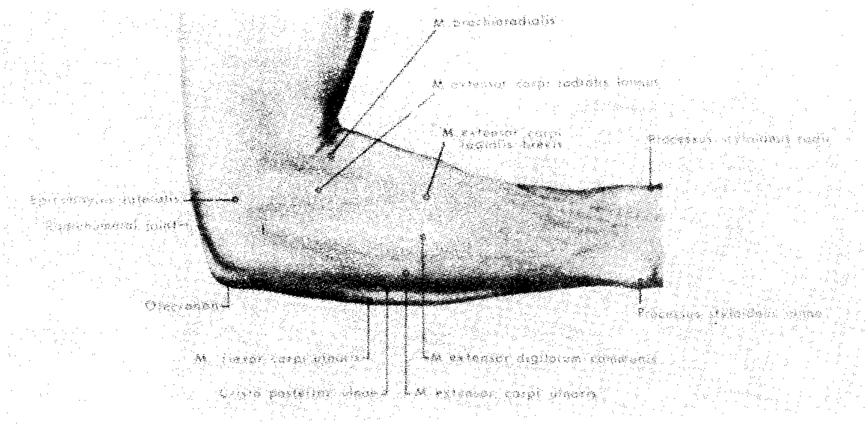


Fig. 2. Lateral view of the forearm musculature and further anatomical landmarks

The patients were asked to perform certain movements of their phantoms in order to contract the corresponding stump muscle.

Six movements (for control of the corresponding three degrees of freedom of the prosthesis) were performed by all patients; finger flexion (FF), finger extension (FE), pronation (P) and supination (S) of the stump, wrist flexion (WF) and wrist extension (WE).

By palpation of the stumps it was then possible to localize the extensor and flexor muscles of the wrist and fingers. The position of the supinator muscle, located proximally and on the radial side of the ulna is easely identified from anatomical landmarks. This is illustrated in Figure 3. When the patients were asked to pronate their forearm stumps the pronator teres muscle was identified. The anatomy is illustrated in Figure 4. Thus, six electrode pairs could be arranged over six carefull evaluated stump muscle positions.

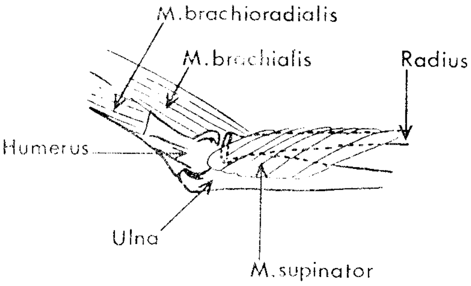


Fig. 3. Lateral view of right forearm showing the supinator muscle

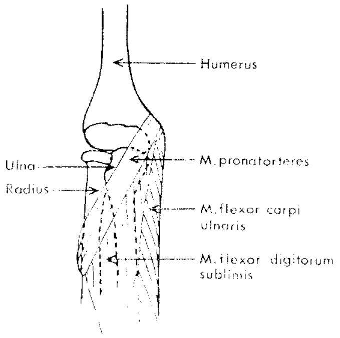


Fig. 4. Frontal view of right arm showing the pronator teres muscle

The wrist extension electrode was always placed over the extensior capri radialis longus muscle (Fig. 2). The wrist flexion electrode was also placed consistantly over the flexior capri ulnaris muscle (Fig. 4). With respect to finger flexion, however, in two patients it was necessary to situate the electrode distally and very ulnar on the stump (over the little finger flexor) in order to get an adequate signal. In placing the finger extention electrode it was necessary to indentify the extensor pollicis longus muscle in three cases. Otherwise these subjects could not produce a finger extention signal pattern that differed from wrist extension.

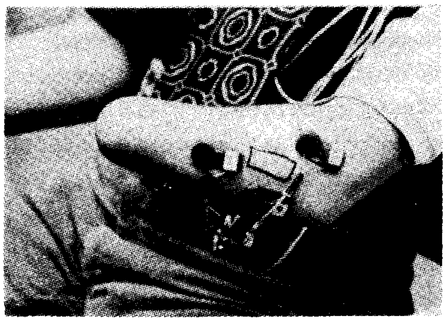


Fig. 5. Extensor side of left forearm showing trial and final electrode positions

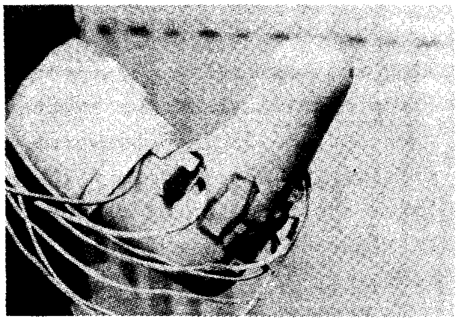


Fig. 6. Flexor side of left forearm showing trial and final electrode positions

A typical electrode pair placement is illustrated in Figures 5 and 6. The figures show how the finger flexion and extension electrode pairs had to be replaced in new positions after the primary graphical signal pattern evaluation.

Technical Description

A block diagram of the components used in control of the multifunctional Swedish hand is shown in Figure 7.

Six pairs of surface electrodes /14/ applied with commercial electrode paste and double-sided tape were used to supply the control signals.

The signal processors consisted of six Grass amplifier pairs (models 7P3B and 7DAD) which provided high pass filtering at 10 Hz cutoff to remove motion artifact, full wave rectification and low pass filtering at 0.8 Hz. The processed signals were then sampled at 25 Hz per channel by an analog-to-digital converter for computer processing.

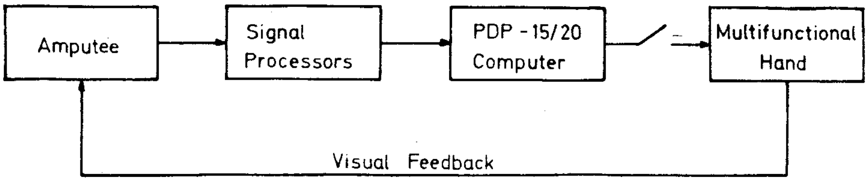


Fig. 7. Block diagram of experimental equipment

The computer had two basic functions in the experiments. With the switch (Fig. 7) open at the beginning of an experiment, on-line recordings of the amputee's stump myoelectric signals were made and the decison networks were designed using pattern classiffication algorithms. With the switch closed, the computer simulated the function of six of the linear threshold devices shown in Figure 1 and the amputee then operated the hand with visual feedback.

The program system used for multichannel myoelectric pattern classification has been previously reported /17/. Techniques of pattern recognition described by Specht /18/, Anderson /19/, Peterson /20/, and Ho /21/ were incorporated in this system.

The linear decision logic used for this investigation consisted of six hyperplane surfaces. Each hyperplane separated patterns of one movement from patterns belonging to any of the five other hand movements and the resting level in the second group ensured that no hand movement would take place if no contraction was made.

Nine data points for each movement were selected during a five second recording over a single constant contraction. Five data points were similarly recorded from a five second sequence at rest. Thus each of the six decision hyperplanes was defined on the basis of nine data points from one class and fifty data points from the other class in a two class recognition scheme. The set of seven weights calculated for each of the six hyperplanes was filed for use in the real-time prosthesis control routine.

During each cycle of the control routine, the six EMG signal input channels were read by the A/D converters, the functions $f_i(E)$; $i = 1...6$ were computed and a movement decision was output to the prosthesis. The movement decision $(f_i(E) > 0)$ resulted in an output level on a D/A channel which drove the selected hand axis at fixed velocity for the period of time that $f(E) > 0$.

An evaluation of the patient's performance was also computed during the hand operation. This evaluation recorded the requested move he was asked to perform, the completion time, and the proportion of time that he spent in driving each axis.

Experimental Procedure

After the clinical examination and placement of the electrode as described previously, each amputee was given similar instructions. Each was requested to find a confortable position in the chair with the lower arm flexed at approximately 90° to the upper. Medium contractions were requested to be performed with both arms on each of the six movements in the order FF, FE, P, S, WF and WE. The amputees were instructed to completely relax before and after each contraction.

A sequence of graphical recordings was then made during each of the six moves in order and the signal patterns were compared. If similar patterns for different movements were observed, an electrode was moved with objective of increasing the signal on the electrode dedicated to the particular pattern to be improved. For example if wrist flexion and finger flexion produces similar patterns, the electrode over the FF flexors would be moved to obtain an increase in the FF electrode signal for the FF movement.

Once the patterns had been accepted on the graph recorder, each of the movements in the above sequence was performed again, at which time a five second recording of each movement was stored on computer tape for pattern analysis.

The pattern classification programs were run and the separation ability observed. Poor classification required either a new set of recordings if irregularities were observed or new electrode positions.

When adequate separation was obtained, the subject was connected to the arm and immediately evaluated on a set of twelve sequences of the six movements in the order described above. The experimental setup is shown in Figure 8. The subject's task was to move a particular degree of freedom of the hand from one extreme mechanical position to the other in the direction of the requested movement. If task was not completed in 15 seconds, this fact was recorded and the next movement in the sequence was evaluated, to avoid tiring the subject.

If the patient was not performing properly during the sequence he was re-instructed to relax or perform the movements bilaterally ect. After the fourth and the eighth sequence, if the subject was having difficulty, he was allowed to make up to four unevaluated movements or rest if he desired.

Following the experiment described above, Case A's electrode positions were marked on the stump. The next day the electrodes

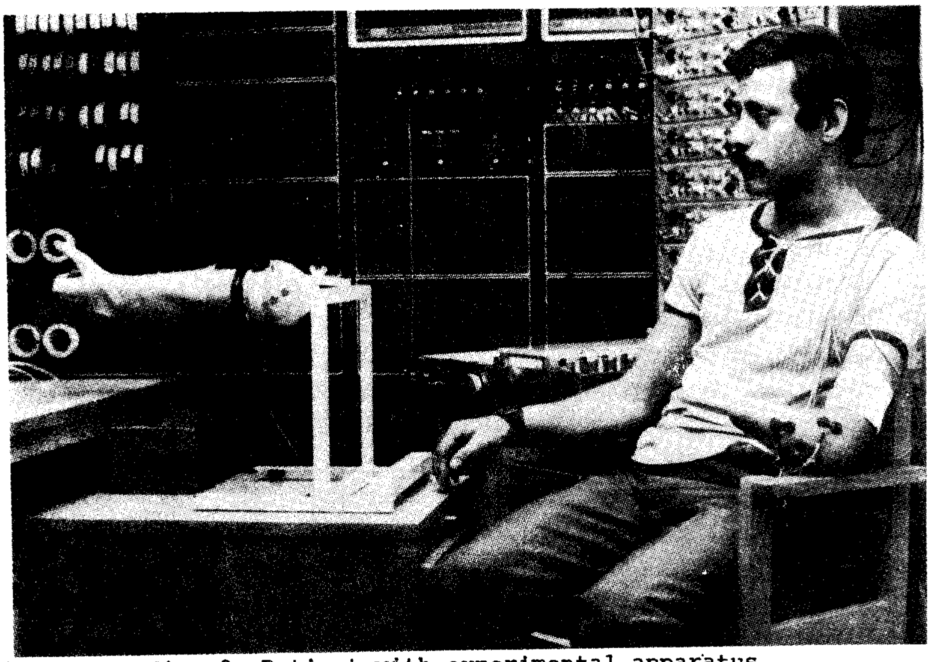


Fig. 8. Patient with experimental apparatus

were replaced and four sequences of the above evaluation were performed using the same discriminant function weights that had been derived the previous day. An evaluation sequence was performed on this subject as well, following the suspension of 1, 2 and 3 kg load at 15 cm from the olecranon with the elbow flexed at 90°. In addition, the effects of slight training on FF and FE were evaluated on this subject by recording 10 FF-FE moves after one 10 minute practice session.

Results

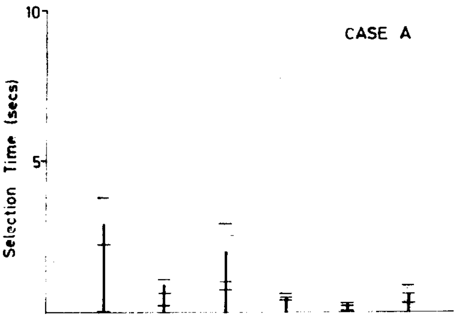
From the clinical examination it was evident that all five forearm stumps were of a good shape (Figs. 5 and 6). The skin was normal and the scar was thin and movable. The stump muscles were in two cases moderately reduced and in one case (E) retracted on the extensor side. The physical strength on the amputated side was almost normal with respect to the shoulder and elbow joint movements in all patients. Also the range of motion was normal in these joints. The remaining ability to pronate and supinate depended on the length of the stump. If the stump length exceeded 15 cm the patients could rotate their forearm more than

90°. The sensibility within the stumps was normal except for very small areas localized along the scars.

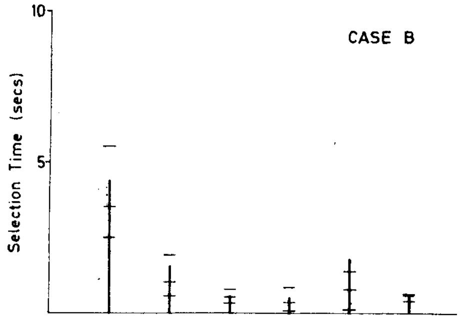
The performance of each patiemt is summarized in Figure 9. In the following presentation the term "completion time" is the total time required by the subject to move the degree of freedom from one extreme to the other. Because of the time required to move between the extremes of each axis, there was a "minimum movement time" for each movement of the prosthesis. For each of six movements: FF, FE, P, S, WF, and WE, the minimum movement time was 1.5, 1.0, 2.0, 2.0, 0.8, and 0.8 seconds respectively. The time for FF was longer than FE due to the compressive forces generated by the cosmetic glove. In order to get a uniform measure of performance for each axis the "selection time", defined as the completion time less the minimum movement time, was plotted. In the performance of a task if a subject was unable to reach the axis extreme in 15 seconds, the task was termed a "failure" and the number of failures throughout the experiment is shown. The "mean selection time" (over the successful tasks) is shown as a solid vertical bar. The uppermost, middle and lowest horizontal line on each bar represent the upper, middle (median), and lower quartiles of selection times, respectively. The "error factor" is defined as the fraction of the sum of the completion times, that the amputee spent in selecting movements other than the one specified in the task.

The S movement of Case D was not evaluated. When the initial recordings were made, the subject gave a very high level contraction for the supination movement. When the evaluation was performed he was unable to reach these values of contraction and thus the task was eliminated from the sequence. Following the experiment, graph recordings og lower level S movements were made, clearly showing a possibility for separation.

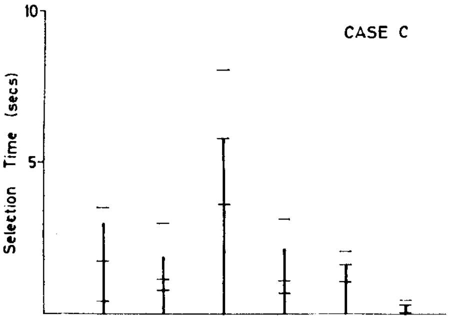
In general, mean selection times under one second were considered to be quite acceptable, especially if the error factor is small (Case A: S, WF / Case B: P, S, WE / Case C: WE / Case D: P / Case E: P, S, WE). In some of these cases it was possible that the subject was a little slow in responding to the start command. Even when the error factor is higher and the mean selection time under one second (A: FE, WE / D: FE, WF) the actual time that undesired signals are being output to the devices is very small since the



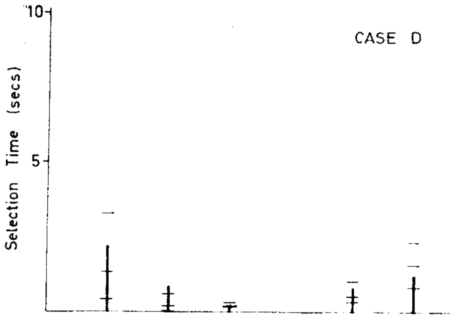
Movement	FF	FE	P	S	WF	WE
No. of Failures	1	0	0	0	0	0
Error Factor	.64	.27	.28	.01	.00	.33



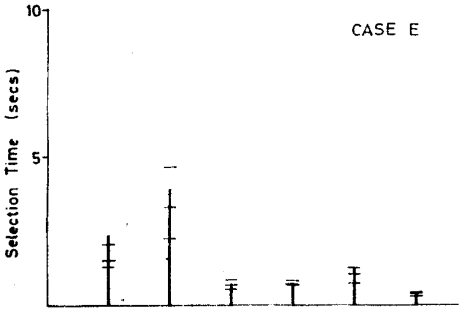
Movement	FF	FE	P	S	WF	WE
No. of Failures	1	1	0	0	1	0
Error Factor	.63	.32	.02	.00	.56	.01



Movement	FF	FE	P	S	WF	WE
No. of Failures	1	3	7	3	0	0
Error Factor	.55	.42	.41	.42	.51	.00



Movement	FF	FE	P	S	WF	WE
No. of Failures	0	0	0	—	0	0
Error Factor	.32	.34	.06	—	.16	.46



Movement	FF	FE	P	S	WF	WE
No. of Failures	0	3	1	0	0	0
Error Factor	.26	.64	.01	.00	.24	.03

Fig.9. Performance of each amputee in operation of the six hand functions

selection time is then made up of several signal processor and electromechanical time constants which reduce the possible movement time on the wrong axis considerably. In the above-mentioned cases, the control was considered to be very good since these axes can be used reliabily at once.

In some cases (A: FF, P / B: FE, WF / C: FF, FE, S, WF / D: FF, WE / E: WF) the mean selection time and the upper quartile were over one or two seconds but the lower quartile was a second or less. The fact that the subject can find the correct pattern some of the times indicates that there may be potential for improvement either by a recomputation or the weights based on additional sample patterns to try to improve the selection problem, or a slight amount of training to "lock" on the correct pattern. The outlock in these situations was considered good although not as desirable as the previous cases.

However, in some cases (B: FF / C: P / E: FF, FE) even the lower quartile was at several seconds with each case exept (E: FF) containing a number of failures. In each case the subject had more difficulty in isolating a specific pattern from a similar one for another movement. In the cases mentioned, FF was similar to P, FE to WE, and P to WE. These cases were more difficult since either new electrode positions for the movement pairs that were similar would be needed to further separate patterns, or training sessions so that better isolation could eventually be learned.

Electrode Replacement

The effect of replacing Case A's electrodes on the previous day's marked locations can be seen in Figure 10. The "selection time increase" is the mean selection time after replacement less the mean selection time before. Although a complete investigation into these effects was not the objective of these experiments, it can be seen that there are both increases and decreases in selection times and that the subject could still control all the movements.

Effects of Loading

When loads of 1, 2 and 3 kg were applied to tip of the stump, 15 cm from the olecranon, the effects on the subject can be seen in Figure 11. The only movement that loading seemed to affect was the FF movement. Since the FF was also the most difficult movement for this particular subject in seems natural that external effects such as loading should influence this movement most greately.

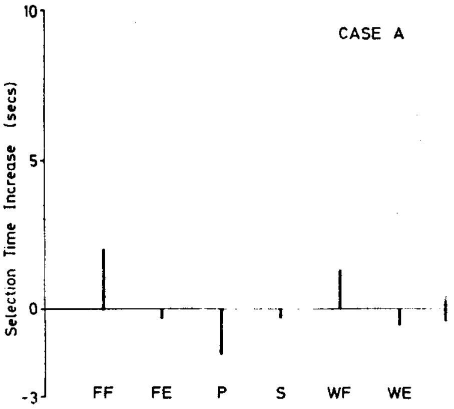


Fig. 10. Effects of electrode replacement.

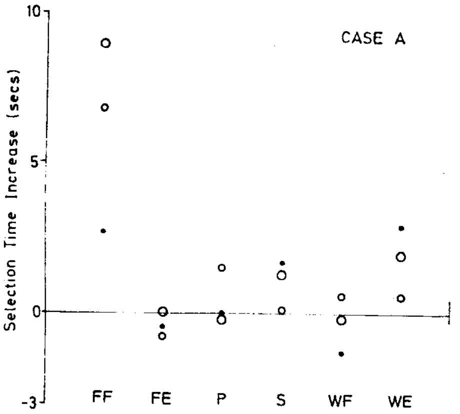


Fig. 11. Effects of loading. Small, medium and large circles correspond to 1, 2 and 3 kg at 15 cm from olecranon with stump in neutral rotation position.

Effects of Slight Training

Prior to training, the mean selection times for FF and FE were 4.9 and 0.7 seconds, respectively. After training for ten minutes, the mean selection time over ten trails were reduced to 4.1 and 0.3 seconds, respectively, indicating a slight improvement in both cases.

Discussion

Since stump musculature contains original prime movers of the hand and the neuromuscular connection are intact, it is desirable to use these muscles for control of the prosthetic hand. In this way the prosthetic system makes use of the natural myoelectric patterns generated by cortical outflow when the patient desires to operate the particular hand function. The technique of adjusting the control device to suit the myoelectric patterns of each individual amputee, allows the use of stump muscles for multifunctional control - despite the differences in such muscles due to individual trauma and the method used in surgery. A myoplastic surgical technique would be very beneficial in preserving the original stump myoelectric patterns and thus contribute to better possibilities for control of a prosthesis.

The patients used here, formed an ideal group in that they had no atrophy or impaired motion within the joints of the amputated side, which can be attributed to their relative youth.

Although six electrodes were applied to each of these patients for uniformity in the investigation, good separations of recorded data have been obtained using only four electrodes. This can be accomplished, for example, by rejecting an electrode that carries the same EMG levels for all movements.

The accurancy with which the six electrodes must be replaced to obtain the same myoelectric pattern depends upon the particular stump but it has been observed that displacement of as little as 2.0 mm can be important.

It has been noticed in these experiments that the separability of the myoelectric patterns can usually be determined by observing the graphical recordings of the average signal level from each electrode for the given movements. As well, slowly changing signal levels on one or more channels, and abnormal spikes were important to avoid in the patterns for analysis.

In the determination of the weighting factors in each discriminant function, it was found that Anderson's method /19/ was usually adequate for separating the patterns. Anderson derived the optimal discriminant function for separating two normally-distributed classes with equal covariance matrices. In practice here, this assumption is probably invalid and when adequate separations were not obtained by this more rapid method, Peterson's technique /20/ was applied to derive an optimal linear discriminant function separating two normal distributions with unequal covariance matrices. In situations where this method as well failed to separate the data, the patterns were very similar on the graphical recordings so new electrode positions were sought. The Ho-Kashyap algorithm /21/ also available in the system could often separate such similar patterns but it was found that the amputee would than be unable to discriminate so finely when operating the hand. Although useful in previous work /14/ where there were two well-defined clusters forming the classes, the method of Specht /18/ was unable to separate the present data adequately. This was possibly due to the fact that in each separation one of the classes was made up of a number of movement patterns with cluster centers at some distance from one another in hyperspace. The effects of distance and non-spherical probability densities on the final boundary have been discussed by Specht /18/.

The performance of the subjects in this work can be summarized as follows. Of the 30 movements (6 moves in 5 patients), 14 could be performed with immediate success. A further 11 had good prospects of being useful with minimal training, slight readjustment of the discriminant function or both. Possible problems lay in isolating the more difficult 4 of the movements. The remaining move can be accounted for by the unevaluated S movement in Case D. Thus 25 of the 30 movements had good possibilities for control with little or no training. These results indicate that control of a below-elbow multifunctional prosthesis is indeed possible using myoelectric signal patterns from the stump itself. Thus it may be possible to make even such a sophisticated device self-contained and easily-controlled. The hardware pattern recognition network can, as indicated in Figure 1, be made quite simple, allowing adequate miniaturization at moderate cost.

The advantages gained by adjusting the pattern recognition network for each amputee and the use of an on-line digital computer in the evaluations have enabled us to obtain these promising, quantitative performance results on below-elbow amputees.

References

/1/ Bousso, D. and Ishai, G., "Report on the use of myoelectric signals for multiple degree-of-freedom arm prosthesis control", Report TDM 69-7, Dept. of Mechanics, Technion-Israel Institute of Technology, Haifa, 1969.

/2/ Germans, F.H., Brekelmans, F.E.M. and Wijkmans, D.W., "Some aspects of the design of an EMG-controlled artificial hand with two functions", *Advances in External Control of Human Extremities*, Yugoslav Committee for Electronics and Automation, Belgrade, pp. 185-189, 1970.

/3/ Skachkov, A.N., "Bioelectrically controlled artificial hands", *External Control of Human Extremities*, Yugoslav Committee for Electronics and Automation, Belgrade, pp. 97-101, 1967.

/4/ Kato, I., Yamakawa, S., Ichikawa, K. and Sano, M., "Multifunctional myoelectric hand prosthesis with pressure sensory feedback system - Waseda hand 4P", *Advances in External Control of Human Extremities*, Yugoslav Committee for Electronics and Automation, Belgrade, pp. 155-170, 1970.

/5/ Klasson, B., "Development on externally powered artificial limbs at NBI", *Advances in External Control of Human Extremities*, Yugoslav Committee for Electronics and Automation, Belgrade, pp. 151-173, 1967.

/6/ Simpson, D.C., "An externally powered prosthesis for the complete arm", *Bio-Med. Engng.*, March, pp. 106-110, 1969.

/7/ Lymark, H. and Möhl, F., "An electromechanical forearm and hand", *External Control of Human Extremities*, Yugoslav Committee for Electronics and Automation, Belgrade, pp.142-150, 1967.

/8/ Childress, D.S. and Billock, J.N., "Self-containment and self-suspension of externally powered prosthesis for the forearm", *Bull. of Prosthetic Research*, BPR 10-14, pp. 4-21, Fall, 1970.

/9/ Cronholm, B., "Phantom limbs in amputees", Thesis, *Acta Psychiat. Scand.*, Suppl. 72, 1951.

/10/ Nagy, G., "State of the art in pattern recognition", *Proc. IEEE*, Vol. 56, pp. 836-862, 1968.

/11/ Cover, T.M., "Geometrical and statistical properties of linear threshold devices", Tech. Rept. No. 6107-1, Stanford Electronics Labs., Stanford Univ., Calif., May, 1964.

/12/ Harrison, L., "Paralytic's Brain + Myocoder = Hope", *Electronics*, pp. 74-78, Nov. 30, 1964.

/13/ Taylor, D.R. and Finley, F.R., "Multiple-axis prosthesis control by muscle synergies", *The Control of Upper-Extremity Orthoses and Prostheses*, (eds. P. Herberts et al) to be published, Thomas, Ft. Landerdale, 1972.

/14/ Lawrence, P.D. and Kadefors, R., "Classification of myoelectric pattern for the control of a prosthesis", *The Control of Upper-Extremity Orthoses and Prostheses*, (eds. P. Herberts et al) to be published, Thomas, Ft. Landerdale, 1972.

/15/ Watkins, A.L., Ford, D.E., "Rehabilitation after amputation of an upper extremity: a ten years study", *Arch. Phys. Med.*, Vol. 43, pp. 293-296, 1962.

/16/ Herberts, P., "Myoelectric signals in control of prosthesis", Thesis, *Acta Orthop. Scand.*, Suppl. 124, 1969.

/17/ Lawrence, P.D., "Computer design and simulation of a myoelectric pattern classifier for controlling a multifunctional prosthetic hand", presented at 3rd Int. Conf. on Med. Physics incl. Med. Engng., Göteborg, Sweden, July, 1972.

/18/ Specht, D.F., "Generation of polynomal discriminant functions for pattern recognition", Technical Report 6764-5, Stanford Electronics Labs., Stanford Univ., May, 1966.

/19/ Anderson, T.W., *An Introduction to Multivariate Statistical Analysis*, Chap. 6, Wiley, N.Y., 1958.

/20/ Peterson, D.W., "Discriminant functions: properties, classes and computational techniques", Technical Report 6761-2, Stanford Electronics Labs., Stanford Univ., April, 1965.

/21/ Ho, Y.-C. and Kashyap, R.L., "An algorithm for linear inequalities and its applications", *IEEE Trans. on Elec. Computers*, EC-11, pp. 683-688, Oct., 1965.