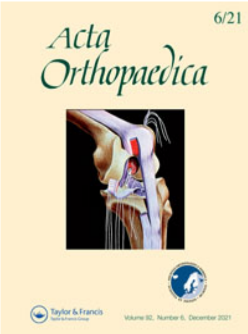

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HAND PROSTHESIS CONTROL VIA MYOELECTRIC PATTERNS

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It is well known that many orthopaedic appliances do not receive the immediate appreciation hoped for. In fact, they are frequently put away on the shelf or in the drawer, and the patient manages without them. This is to some extent true also for myoelectrically controlled artificial hands. Undoubtedly the mechanism of rejection of such a hand prosthesis by an amputee is a complicated one, involving various psychological components. However, it is reasonable to believe that the patient's attitude toward his new device is a result of a cost-benefit analysis in which the cost is made up of technical breakdowns, unsatisfactory function and training time demands. The benefit is calculated on the functional assistance and cosmesis.

Provided a hand prosthesis is well designed, technical breakdowns should be a minor source of trouble. The unsatisfactory function, on the other hand, is a consequence of failure to solve a basic problem: how to provide the patient with some of the vital hand functions he has lost. The ultimate answer cannot be the simple device of today, supplied with active hand opening and closing only. The multifunctional hand concept has been introduced to enhance prosthetic hand function, and to make the patient more likely to accept and draw full advantage of the prosthesis.

So far, multifunctional hands have not been very successful: none is commercially available as of now, despite efforts in many countries (Rakić 1967, Kato et al. 1970, Germans et al. 1970, Voskoboinikova 1970, Schmidl 1971, Lymark & Möhl 1967). In addition to certain engineering problems, this fact is due to the problem of how to learn to operate a complicated device quickly and efficiently.

Very few reports have been presented on the theme of acquisition of skill in the operation of multifunctional prostheses, but the literature on multifunctional orthosis control gives some information. Monster (1970) compared multichannel myoelectric control with mechanical movement control, concluding that it is much easier to acquire skill with movements transformed into control signals than with EMG. Radonjić & Long (1970) attributed the movement superiority to the exquisite proprioception supplied in the control of movements as compared with control of individual muscle tension. Kadefors & Taylor (1973) found that simultaneous operation of individual myoelectric control sites almost never occurs despite intense training. Simpson (1973), using the term "extended physiological proprioception", has constructed a mechanical movement system for children's arm prostheses which very successfully makes use of the ease of training combined with movement control, in particular when the control site is mechanically coupled to the terminal device.

It is unfortunate that practical prosthesis control by body movements sometimes involves intolerable bulky transducers and transmission elements, in contrast to the easily applied electrodes for myoelectric signal pick-up. An efficient system for myoelectric control promoting learning capability would thus be of great advantage in this situation. The problem was attacked by Finley & Wirta (1967) and Taylor & Finley (1973). Pick-up electrodes were placed at anatomical locations over muscles in the shoulder region of normal subjects, and myoelectric levels were recorded during certain well-defined arm movements. An automatic method was applied to recognize the myoelectric activity patterns during the various movements. With an amputee now in place of the normal subject, the activity patterns evoked during movements of the phantom arm could be recognized and used for control of prosthetic arm movements with little or no training requirements.

It has been known for a long time that the loss of a limb may be followed by the illusion that the limb is still there, and this perceptual phenomenon has been well described (Cronholm 1951). The limb which is missing but still perceived is known as the phantom limb and the perception itself is called the phantom experience. Congenital defects do not produce phantoms, nor does this experience occur in children after early amputations. Almost all amputees report a phantom experience which consequently must be regarded as the normal sequela of amputation.

The method of using phantom sensation to facilitate or even elim-

Table 1. Cause of amputations and stump length. Occupation and type of prosthesis used before by the five examined amputees.

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	Malignant tumour	Myoelectric prosthesis	Hospital orderly

inate training has been further developed in the present project (Lawrence & Kadefors 1973, Lawrence et al. 1973). We have focused our attention on the fact that the myoelectric patterns from various electrodes in the stump region show considerable individual variations due to, for instance, the method used in surgery. A well-functioning pattern recognition control system must, in contrast to previous systems, be able to conform to the individual characteristics of the patients.

The present project is carried out using the Swedish hand (Lymark & Möhl 1967) as a display tool intended for clinical application. This hand has six active movements: grasp, release, pronation, supination, wrist flexion and wrist extension. It is believed that this hand has enough functional capability to become beneficial, provided it can be properly controlled.

Summing up, the present project is focused on eliminating the training burden imposed on the amputee when he is fitted with an advanced hand prosthesis. The solution to this clinical problem is approached employing sophisticated digital computer techniques.

MATERIAL AND METHODS

When below-elbow amputees are asked to perform certain movements of their phantom hands, specific muscle contractions are produced within the stump. If a

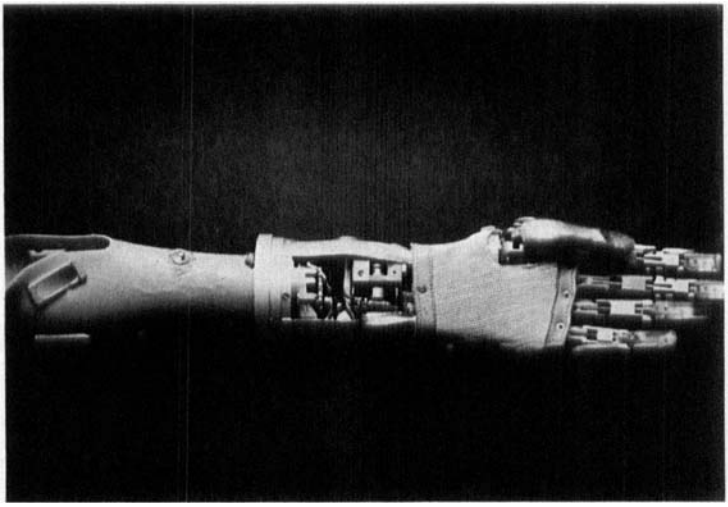

Figure 1. The Swedish multifunctional hand prosthesis with the actual socket used in the experiment.

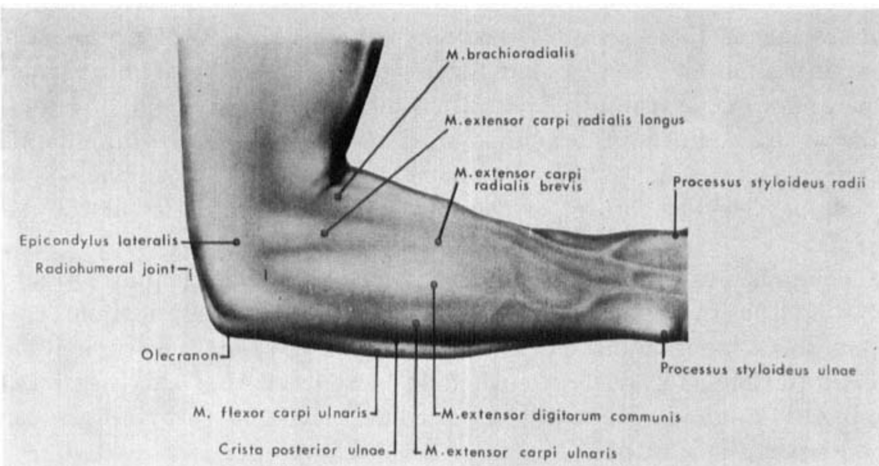

Figure 2. The dorsal view of the normal forearm and anatomical landmarks.

number of surface EMG electrodes are applied around the stump, different patterns of myoelectric activity can be picked up for each movement. With current myoelectric control techniques, it is not possible to make use of the information contained in these multi-channel patterns. However, the use of statistical pattern recognition methods (Nagy 1968) provides a possible solution to this problem.

In the first part of this investigation (Part I), the prospects of using myoelectric patterns to control movements of a multifunctional prosthesis were studied on a

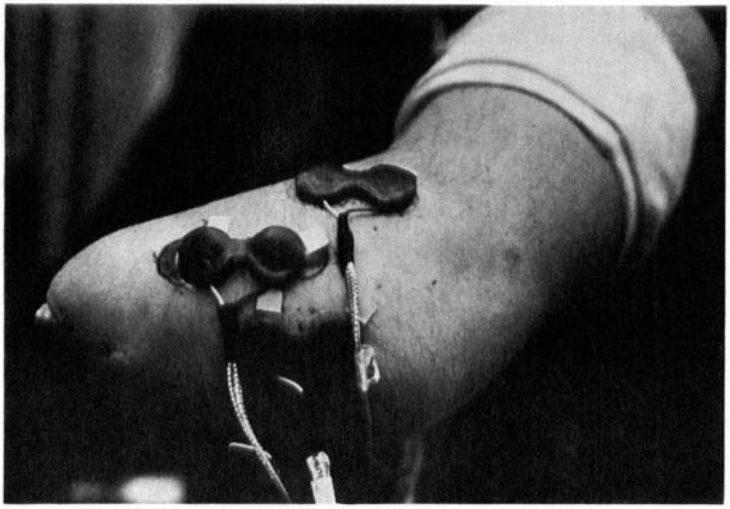

Figure 3. Extensor side of a forearm stump and typical electrode positions.

series of five male BE-amputees. They were aged between 26 and 32 years. The length of the stumps and the cause of the amputations are shown in Table 1. Traumatic lesion was the cause of amputation in four cases: in one case a malignant tumour was present. It is well known that most arm amputations are the result of traumatic injuries in fairly young men (Herberts 1969). The length of the stumps was measured on the dorsal side of the forearm from the tip of the olecranon.

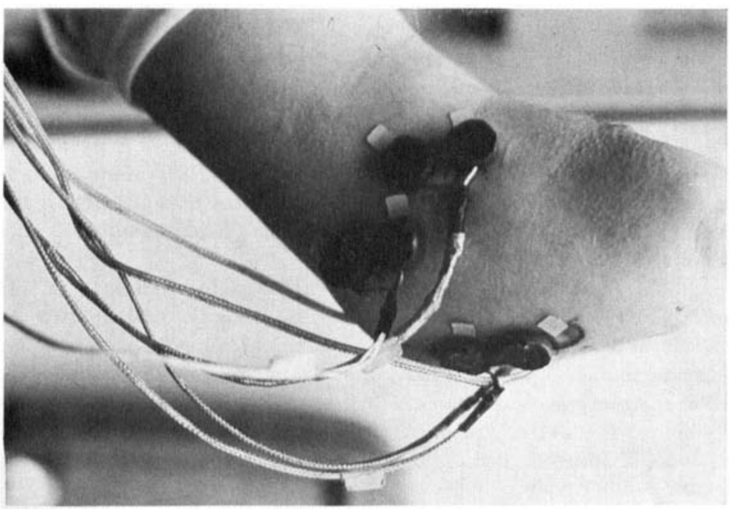

Figure 4. Flexor side of a forearm stump and typical electrode positions.

All five patients had a remaining phantom limb perception of their lost hand. They distinctly perceived the possibility to open and close the phantom hand and to extend and flex the wrist.

The myoelectric signals from the extensor and flexor sides of the stump were evaluated according to conventional, clinical electromyographic methods. EMG signs of lower motor neuron lesion were found for one of the ten stump muscles only (Case D, flexor stump muscle). The lesion was moderate with a reduced activity during maximum voluntary contraction. However, the signal was termed adequate for use in this investigation.

In the second part of the investigation (Part II), one patient was evaluated with the multifunctional hand prosthesis applied. The patient is identified as Case A in Table 1. The socket was made according to the conventional Münster technique and mounted to the prosthesis as illustrated in Figure 1.

Electrode Positioning

By a careful clinical examination, based on anatomical landmarks, it is possible to identify the position of several forearm muscles (see Figure 2). All patients were asked to perform certain movements of their phantoms in order to contract the corresponding stump muscles. Six phantom hand movements were performed for control of the six movements available in the prosthesis: finger flexion (FF), finger extension (FE), pronation (P) and supination (S) of the stump, wrist flexion (WF) and wrist extension (WE), chosen to conform to the movements of the Swedish hand.

The surface electrodes were carefully placed over each individual muscle. A typical electrode pair placement is illustrated in Figures 3 and 4. In all cases one electrode pair was placed over the extensor carpi radialis longus muscle. Furthermore, one electrode pair was consistently placed over the flexor carpi ulnaris muscle. In three cases it was necessary to move the finger extension electrode pair from this muscle to the extensor pollicis longus muscle. Otherwise these subjects could not produce a finger extension signal pattern that differed from wrist extension. The position of the supinator muscle was identified from anatomical considerations. Finally, when the subjects were asked to pronate their forearm stumps the pronator teres muscle could easily be located by palpation. Six electrode pairs could thus be arranged over six carefully evaluated stump muscle positions. The accuracy with which the position of the electrodes had to be reproduced from one day to another to obtain the same myoelectric patterns depended upon the particular stump, but it was observed in one case that displacements of only 2 mm could be important.

Each amputee was then requested to perform six medium strength phantom limb movements: FF, FE, P, S, WF and WE. The subjects were instructed to relax completely before and after each contraction. Graphical recordings were made during each of the six moves. A typical example of the signal patterns obtained is shown in Figure 5. In some cases almost identical patterns for different movements were observed, making it necessary to move an electrode with the objective of increasing the signal on the electrode dedicated to the particular movement.

Technical Description

The activity patterns pertaining to particular phantom movements depicted in Figure 5 look different, which implies that there is information contained in them. In a mathematical sense, each one of these patterns is characterized by a set of numbers, describing the average activity level in the various channels. Sets of numbers can be grouped into classes (classified) using mathematical methods. One such class may be referred to as "finger flexion", another "wrist extension", and so on.

Several mathematical methods are developed for classifying patterns. The main problem is to find a way to separate the classes of patterns using mathematically defined boundaries having the character of surfaces. Methods for computing linear surfaces, hyperplanes, are described by Specht (1966), Ho (1965), Anderson (1958) and Peterson (1965). In the course of the present project, these methods were adapted to a digital computer to separate the EMG-patterns (Lawrence et al. 1973, Lawrence 1972). The hyperplane separating the classes "A" and "B" is mathematically described by the equations

$$f_{AB}(x) = 0$$

$$f_{AB}(x) = W_o + \sum_{i=1}^{6} W_i X_i$$

where X_i in our case denotes the rectified EMG-signal from site i, W_i the corresponding weight factor and W_0 a constant term. In the case $f_{AB}(X) > 0$ the signal pattern belongs to class "A", otherwise it belongs to class "B". The method is illustrated in Figure 6.

The myoelectric signals were processed by means of a Grass amplifier (models 7P3B and 7DAD), which provided high-pass filtering at 10 Hz cutoff, amplification, full wave rectification and low pass filtering of the rectified signal at 0.8 Hz. After visual check of the graphic recordings the signals were fed into the analog to digital converter of the computer, a PDP-15. Patterns from each one of the six hand movements as well as during relaxation were recorded and stored. The time duration for recording one pattern was in all cases chosen as 5 seconds.

At a later stage in the project the method for signal processing was modified in relation to how it was performed in the first period (see Table 2). The table shows that in Part II, any number of data points are allowed. This facility makes it possible to use several recordings of training data and superimpose them.

The seven groups of training data were separated: one group supposed to belong to class "A" was placed in category "A" and the remaining six in category "B" (see Figure 6). The weight factors were computed and a simple analysis was performed. This analysis showed how many of the data points from category "A" fell into class "B" and how many of those from category "B" fell into class "A". This computation and analysis was carried out for all of the six movements, so that six sets of weight factors representing the hyperplanes were generated.

Once this training phase had been finished, a computer on-line classifying test was performed. Real-time EMG signals from the subject were then processed by the computer-generated weight functions. A pattern belonging to any one of the movement classes resulted in a signal from the digital to analog converter to the driving electronics of the prosthesis movement concerned.

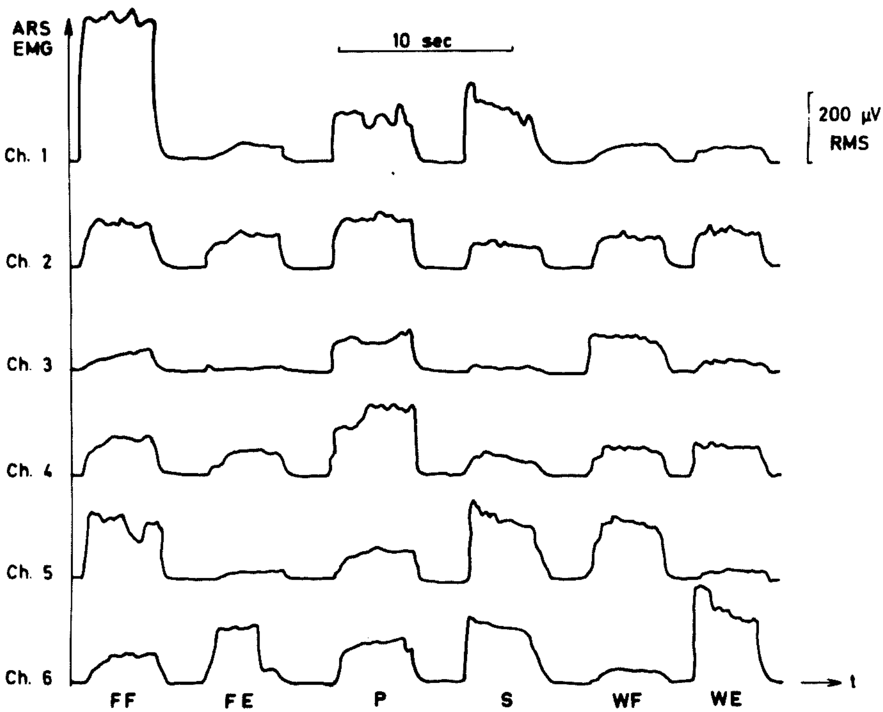

Figure 5. Amplified, rectified and smoothed EMG from six electrode pairs applied on a forearm stump. The patient performs six phantom hand movements (see the text).

As described above, the pattern recognition procedure is performed in two main phases, one training phase and one test phase (see Figure 7). The next step is to make the classification of the patterns with the computer off line. The mathematical operation, f(X), and the classification procedure are easily realized by means of an electronic network. This network generates the function and a threshold logic unit checks whether the function value is greater than zero or not (see Figure 8). The complete network contains six channels, one for each movement. Every one of the processed EMG signals is fed into every channel, responding with a 1 out if the pattern belongs to the class of movement of this channel; otherwise the output is a 0. The channels for opposing movements are connected to one output in such a way that when both are giving a 1, the resulting output is a 0. The three outputs are then connected to the Swedish hand. The way the channels are connected allows the operator to make the three bidirectional movements simultaneously.

The objective is of course not to have the patient carry around a computer. The method employed for the pattern recognition (Lawrence 1972) requires only linear mathematical operations and is thus easily realized in a miniaturized electronic circuit adjusted to the individual patient (see Figure 9). This circuit can be made small and lightweight, it is inexpensive and easy to adapt to the patient.

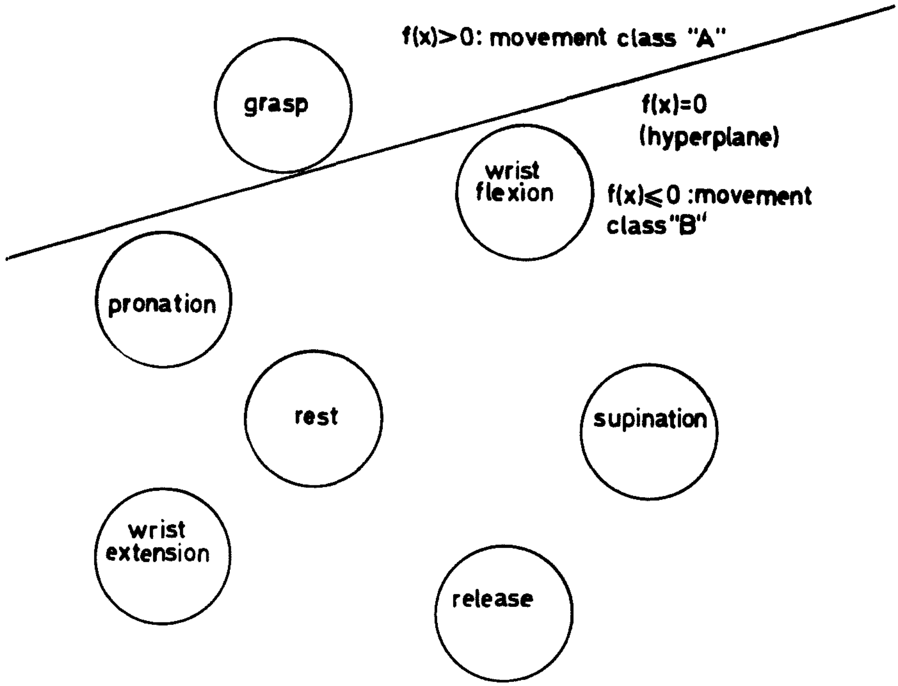

Figure 6. Schematic illustration showing the separation process. In this example, a hyperplane $f(x)=0$ separates grasp, belonging to class "A", from the remaining five movements, lumped in class "B".

Table 2. Technical details of the two parts of the investigation.

	Part I (first period)	Part II (later period)
Sampling frequency	25 Hz	50 Hz
Number of data points from each pattern	9	infinite
Type of electrodes	passive	active, gain $\times$ 25

Experimental Set Up

In Part I of this investigation each subject was requested to find a comfortable position in the chair. When adequate separation of the myoelectric signal patterns was obtained, the subject was connected to the Swedish multifunctional prosthesis which was mounted on the bench. Each subject was immediately evaluated on a set of twelve sequences of six movements in the order described above. The task of

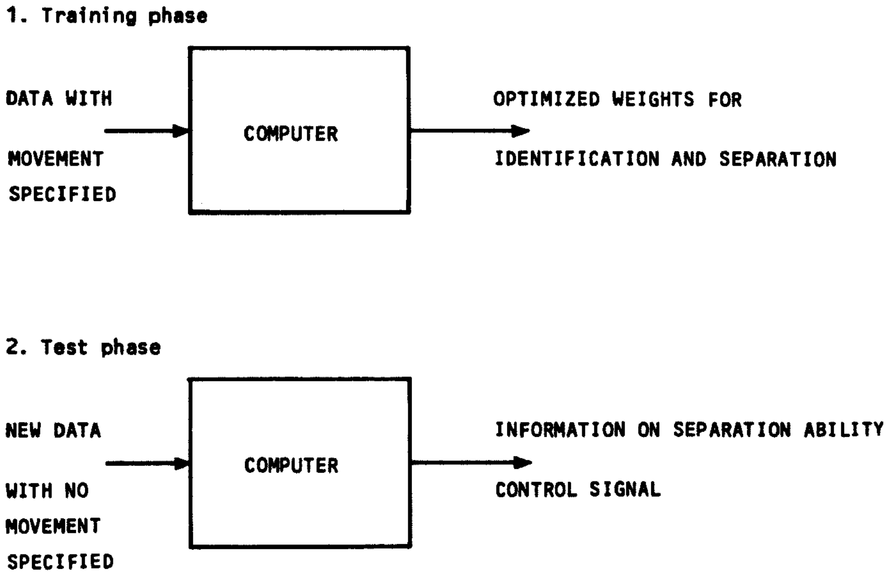

Figure 7. Pattern recognition procedure.

each subject was to activate a particular motorized movement of the prosthesis from one extreme mechanical position to the other in the direction of the requested movement. The total time from start command until the prosthesis reached its extreme position was registered. If the task was not completed in 15 seconds, the run was recorded as a failure and the next movement in the sequence was evaluated, to avoid fatiguing the subject.

In Part II of the investigation the multifunctional prosthesis was applied to one patient as illustrated in Figure 10. In this case, the prosthesis was not controlled through the computer but through the electronic network described in the preceding paragraph. The performance of this patient for each of the six movements was evaluated in accordance with the method described above for the Part I experiments.

Thus the functions of the digital computer in the investigations were as follows:

1. Record and store multichannel EMG signals.
2. Calculate weighting factors for the pattern recognition network.
3. Simulate the pattern recognition network while the patient operates the prosthesis (Part I only).
4. Analyze the patient's performance.

RESULTS

Part I

In the first part of the investigation each subject was connected to the prosthesis mounted on the bench and evaluated on the six movements described above. The total time for each task was registered. However, there was a minimum mechanical movement time for each of the six movements: FF, FE, P, S, WF and WE. This minimum movement time was 1.5, 1.0, 2.0, 2.0, 0.8 and 0.8 seconds respectively. In order to get a uniform measure of performance for each access the "selection time", defined as the total time less the minimum mechanical movement time, was plotted. This time represents the real time during which each patient is trying to produce the correct signal pattern by performing a natural movement with his phantom hand. The selection times of the various patients and movements are presented in Table 3. In Figure 11, the mean values of each patient are depicted and the number of failures throughout the experiments is also shown.

Table 3. Selection time in seconds for various movements. Medians and quartiles.

Case	Finger flexion	Finger extension	Pronation	Supination	Wrist flexion	Wrist extension
	3.8	1.1	2.9	0.6	0.3	0.9
A	2.2	0.6	1.0	0.5	0.2	0.6
	0.1	0.3	0.8	0.4	0.1	0.3
	5.5	1.9	0.8	0.9	1.4	0.7
B	3.5	1.0	0.5	0.4	0.8	0.6
	2.5	0.6	0.3	0.1	0.1	0.4
	3.5	3.0	8.0	3.1	2.1	0.5
C	1.8	1.2	5.7	1.1	1.6	0.3
	0.4	0.8	3.6	0.7	1.1	0.1
	3.3	0.6	0.3		1.0	2.3
D	1.3	0.2	0.2	–	0.5	1.5
	0.4	0.1	0.1		0.3	0.8
	2.1	4.7	0.9	0.8	1.3	0.4
E	1.5	3.3	0.7	0.7	1.1	0.4
	1.3	2.2	0.5	0.7	0.7	0.3

We have considered mean selection times under one second to be a very good result, especially as certain patients were slow in responding to the start command. In some tasks (Case A: FF, P; Case B: FE, WF; Case C: FF, FE, S, WF; Case D: FF, WE; Case E: WF) the mean selection time and also the upper quartile were over one or two seconds but the lower quartile was one second or less. These results were also considered good. The subjects can find the correct patterns most of the time and a recomputation of the weights to improve the selection problem, or a slight amount of training can easily improve the performance.

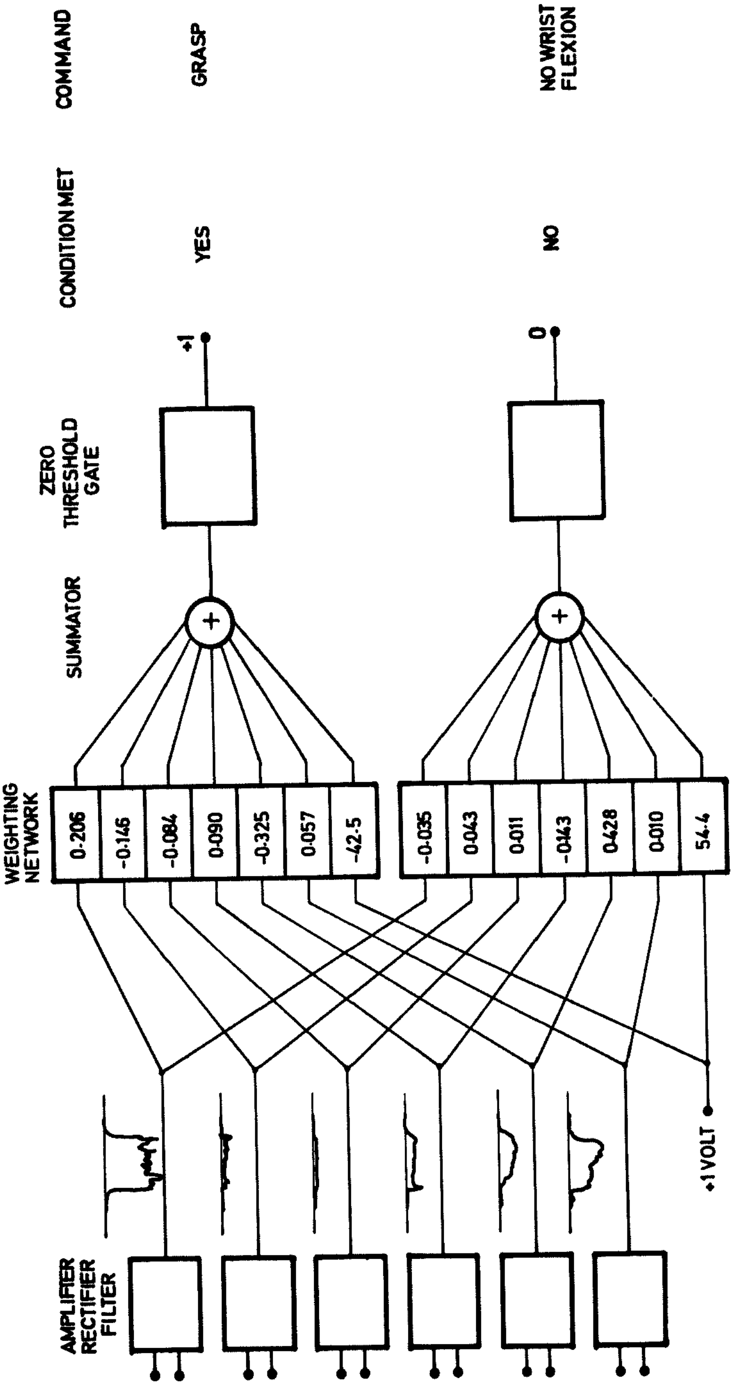
COMMAND
GRASP
NO WRIST FLEXION
CONDITION MET
YES
NO
+1
0
ZERO THRESHOLD GATE
SUMMATOR
WEIGHTING NETWORK
0·206
-0·146
-0·084
0·090
-0·325
0·057
-42·5
-0·035
0·043
0·011
-0·143
0·428
0·010
54·4
+1 VOLT
AMPLIFIER RECTIFIER FILTER

Figure 8 (a)

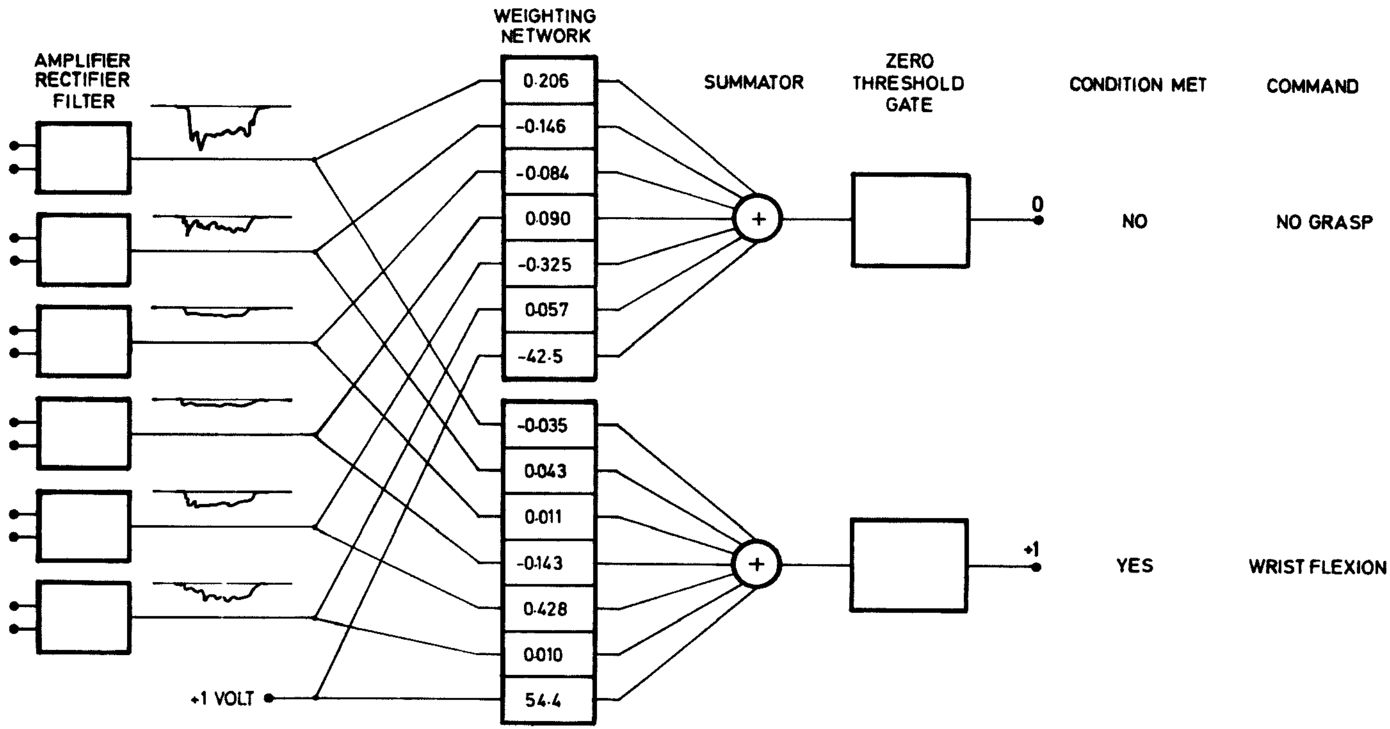

Figure 8 (b)

Figure 8. Illustration of the principle of pattern recognition control as performed with the electronic circuit shown in Figure 9. In (a), the patient intends to perform finger flexion, in (b) wrist flexion. The circuit responds with a command, in the first case for the prosthesis to grasp, in the second to flex the wrist. Only the two portions of the circuit dedicated to grasp and wrist flexion are shown.

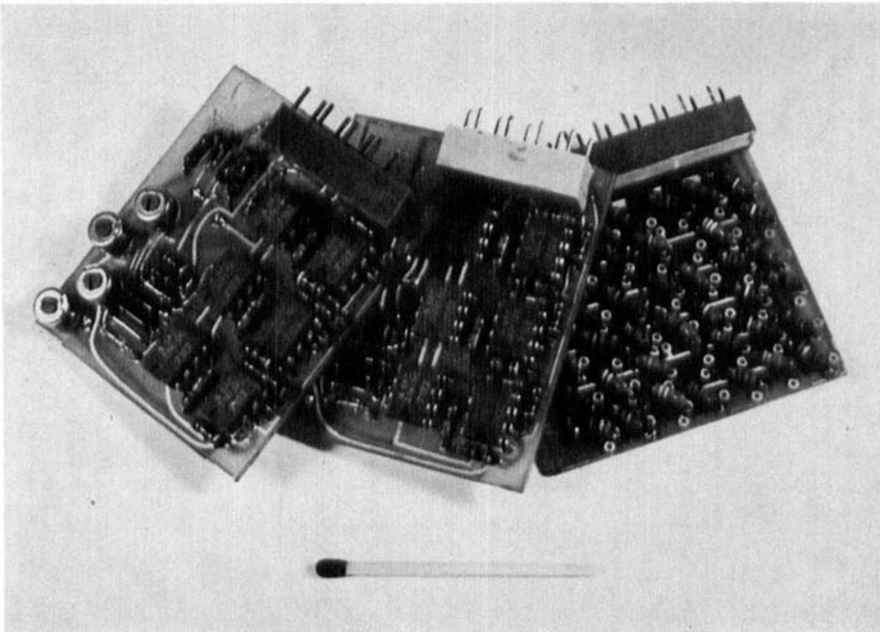

Figure 9. The miniaturized electronic circuit.

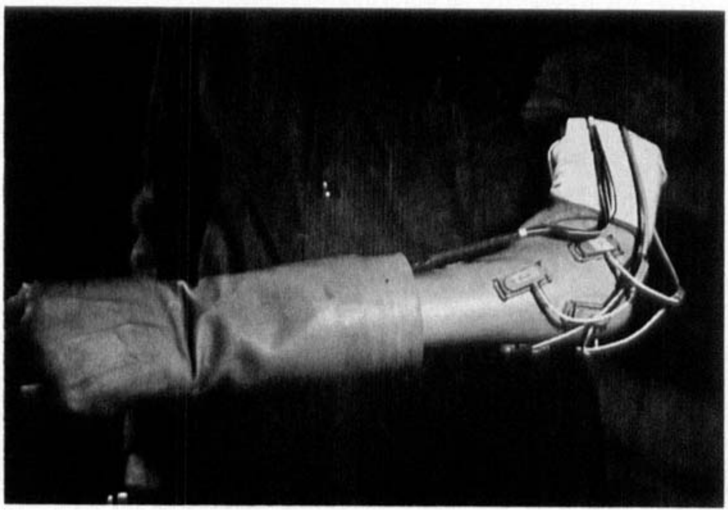

Figure 10. The multifunctional prosthesis applied.

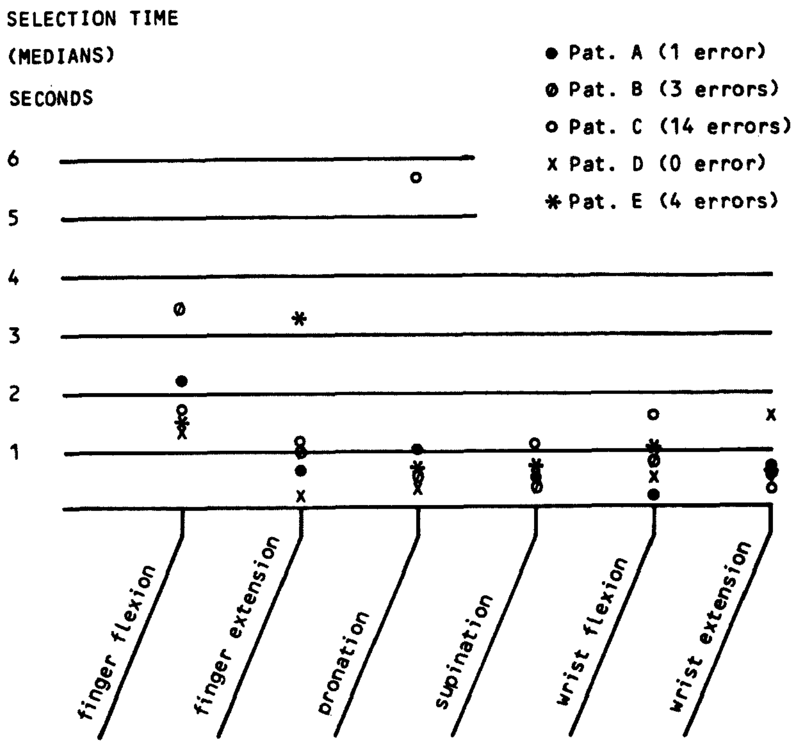

Figure 11. Medians of selection time for five patients in six movements.

However, in some tasks (Case B: FF; Case C: P; Case E: FF, FE) even the lower quartile was at several seconds containing a number of failures. New electrode positions would be needed to further separate the patterns in these cases, or training sessions so that better isolation could be learned. Technical failure made it impossible to evaluate the supination movement of Case D.

The performance of the subjects in this part of the investigation can be summarized as follows. Of the 30 movements (six moves in five patients), 14 could be performed at once and a further 11 had as good prospect with minimal readjustment or training. Thus 25 of the 30 movements had good possibilities for control with almost no training.

Part II

In the second part of the investigation, one patient (Case A) was fitted with the prosthesis as shown in Figure 10. The weighting factors were calculated on the basis of two different recordings of training data. After adjustment of the electronic network to the weights thus obtained, a test run was performed. Table 4 shows the results of this experiment. It is evident from this table and from Figure 12 that the selection times were even shorter in this part of the investigation than in Part I. Here, selection times for all six movements were shorter than one second, and all runs could thus be termed very good.

Table 4. Mean selection time (seconds) for the various movements using miniature hardware electronics.

Finger flexion	0.03
Finger extension	0.03
Pronation	0.02
Supination	0.30
Wrist flexion	0.18
Wrist extension	0.42

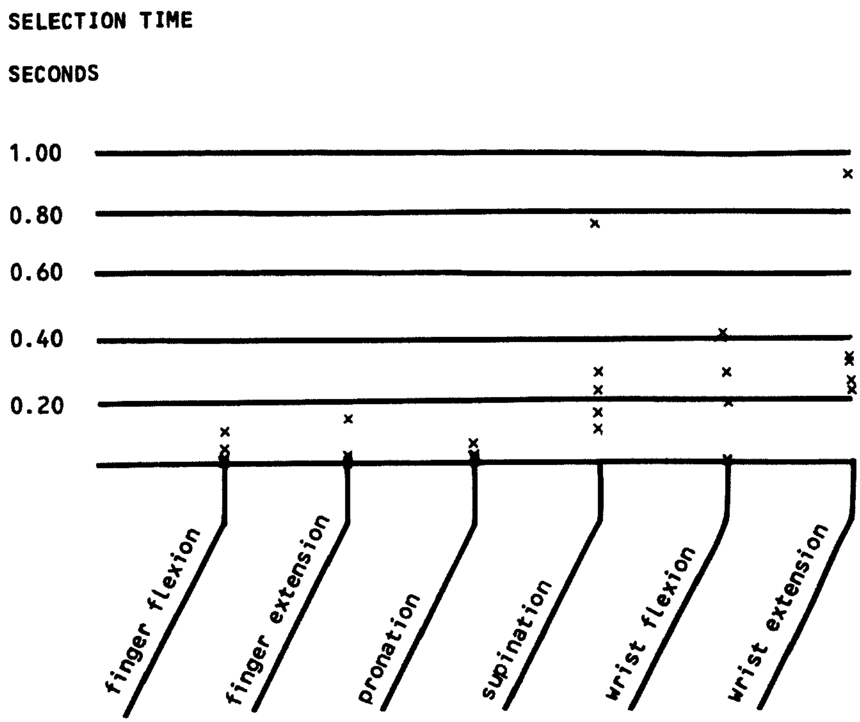

Figure 12. Selection times for one of the patients (Case A) using the electronic circuit of Figure 9. Note the expanded scale as compared to Figure 11.

Several observations of interest were made during the experiments with this patient. The effect of loading of the stump during bench control was tested (Lawrence et al. 1973) and it was found that only minor alterations in performance were present. Likewise, different arm positions with the prosthesis applied did not deteriorate the controllability significantly.

Evaluation of performance was made on different occasions with the same weighting factors. The performance was not affected by the patient's taking on and off his prosthesis, and thus the positioning of the electrodes once mounted in the socket was not crucial.

In Part II the system allowed the operator to perform simultaneous movements. Although this option has not been evaluated thoroughly, it was observed that the patient could instantly perform combinations of movements.

DISCUSSION

Efficient control of assistive devices with more than two motorized movements requires tedious and sometimes unacceptable training (Lyman et al. 1964). Consequently, the acceptance of the device and the functional benefit is unsatisfactory and not as good as hoped for. It is therefore desirable to employ the intact neuromuscular paths of the stump when using myoelectric control of prostheses. Such a system takes advantage of the natural myoelectric patterns, produced when the patient desires to operate a particular hand function. At the same time the patient gets a small but important conscious perception from the sensible skin when the stump muscles are performing active movements within the socket. It has recently been stated by Moberg (1972) that the sensible skin is the most important factor for conscious control of position, of passive and active motion and of the strength applied.

The technique of pattern recognition also allows more functions to be controlled than is possible using isolated myoelectric signals from individual muscles. By adjusting the electronic circuits to suit the individual amputee, in contrast to other methods, the differences due to individual trauma and the surgery performed are not crucial. This does not mean, however, that the surgical technique is unimportant. In our experience a careful myoplastic technique is very important in preserving the original myoelectric patterns by reducing atrophy and retraction of the muscles, and thus contributes to better possibilities for control of a prosthesis.

In the first part of the investigation, the placement of the electrodes was critical in a few positions. Thus, it was observed that displacements of 2–3 mm could be important. By gaining more experience we found that this problem diminished and in the second part of the experiment we observed no alterations of the performance due to electrode displacements when the patient replaced the socket on his stump.

Although six electrode pairs were applied to each patient in the two parts of this investigation, it was observed that good separation of recorded data was obtained using only four electrodes. This can be accomplished, for instance, by excluding an electrode that carries the same myoelectric signal levels for all movements.

The method used in the present investigation for classifying patterns is in a mathematical sense moderately powerful but easily realized in hardware electronics. If necessary, a more sophisticated method can be applied with somewhat improved recognition capability. It seems, however, that the present method is sufficient for its purpose.

As indicated in the results, the system was expanded to allow simultaneous movements. It was striking that this asset made the performance with the prosthetic hand look much more natural. It is also likely that this improved cosmesis will enhance the patient's functional gain and acceptance.

Our results indicate that control of a below-elbow multifunctional prosthesis is indeed possible using myoelectric signal patterns from the stump itself. It is possible to exclude a tedious training period that will demand more of the patient than he can muster physiologically or psychologically. An important finding was that loading of the stump did not significantly alter the recorded data (Lawrence et al. 1973). The performance with the prosthesis applied was also as good with the patient standing with his arm in various positions as it was in the sitting position. A simple functional test revealed that the patient was able, on the very first day, without any training to take advantage of all six prosthetic movements in different tasks.

However, the functional benefit of a sophisticated motorized hand prosthesis for the unilateral amputee cannot be evaluated until a series of applications have been performed. Ultimately, the most important factor for the acceptance of these devices is to provide them with some sort of feedback signal to the sensible skin receptors, for instance within the stump region.

The system employed here incorporated some instrumentation for signal amplification and processing. In the final system, now under development, this function will be efficiently taken care of in the very pick-up electrode. Only the pattern recognition electronics will, for the time being, be housed outside of the prosthesis.

The individual alignment of such a prosthesis system demands an advanced technical organization. A digital computer is necessary for on-line evaluation of the myoelectric signal patterns, simulation control and individual adjustments of the electronic circuits. To this end a centre with good medical and engineering basic resources must be provided for. The equipment required for the control can, however, be made quite simple (see Figure 9), allowing adequate miniaturization at moderate cost. The electronic hardware can easily be worn by the patient together with the battery necessary to power the prosthesis. With this exception the prosthesis is self-contained and applied to the patient with a conventional socket. The prosthetic service can be provided for by any skilled orthopaedic workshop used to apply commercially available myoelectric hands.

SUMMARY

In the control of multifunctional hand prostheses, the lack of control sites and the demand for tedious training present difficult problems. Myoelectric signal patterns from the stump muscles as evoked by movements of the phantom hand were found to be useful as control signals with the aid of computer techniques. The method was successfully applied on five male amputees, and will now be possible to apply in an extended clinical evaluation.

ACKNOWLEDGEMENTS

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