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POSSIBILITIES FOR CONTROL OF POWERED DEVICES BY MYOELECTRIC SIGNALS

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ABSTRACT. The possibility of controlling externally powered prostheses by myoelectric signals has been studied in Sweden during the last decade. A significant research program is being carried out on a collaborative basis within the SVEN-group, comprising engineers, ergonomists, physicians as well as psychologists. A sophisticated electrical hand prosthesis with several degrees of freedom has been developed and the first prototype has been applied to a patient. The evaluation of the hand is expected to take several years. The goal has been to design a complete forearm as a modular system so that for each individual the prosthesis can be given exactly the appropriate movements.

The extent of pathological EMG-modifications in the stump muscles of arm amputees has been studied in brisk and in prolonged, fatiguing muscle contractions as well. Investigation of the power spectrum of myoelectric signals has revealed statistically significant intramuscular, intermuscular and interindividual spectrum differences. The time dependence of the signal spectrum and thereby the fatigue and recovery in connection with sustained muscle contractions has been the object of study. Furthermore, the independence of the signal spectrum with respect to muscle contraction level has been investigated in normals and in arm amputees. Thus the control properties of the myoelectric signal can be characterized individually throughout the dynamic range by means of its power spectrum. Design of suitable signal processing filters which, after tuning, allow optimal prosthesis control is then possible.

Different types of electrodes have been evaluated and an implantable electrode has been developed and tested on volunteers with satisfactory results.

The number of available muscle control sites varies in each patient and cannot be generalized. These variations are due to the cause of amputation, the surgical procedure and differences in intellectual and psychological capacities of the patients. Only advanced systems analysis or direct application to patients can demonstrate the benefit of myoelectrically controlled devices.

The research within the area of externally powered orthoses is in the first stage of development but certain basic technical studies have been undertaken. A development and evaluation laboratory for advanced studies on patients is essential and is being planned.

During World War II there was a renewed interest in various types of prostheses and orthoses, made necessary due to the large numbers of traumatically handicapped soldiers surviving the battlefields. The standard method of controlling technical devices for the upper extremities is a mechanical control by means of gross body movements and cables attached to the harness. However, this type of mechanical control has many drawbacks. The force of the movements in, for instance, the prosthesis will be limited and the range of motion will be small. The necessary movements will also cause the patient discomfort and fatigue. Furthermore, the function of the prosthesis is limited, since the patient cannot perform several movements simultaneously without important parts of the body being bound to the control function in a very disturbing way.

The advanced technical development during recent decades have permitted the design of new types of prostheses and orthoses (4, 26). An external source of power, electric, hydraulic or pneumatic is supplied to the prosthesis whereby more degrees of freedom can be added. The possible number of degrees of freedom of the prosthesis and the power of the movements is thus reduced to a technical problem. Still, the patient must be able to control these externally powered prostheses in a natural way. This difficulty is further aggravated by complicated devices having many degrees of freedom. Each prosthesis movement as a rule demands one control site, i.e. a part of the body where we can pick up signals in order to control the device. The great problem has been to find a sufficient number of suitable control signals and process them so that we can achieve optimum control.

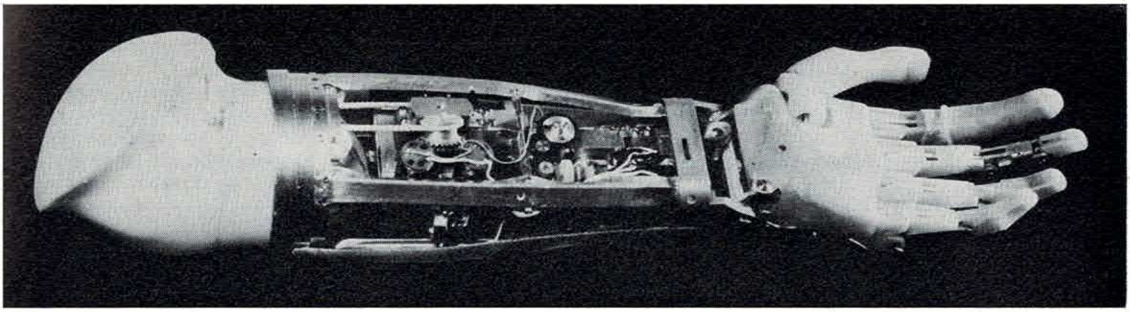

Fig. 1. The electrical prosthesis for the upper extremities developed by FOA in Sweden.

New types of prostheses and orthoses

It was shown 1952 that myoelectric signals could be used as control signals to obtain better control of an electric hand prosthesis (1). However, it took some years before this idea was further developed (2). This type of control will be experienced by the patient as more natural than the conventional mechanical (18). The myoelectric control will not demand the great and disturbing gross body movements which are necessary for mechanical control. Less muscular force is required and the risk of the patient becoming fatigued is reduced. A further important fact is that the patient will receive proprioceptive impulses from the muscles involved, giving a sensation of communication with the prosthesis (23, 24). It is favourable to utilize the remaining stump muscles as control sites for the amputees. These muscles do not have any physiological function and can be used for the control of the prosthesis exclusively. In the last decade a number of myoelectrically controlled hand prostheses have been introduced and many of them are commercially available.

The Russian electric hand was presented in 1960 and has been applied to at least one thousand patients and also sold on a licence basis for clinical application to Great Britain and Canada (17, 25). All these systems merely offer one function, prehension. The remaining extensor- and flexor muscles of the forearm stump are utilized as control sites. The fingers are stiff and no adaptive grip can be performed by the prosthetic hand.

In 1965, a special group for prosthetic research was established in Sweden, the SVEN-group, and a significant part of the Swedish research within this field has been done by this group. Several large institutions, having a solid background of basic knowledge in the different specialities, joined this group, i.e.: The Departments of Orthopaedics in Stockholm and Göteborg, the Department of Clinical Neurophysiology in Göteborg, the Kaiser Laboratory in København (medical electronics), the Division of Applied Electronics and the Division of Control Engineering within the Technical Universities in Göteborg and Stockholm respectively, the Swedish Institute of the Handicapped and FOA (The Swedish Research Institute of National Defence). The biggest project has been the development of an electric hand prosthesis with many degrees of freedom. FOA is working on the mechanical construction of this device. This hand has four active movements finger extension and flexion, thumb flexion and rotation, carpal flexion and extension and pronation–supination. An adaptive hand which allows the prosthesis to grip around the object has been the goal. Therefore the fingers are supplied with three joints; the power and the speed is proportional to the control signal. In Fig. 1 this prosthesis is shown. The first prototype of the prosthesis has just been applied to a patient who is now training under careful supervision.

The problems are greater with externally powered orthoses but in research laboratories electric as well as pneumatic systems have been applied to tetraplegics in USA (4, 26). Orthoses are technical devices applied to patients with impaired motor function of different types. The goal is to give these patients maximum independence, some daily activities and perhaps the possibility of managing easy work. In principle there are two different types of orthosis, light and heavy. Pneumatic or electric hand splints for in-

Table I. *EMG findings in different muscles of the amputation side, in relation to level of amputation*

Investigated muscles	Above elbow				Below elbow			
	Normal EMG	Lower motor-neuron lesion	Myopathy or rein-nervation	No. of muscles available for exam.	Normal EMG	Lower motor-neuron lesion	Myopathy or rein-nervation	No. of muscles available for exam.
M. deltoideus	6	1	—	7	23	—	—	23
M. biceps brachii	4	3	—	7	20	3	—	23
M. triceps	2	2	—	4	21	2	—	23
M. brachioradialis					18	2	1	21
M. extensor digitorum					13	8	1	22
M. flexor digitorum					15	6	—	21
Total	12	6	—	18	110	21	2	133

stance are light orthoses already commercially available. Evaluation and a certain development of these light orthoses is planned to take place at some Swedish institutions. The development of heavy motorized arm orthoses as well as of manipulators is still on a research stage. These devices are preferably electric as the patients concerned are wheelchair bound and already carrying an electric power source in the batteries of the chair. Basic technical research within the area of manipulators and arm orthoses has been carried out in Sweden during recent years (21). The intention is to develop further this area at some Swedish institutions in collaboration with institutions in the USA. When these heavy orthoses are ready for application and evaluation on patients the myoelectric control problems will be similar to those present in connection with sophisticated prostheses.

Up to the present we have studied several problems in connection with myoelectric control of prostheses. These studies have included clinical examination, conventional EMG, analysis of myoelectric power spectra and analysis of the muscle control ability (9). The attempt was to obtain detailed characterization of myoelectric signals in normal and arm amputated males. The characteristics of the myoelectric signal thus obtained, would increase the possibilities of optimizing the signal by suitable filters.

In principle, arms can be amputated at six functionally different levels. The level of amputation is decisive for the degree of loss of function and the resulting handicap. Statistics show that there is a significant predominance of below-elbow amputees in series representative of countries in peace (27, 10). The total number of arm amputees is estimated at 1500 patients in Sweden and the frequency assessed at 100 per annum (5). Most arm amputated patients are young men and the predominant cause of the operation is trauma, mostly due to industrial accidents. It is the high unilateral and bilateral arm amputees who are in the greatest need of multiple control sites to control prostheses with several degrees of freedom. However, a clinical examination of arm amputees revealed that stump muscles of above-elbow amputees are atrophic, retracted and even absent in several cases (9). Thus very few bioelectrical control sites are available in these patients. Another important clinical detail is the sensibility of the defect extremity of the amputees as well as of the paretic patients. Practical application of, i.e., hand prostheses, has shown that the mechanical irritation may cause sores if the sensibility of the stump is deficient. Paretic patients with deficient sensibility in the upper extremities will therefore probably be better off with a manipulator than with complicated orthoses applied to the arms. Lack of sensibility was the reason for treating a patient who had a complete injury of the brachial plexus by amputation above elbow, fusion of the humero-sculpular joint and application of a functional prosthesis. The sensibility must be considered in all cases of application of prostheses and orthoses.

Signal characterization

The neurophysiological basis for the myoelectric signal is the depolarization of the muscle endplate and the potential which then propagates along the muscle fibre initiating the contraction.

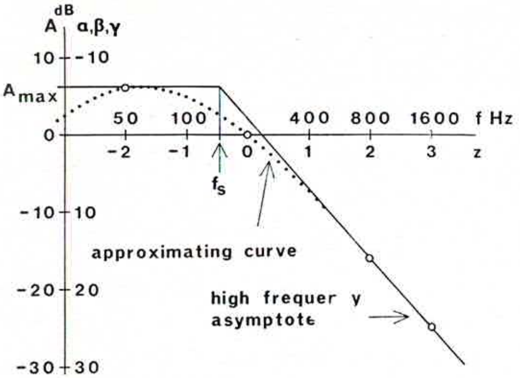

Fig. 2. Piece-wise linear model of the shape of the power spectrum. The average power spectrum of myoelectric signals from a particular muscle passes through the four points at 50, 200, 800 and 1600 Hz (open circles). For further information on the method see Herberts, Kaiser, Magnusson & Petersén (8).

The myopotentials can be detected by means of surface electrodes placed on the skin or electrodes placed within the muscle; in clinical practice usually needle electrodes. However, needle electrodes cannot be used in controlling prostheses and orthoses, due to the pain and the risk of infection. All myoelectric hand prostheses, which are commercially available to-day, are operated by means of surface electrodes. Nevertheless there are many problems connected with surface electrodes if we wish to utilize the information content of the myoelectric signal for optimal control of the prostheses (13).

The myoelectric signals picked up from different muscles in an amputated arm are often pathological according to conventional electromyography. The frequency and degree of these changes in various muscles of traumatically arm amputated men has been studied (22, 9). The changes were signs of lower motor neuron lesions in several muscles, principally within the region of the stump. The extent of the pathological changes depends on the level at which the nerve has been damaged in connection with the trauma or at the operation. Table I shows the distribution of the EMG-findings in one series of arm amputees (9). The peripheral neuron lesions were usually moderate but in some cases a pronounced lesion was found. It is interesting that large single potentials detected from an extremely small muscle have proved satisfactory as control signals in practical application of electric hand prostheses (9).

Stump muscles which are not attached distally at the operation will lose their contraction ability because of retraction and atrophy (28). In one series of above-elbow amputees there were retraction and atrophy and pathological myoelectric signals in 50% of the stump muscles (9). These findings underline the necessity of a correct operation technique. The orthopaedic surgeons must adjust themselves to the new technical devices which are now available. A myoplastic amputation procedure is necessary in order to increase the number of suitable control sites.

An essential point in myoelectric control of externally powered prostheses and orthoses is the dynamic range of the control. In order to achieve proportional control instead of on–off control we need many well-defined separate levels of the output of the myoelectric signal. Large dynamic output range requires that full contraction range of the control muscle is utilized. However, even a slight increase of the muscle contraction causes the myoelectric signal to take on the character of random noise. The rectified average of the signal is the parameter which is utilized in the signal processing for the control of the prosthesis. The character of random noise of the myoelectric signal, however, will make the average of the signal very unstable. The noise character of the signal varies within its power spectrum and thus the control properties of the signal can be characterized by means of the signal power spectrum. Therefore, the power spectrum of the myoelectric signal was studied in normal and arm amputated males by the method described by Kaiser & Petersén (14, 15). The method is based on transmission of the myoelectric signal through four octave bandpass filters centered at 50 Hz, 200 Hz, 800 Hz and 1600 Hz, respectively. The four filter outputs are presented using the voltage from the 200 Hz filter as a reference. The three ratios obtained provide a measure of the shape of the power spectrum (8). Fig. 2 shows the parameters used to give a simple description of power spectrum shape.

In an extensive investigation of several muscles the existence of statistically significant intramuscular, intermuscular and interindividual power spectrum differences was demonstrated. Also, stump muscles in arm amputees and muscles

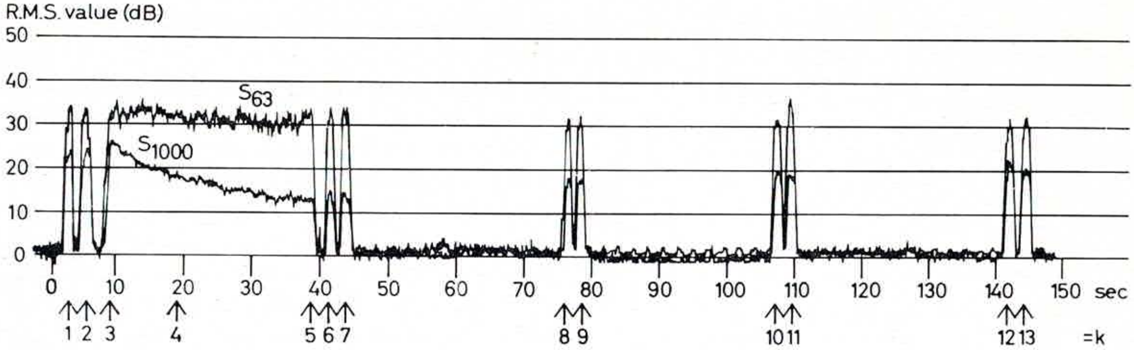

Fig. 3. Myoelectric signal activity in the 63 Hz band and the 1000 Hz band during a maximum contraction followed by a relaxation period. The recovery is studied from the analysis of brisk contractions and compared to the initial state. From Kadefors, Kaiser & Petersén (12), by permission.

showing signs of lower motor neuron lesion had significantly different power spectra in comparison with that of corresponding normal muscles. This discovery underlines the necessity of processing the myoelectric signals in suitable filters for each control site in every patient in order to achieve optimum control of the prosthesis (8).

There is another reason for a careful individual alignment of these filters. During a sustained, maximum muscle contraction, modifications of the power spectrum appear. Fig. 3 shows the steep fall of the signal activity within high frequency ranges during a maximum contraction for 30 sec and the recovery within 60–90 sec of rest. This is the normal pattern in human extremity muscles (12). In arm amputees, however, these changes will not appear in about 50%, probably due to a reduced contraction ability with stump muscles. Thus, the blood flow will not be affected enough to give these power spectrum modifications (19). These modifications are of such a magnitude that they should be taken into account in the processing of the control signal. Similar power spectrum modifications will probably be found in future investigations of myoelectric signals in patients with different types of paresis.

Electrodes

As mentioned above there are many problems with surface electrodes and they do not provide a myoelectric signal reliable enough for proportional control of terminal devices. Irritation of the skin can be very troublesome, electrode movements cause potential errors, there is a bad signal-to-noise ratio and a low amount of high frequency power in the spectrum. These problems associated with surface electrodes, have motivated research regarding the possibility of detecting myoelectric potentials by means of electrodes placed within the body. One solution that has been studied is electrodes supplied with an implantable transmitter for wireless transmission of myoelectric potentials through the skin to a receiver in the prosthesis. The implanted transmitter is electromagnetically coupled to an external high frequency energy source. The myoelectric potentials modulate the frequency of oscillation of the implanted transmitter. One important point is that no batteries are implanted. Such electrodes have been developed in the USA (16) and independently by Hirsch, Kaiser & Petersén who performed the first implantation in a human being (11). Fig. 4 shows a refined type of this electrode,

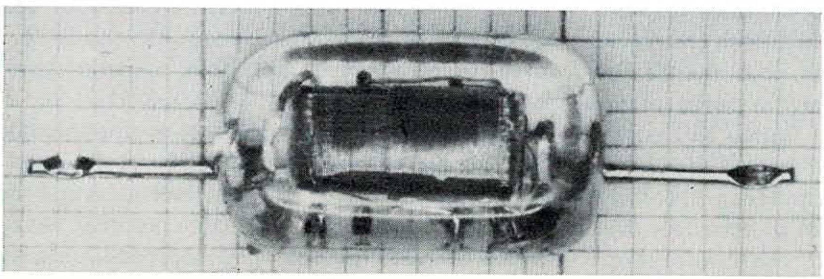

Fig. 4. The implantable electrode embedded in a plastic material (Epoxy), the gold wires serve as tissue terminals. The overall size is 5 × 11 × 4 mm.

which is embedded in Epoxy, a plastic material with excellent mechanical, electrical and chemical stability and low toxicity. The technical and clinical aspects of the electrodes have been extensively reported (7).

During recent years seven electrodes have been implanted in five volunteers, three normal subjects and two below-elbow amputees. The operative procedures were short and performed under local anaesthesia and the patients were not inconvenienced by having the electrodes implanted. At removal, a tolerable reaction was found in the surrounding tissues. Around the electrodes there was a capsule which showed only slight inflammatory reaction and some foreign body giant cells. The evaluation showed that the transmitters are capable of supplying high-quality signals over at least a year. The signals were reliable and reproducible over long periods regarding shape and power spectrum. Thus it seems clear that no progressive shunting effect occurs as a result of the encapsulation of the electrodes. The limiting factor so far has been fatigue-breakdown of the gold signal electrodes, but there is hope that further developments can solve this problem. This failure can thus be overcome by using thin and flexible wires for the tissue connection. Such a modified electrode has been developed and recently implanted in a volunteer with good results. The implantable electrodes are now being further developed in order to avoid mechanical effects on the signal electrodes outside the protective plastic material. This can be achieved by choosing an optimized electrode configuration and by reducing the external portion of the electrodes. The signal electrodes may also be completely removed. In such a case the myoelectric potentials are picked up by capacitive coupling. This latter solution requires more sophisticated and sensitive elements in the electronic circuit. Such elements, MOS capacitors with a special oxide layer, are under development in Göteborg.

Control ability and coordination of control sites

When a muscle is utilized for the control of prostheses and orthoses the fact that anatomical and physiological conditions differ between various muscles is of importance. The distal extremity muscles often have a larger degree of innervation (3) and their control is more appropriate, compared with proximal muscles. This probably causes differences in speed, precision and fatiguability. Arm amputees and paralysed patients will have special problems in performing well quantified muscle contractions within the handicapped extremities. Control ability with several muscles has been investigated in normal and arm amputated males by means of a specially designed electro-mechanical apparatus. The purpose was to get an idea of the ability to manoeuvre an apparatus using myoelectric signals. The technical description or the test instrument and method has been extensively covered before (6, 9).

The results showed that the trapezoid muscle, which participates in gross activities, could not perform such rapid and precise movements as more distal muscles within the upper extremities. The moderate pathological changes of the myoelectric signals, present in muscles of several amputees, did not affect the controllability. Most stump muscles are thus cerebrally well controlled and can be used for on–off control of the prosthesis. The dynamic range of these signals is, however, limited in the stump muscles of amputees. The possibilities of achieving good proportional control are therefore reduced and this also applies to handicapped patients, if paralysed muscles are used for control of externally powered orthoses. Arm amputees also have greater difficulty manoeuvring an apparatus with proximal extremity muscles than do normal subjects. Less daily activity and training can partly explain this, but there is also a changed sensory information when part of an extremity is missing. This is important since tests with man-machine systems are generally performed on normal subjects and these results are not relevant for amputees with respect to certain muscles.

Further investigations using man-machine systems or by means of direct clinical application of devices to patients are necessary. Complicated prostheses and orthoses will demand a high controllability, coordination of control sites and adaptability of the patient to the control task. These tests must involve much training and it will probably be advantageous to use patterns or movements already present in the body.

One of the primary problems arising in the development of myoelectric control systems is, no doubt, the lack of suitable control sites. One solution to this problem is an improved surgical technique, which will prevent retraction and atrophy of stump muscles, in order to increase the number of control sites. With correct surgical technique it should be possible to get at least four separate control sites in the stumps of most below-elbow amputees. It will not be possible, however, in very short stumps and after severe traumas. Another solution is offered by extremely careful investigation of the amputation stump, so-called myotopography (20). By means of this mapping of below-stump muscles as many as six possible control sites have been found in some patients.

A series of male arm amputees, with myoelectric hand prostheses applied, have been trained and followed during recent years. It is obvious that the patients during the first months will increase their controllability considerably. Thus, it can be concluded that all myoelectric control involves training, and the more complex the control task, the longer the training period. A very complicated prosthesis may, however, require more in terms of information from the patient than is physiologically or psychologically possible for him to mobilize.

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