WHY MYOELECTRIC CONTROL IS SO DIFFICULT

D. Radonjić and C. Long, II

Summary

Begining with the thesis that myoelectric control has proven difficult to use clinically and experimentally, this paper discusses the possible neurophysiologic explanations for the problems which are met. Considerations of the conscious and unconscious nature of normal muscle control, the participation of physiologic feedback mechanisms, the basis of "single motor unit control", the nature of human control of simple and complex machines, and the phenomena of motor retraining in muscle transfer are all included in a general hypothesis of myolectric control. Suggestions are made to circumvent the observed difficulties.

For the past five years the Ampersand Research Group for Medical Engineering at Highland View Hospital has used myolectric control in clinical and experimental orthotic applications. These applications have included single channel and multichannel devices, simple and complex; the devices have used various types of output actuators, ranging from electrical stimulation systems to multiaxis orthoses. All of the myoelectric applications and all of the myoelectric systems had one point in common: they were diffucult to operate, the difficulty increasing in proportion to the complexity of the system being operated. It is the purpose of this paper to explain in neurophysiologic terms some of the possible causes for the difficulties we have encountered. We will also suggest a possible solution as it applies especially to multiaxis devices. Most of the possible problems and solutions are typified in the coordinate-controlled arm-hand complex; control of this complex will serve as the basis for this paper.

The necessary theoretical concept for introducing myoelectric control was provided by two well established facts in electromyography: that electrical activity of the muscle can be voluntarily initiated, maintained and ended, and that there is a fairly constant relationship between muscle tension during an isometric contraction, and voltage of a rectified and integrated EMG [5]. The concept, in its general form, that information can be transmitted from the central nervous system by means of EMG signals to another functional system has determined theoretical as well as practical work in the field of myoelectric control.

A block diagram in Figure 1 demonstrates this concept in the form favored by the workers in this field.

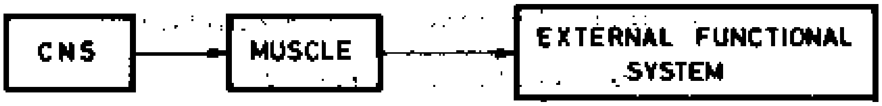

Fig. 1.

The first part of the relationship shown in the block diagram has not been separately analyzed, and the CNS-muscle complex has been reduced to the concept of myoelectric control site. The practical needs of orthotics and prosthetics have directed research mainly toward problem represented by the right side of the block diagram (muscle-external functional system). A great deal of attention has been paid to physiological as well as technological aspects of electrical phenomena produced by muscle contraction, and to the relationship between EMG and the voluntary controllable aspects of muscle activity [2], [6], [12].

The essence of all myolectrical control systems is that they are designed to reproduce a function of a muscle outside of the human body. The term muscle function transfer might be quite pertinent to describe this procedure. The actuator acts as a representative and eventually as an amplifier of activity of the control muscle. The remaining units of the myoelectric system serve as a communication system between the control muscle and actuator. The analogy with a muscle transfer can be drawn further. In a recently published paper on myoelectric control [11] some requirements for a myoelectric control site are similar to those for an anatomical muscle transfer. For example, the control muscle is no longer expected to contract according to its normal pattern of innervation and, in addition, should obtain a new function.

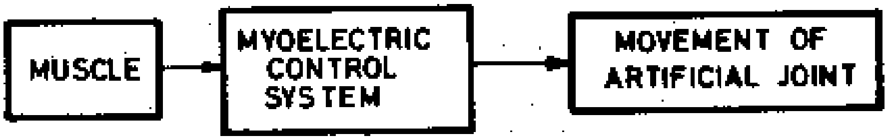

Fig. 2.

The block diagram in Figure 2 demonstrates the basic idea of *muscle function transfer* underlying all known myoelectric control systems. The design of a single channel of myoelectric control tells practically the whole story, for multichannel systems are basically a collection of single channels. It remains for a human being to integrate such a collection of separate functions into a goal-directed action. In the development of the technology of myoelectric control, considerations of integration have been replaced by considerations of control site. Since it has been found that normal subjects are capable of exercising voluntary control over contraction of as many as 5 or 6 skeletal muscles simultaneously and independently, it has been assumed that the human being can control multichannel myoelectric devices. Additionally, the more severe the loss of motor function is, the fewer myoelectric control sites, there are available, but the more functions an assistive device must have. In such a situation the solution has been sought in splitting a single muscle into several control sites by making use of single motor unit action potentials.

It is apparent from this brief analysis that physiology of the muscle contraction process itself has played the decisive role in development of ideas and principles underlying MEC, while some more general aspects of physiology of motor activity have had little or no influence at all on the current work in this field. Because the control of assistive devices belongs to the category of so-called manipulative activities, it is likely that some aspects of physiology of motor activity might be of decisive influence on further development of MEC. We shall try here to consider briefly some essential features of coordination of voluntary movement as well as their possible implications on myoelectric control.

It will be pertinent to start considering coordination of voluntary movements with Duchenne de Boulogne's statement that "an isolated muscle action does not exist in nature" [3]. Every voluntary motor act, either movement or maintainance of position, is a result of cooperative active action of a number of muscles. During this cooperative action muscle behave according to a pattern of innervation underlying each motor act. The patterning of voluntary movements is a function of a number of neuronal systems from segmental level to the motor cortex with the cortical mechanisms playing a dominant role. Due to the great complexity of cortical organization the patterning action is extremely flexible and the spatio-temporal pattern of muscular activity is precisely adjusted to the initial posture of the moving segments and to the resisting forces. However, this precise and flexible patterning action is based on certain innate mechanisms involved in fundamental coordination of elementary voluntary motor acts. Muscle behavior within these elementary motor patterns can vary greatly, but fundamental relationships are constant.

Figure 3 demonstrates the behavior of six wrist muscles during extension of the fingers. Although none of them is a prime mover during motion, they act simultaneously with the extensor digitorum as a part of a pre-established pattern of innervation. Apart from the fact that activities of the wrist muscles are necessary to achieve precise coordination of finger movements, their action is predetermined and inevitable. An example from our study of tendon transfer at the wrist and hand ilustrates this statement (Fig. 4). The EMG traces show the activity of the right and left flexor carpi radialis of the same subject. The distal tendon of the right flexor carpi radialis was transferred to oppose the thumb three years before the examination took place. The left hand was normal. The motion recorded was opening of the hand. As it can be seen the left flexor carpi radialis behaved in the same way as the normal muscle did, although in the

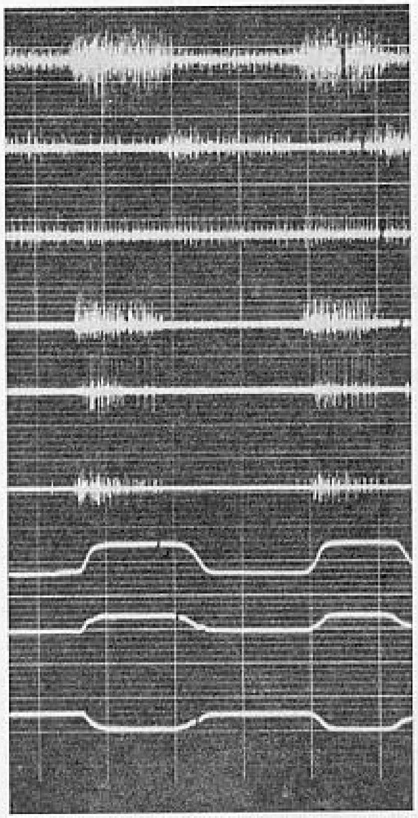

Fig. 3. Behavior of six wrist muscles during finger extension. From the top downward the tracings indicate: electromyograms of extensor carpi ulnaris, extensor carpi radialis brevis, extensor carpi radialis longus, flexor carpi radialis, palmaris longus, flexor carpi ulnaris; electrogoniograms (flexion down, extension up) of proximal interphalangeal joint, metacarpophalangeal joint (of middle finger), and wrist joint.

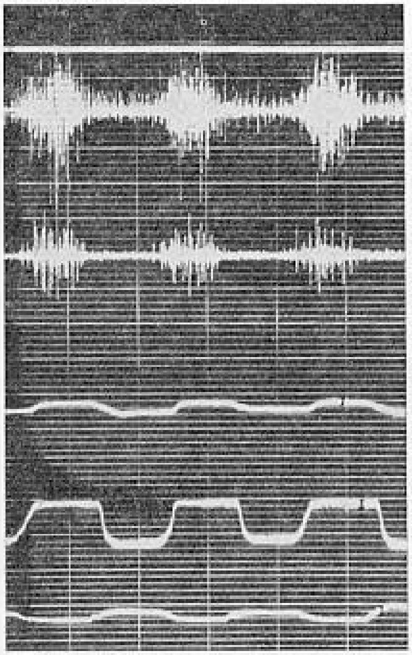

Fig. 4. Electromyographic behavior of normal and transferred flexor carpi radialis muscles in a single subject. From the top downward, the tracings show EMG of right flexor carpi radialis (transferred to first phalanx of thumb for opposition), left flexor carpi radialis (not transferred); electrogoniograms of right middle finger proximal interphalangeal joint and metacarpophalangeal joint, and wrist.

new anatomical arrangement its contraction was useless for this particular motion. After three years of training, the pattern of innervation was unchanged. The significance of this finding is clear: the pattern of innervation underlying a motion cannot easily be changed at will. This along with the fact that voluntary control of motor activity deals with movements, and not with muscle contraction, has important implications for myoelectric control.

It is apparent that a so-called control muscle can act only as a part of complex patterns of innervation underlying movements in the corresponding joint. Therefore, as in any other kind of manipulative activity, the basis of MEC is a motion. From a physiological point of view the only important difference is that MEC deals with action potentials produced by a "control muscle" acting usually as a prime mover, instead of with the "natural effects" of a motor act. However, the voluntary control of skilled movements involved in manipulative activities is principally the control of position. In terms of muscular activity, this implies that muscles should automatically adjust their lengths according to the position defined by voluntary command. The tension produced by the muscle during this adjustment depends upon a variety of conditions offered to the motion, and it is taken care of by mechanisms below the level of voluntary control. The major feedback loops of tension control are contained within subconscious nervous mechanisms, which control a muscular contraction. Furthermore, because muscular receptors do not contribute substantially to conscious proprioception [7], there is no appropriate feedback for the precise conscious control of muscular tension.

This makes muscle tension the least convenient aspect of the motor act to be used as a control signal for manipulative purposes; yet, the myoelectric control signal itself is known to be most related to muscle tension. Obviously, then, contact is being made at an inappropriate part of the motor system. The absence of appropriate, conscious, proprioceptive feedback makes the user of a MEC system rely mostly on visual information. This is a very inefficient situation, so the subjects trained to use myoelectric control keep trying to find some kind of substitute for proprioceptive feedback. They usually choose a certain position and stabilize it by action of the "control muscle" and its antagonist until desired muscular tension is achieved. When a motion is carried out against external resistance, then the task becomes simpler, since "pressure sense" provides fairly accurate feedback of muscular tension.

One more problem remains to be mentioned here. On the basis of Basmajian's findings and interpretation, it is suggested that activities of single motor units are directly subjected to the conscious voluntary control [1]. This is a misinterpretation of physiological mechanisms involved in motor control. The spatio-temporal pattern of recruitment of motor units underlying a voluntary movement is fairly constant for the same movement, but it is never identical in different voluntary movements [9]. Therefore, it is no wonder that when we initiate different voluntary movements, different motor units will appear first. But, again, it is movement and pattern of recruitment of motor units implicated in a voluntary command that is controlled, and not an activity of the particular motor unit.

At this point it is obvious that the idea of using a muscle independently of its physiological pattern of innervation cannot work. Furthermore, the idea of muscle function transfer, in the light of physiological mechanisms of motor control, means nothing but contact with the complex voluntary motor act at the level of the muscular tension-controlling mechanisms.

Contrary to tension control, the position-controlling system acts as a closed loop servo system at the conscious level of motor control. The major feedback of this system is the conscious proprioception based mainly on information from the joint receptors. In other words, the position-controlling system has advantages of the higher level of sensory as well as of motor integration. The significance of this arrangement becomes clear in that any control system of externally powered assistive devices should function, first of all, as a position-controlling system, and therefore must include position feedback. The myoelectric control signal does not carry information on the position, and therefore cannot stand a comparison with position of the moving segment as a control signal for externally powered assistive devices.

When complex motor coordination and the motor learning process are involved, as is the case in the clinical application of multichannel MEC, then the appropriate sensorimotor relations are fundamental, and the lack of adequate proprioceptive regulation of motor activity is an immense disadvantage. It is a well-known physiological fact that proprioception plays a decisive role in acquisition of motor skills and the learning process. It is important during the initial phase of learning, which involves the higher level of motor control, to set up a new, complex, purposeful motor act from more simple inborn patterns of coordination. Proprioception is also necessary for automation of any new pattern of action, without which it cannot become a part of the individual's motor repertory. In manipulative activities automation decreases the degree of participation of the higher controlling systems as well as the visual feedback in the motor act. Automation of a skilled motor act appears as a result of linking of each sequence in perfect kinetic melody, which cannot be achieved without participation of proprioceptive feedback [8], [10].

The discussion of MEC of multi-functional orthotic and prosthetic systems requires attention to some fundamental problems concerning the nature of these devices. Although words such as hand, arm, and limb are in current usage to designate orthotic and prosthetic devices, they should not be mistaken for anything other than the tools designed to match the simple manipulative abilities of handicapped persons. In other words, they are tools for those who do not have mechanical and functional advantages of the distal segments of the human extremities. The loss of a hand, for instance, makes useless the nervous mechanisms of command which evokes its action. What is then left are the proximal segments, which have limited functional capacity of finely coordinated manipulative activities.

For our purpose it will be interesting to consider two types of tools and consequently two kinds of manipulative activities.

Simple mechanical instruments such as a pencil, hammer, or knife have simple input-output relationships. Their outputs reproduce practically all effects of the controlling motion, thereby preserving all the advantages of proprioceptive feedback. This type of tool extends the hand, providing a convenient output for its action, and becoming a functional part of the segment. Take, for example, the pencil; it transmits directly on the paper the action of the hand; the hand acts at the tip of the pencil. That is why the manipulation of this type of tool is as automated as control of the movement itself. This implies that we do not have to think how to draw a line with a pencil any more than how to close the hand. This is a crucial point because only this type of manipulative activity has this feature which is typical of control of skilled movements. Since the task of performing a motor act is taken care of by mechanisms below a conscious level, voluntary control can concentrate on what to do, where, and when to do it, and not have to be bothered with how to do it.

In contradistinction to the type of tools just described, complex machines have several components which must be controlled separately and adjusted to each other in order to obtain an output typical of the given machine. When, for instance, a position is to be controlled, then each degree of freedom requires a separate channel of communication and a separate manipulative action. The manipulation of each component of complex input can be automated to a great extent, but integration of all components into meaningful action at output requires a continuous mental effort and visual feedback. Here the task of voluntary control is clearly to tell the device how to operate, as opposed to the first class of manipulative devices which already know how to operate since they are extensions of the body. The major manipulative effort takes place at the input of the complex machine; consequently the output of a complex machine must be simple and stereotyped action. Since the purpose of orthotic and prosthetic devices is to enable the patient to manipulate other objects, rather than the devices themselves, they should reproduce at the output as much of the manipulative abilities acting at the input as possible. This only happens when an assistive device functions in a similar way to the first type of devices we have considered here, such as a pencil in writing or the hook in a below-elbow amputee. Complex assistive devices require all manipulative capacity available to operate the device alone, and it would appear that the patient instead of working with it, would work on it.

Whenever a clinical application of multichannel myoelectric control has been considered, the number of control sites available has been a matter of great concern. Behind this concern about the number of control sites are two implications of the basic concept of myoelectric control: (1) one myolectric control site can control one functional component of a multi-functional system at a time; (2) it is expected that integration of separate components into a goal-directed act should be possible as long as enough control sites are available.

Unfortunately, when the matter comes to the clinical application it appears that this simple concept does not work. It does not work either on patients or on normal subjects. It is not lack of adequate control sites that is the main problem of myoelectric control. Our experiments have shown that normal subjects, for example, can exercise voluntary control over at least four motions simultaneously. The reason MEC of multifunctional assistive devices is so difficult lies in the basic concept of MEC. As we have pointed out before, it is implicit in the concept of MEC that each of the components of a multifunctional system be controlled separately. It is therefore obvious that prosthetic and orthotic devices must be manipulated as complex machines, and with the subsequent disadvantage when the task of voluntary control is to tell the device how to operate. Further; more, the uselessness of physiological proprioceptive feedback at the level of the motor system from which the myolectric control signal comes makes necessary participation of visual feedback even in functioning of a single channel of MEC. The result is that the single component of multi-functional system cannot be manipulated as automatically as in a normal motor act. This adds another problem to the task of integration of separate components into meaningful action at the output of multi-functional devices. In addition, the proximal segments of the human body, which are all that is available in most patients, are not very adequate tor finely coordinated motor activities. Finally, the continuous mental effort and permanent need for visual feedback overloads the human system of motor control. It should be pointed out that the main problem is not in the patient's inability to control a myoelectric multi-functional system. The point is that such a system absorbs all manipulative capacities of the patient; as a result, the benefits he can obtain from the system cannot stand a comparison with the tremendous effort required to control it.

We may conclude that the clinical value of multichannel myoelectric control is dubious, while the single channel myoelectric control might have some, but, limited, clinical value. Its clinical application should be considered when there is not a motion available for manipulative purposes or when muscle contraction does not produce appreciable motor effect due either to an amputation, weakness od the normal anatomo-physiologic relationships (e.g. platysma). However, even the stump muscles are unsuitable when their motor control is impaired by the amputation [4].

Although myoelectric control is fraught with problems, the general idea that motor function can be transmitted outside of the human body by means of an electronic communication system is likely to be productive in another clinical application of control theory. If, instead of transmitting elecromyographic signals to the orthotic logic system, one transmits the position of a moving segment, many of the objections to myoelectric control are circumvented and the benefits of the electronic logic are capitalized upon. The effect of this system is similar to the pencil in the hand; all of the control problems are worked out in connection with conscious feedback control in the motion of the controlling segment; all of the electronic logic that connects the moving part to the orthotic device is "subconscious". The orthotic device precisely mirrors the movements produced by the central nervous system without the need for new training of the nervous system.

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