MYOELECTRIC CONTROL OF PROSTHESES AND ORTHOSES

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INTRODUCTION

A myoelectric control system is one in which operation of the output apparatus is controlled by the electric potentials which accompany the contraction of one or more muscles. In contrast to a myoelectric control system, all other systems are controlled by actual physical motion of the body. The advantages of myoelectric control over other control methods are several, their respective importance being determined chiefly by the specific application.

Myoelectric control may be inherently superior to manual control because it is more direct. The normal or "manual" coupling between a human operator and a controlled machine typically uses physical movement of a limb to move a lever to operate a transducer to produce an electric control signal. In a myoelectric control system, this electric control signal is derived directly from the action of the controlling muscle.

A myoelectric control system is not disturbed by physical movement of the user, provided that there is no contraction of the "control" muscles, and this may be important under certain conditions. For instance, it has been proposed that myoelectric control may be used in "servo-restraint" systems to assist pilots during conditions of severe turbulence. Physical motion sensors, in such systems, would be unable to distinguish between environmental disturbances and voluntary limb movements.

The primary advantage of a myoelectric control system for the amputee or paralytic is, however, the fact that it does not require any physical motion of the body for its operation. Even at the present time it is practical to utilize, for control purposes, myoelectric potentials resulting from muscle activity which is imperceptible by any other means. There is reason to assume that myoelectric systems will become more sensitive in the future. As a consequence of their sensitivity, myoelectric systems may employ the output of very small muscle remnants, in the case of amputation, or of the remaining one or two motor units in an almost totally paralyzed muscle. Alternatively, should the controlling muscle be capable of normal contraction, the effort required to use it for myoelectric control may be made much less than the corresponding effort in a "normal" control system, thus greatly reducing patient fatigue. Finally, it is sometimes easier to harness the electrical than the mechanical output of a muscle.

Myoelectric control systems have been discussed and studied for a considerable period of time, and it is interesting to trace the early development of this concept in America (1), England (2), and Russia (3, 4). In retrospect, it is too easy to be critical of the early investigators who concluded that myoelectric control, while perhaps possible, was not practical. The practicality of any control system is dependent upon the technological level of the society in which it is proposed. Moreover, the level of technology available to research personnel working with patient-oriented problems lags significantly behind that available to individuals engaged, for instance, in the missile industry. In any event, during the period since 1960 the possibility of myoelectric control has received considerable attention, and the related technologies, particularly in electronic components production, have advanced sufficiently to make possible significant progress.

The purpose of this paper is to describe some of the important myoelectric control systems which are now in existence and which have been fitted to patients, at least for clinical evaluation. Certain basic limitations of myoelectric control systems will become apparent in this process, and these will be discussed in some detail together with the trends in research at the present time. No attempt will be made, except peripherally, to describe or comment upon the externally powered prostheses which are being controlled by the myoelectric systems. It is, in the author's opinion, important to differentiate between the control system and the controlled appliance if any objective evaluation of the control system is to be achieved.

PRESENT MYOELECTRIC SYSTEMS

Russian

The only myoelectric control system which is now in wide use by patients outside the laboratory is incorporated in a prosthesis developed in Russia for below-elbow amputees. The research which led to the development of this control system began, at the Central Prosthetics Research Institute, Moscow, in 1957. By 1959 (5), a laboratory model of a myoelectric control system, driving a stepping motor, had been constructed. By 1960, the stepping motor had been replaced by a permanent-magnet d.c. motor, and the new myoelectric control system incorporated within a below-elbow prosthesis (6). This control system, which was demonstrated at the First International Congress of the International Federation of Automatic Control in Moscow in 1960 (4), apparently incorporated proportional control of the armature current of the motor, although this point was not emphasized by the designers.

In a paper published in 1963 (7), a history of the development of the control circuit is given. Included in that paper is a brief comment to the effect that the output transistors were replaced by electromagnetic relays, resulting in much higher stability and reliability. This, of course, represents a change from proportional to on-off control. The final system described by Polyan and Esov (7) is, to the best of our knowledge, the control system incorporated in the myoelectrically controlled prosthesis now in wide use in Russia. A concise description of this prosthesis, together with comments on the design philosophy, has been published recently by Popov (8). A sketch of the prosthesis, showing the control system configuration, is given in Figure 1, and the control system block diagram is shown in Figure 4.

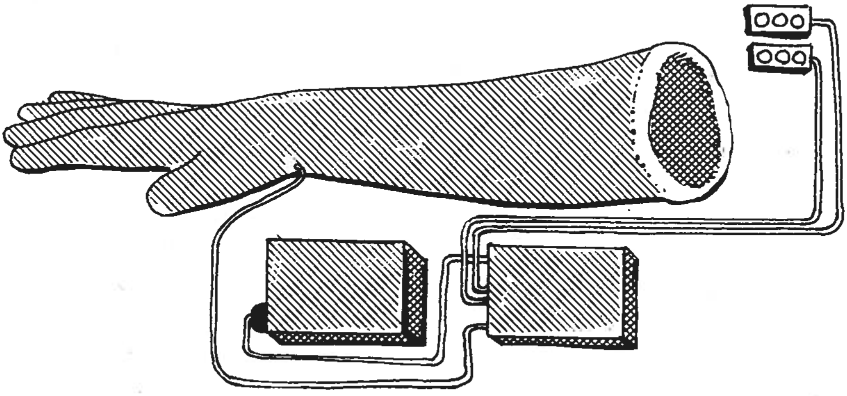

FIGURE 1.—Russian myoelectric control system (prosthesis sketched for illustration only).

The control system requires the use of two muscles to control, respectively, opening and closing of the terminal device. Surface electrodes are employed, and after amplification the rectified and smoothed myoelectric signal is used to operate relays which in turn control the motor.

It is difficult to obtain an objective evaluation of the myoelectric control system described above. It is understood (9) that the prosthesis has now been fitted to some 1000 below-elbow emputees in Russia, so it is evident that the system works. Licensing agreements have been arranged both in England and in Canada for the import and/or production of the Russian prosthesis. The Canadian license was obtained in 1964 by the Rehabilitation Institute of Montreal, and that Institute has purchased and fitted a number of the prostheses. They have not been made available to other institutions, either in Canada or the United States, for study or evaluation.

In a paper read at the Assembly of the American Academy of Physical Medicine and Rehabilitation in August of 1965 (10), the Montreal group reported experiencing difficulty with low reliability of electronic components in the Russian prosthesis and with intermittent electrode contact, as well as confusion of the subject under conditions where both controlling muscles were contracted simultaneously. In that paper, as in the Russian publications, stress is laid upon the utilization of a phantom limb concept for subject training, and the advantage of a system in which there is a high correlation between the original function of the controlling muscles and their use in the myoelectric system. While the paper closes with predictions of six-channel control, no attempt is made to compare, for example, myoelectric control with other alternatives or to compare the Russian system with other myoelectric systems.

Of the British experience with the Russian arm, even less evaluation is available. In a recent publication (11), McKenzie states "it is too early yet to form an opinion as to the value of myoelectric systems in general or of the Russian arm in particular." He does point out that difficulty has been experienced in training patients to produce isolated contraction of the two muscles required to control this prosthesis, mentioning again the confusion which arises when both muscles contract simultaneously. He concludes with a very favorable reference to British myoelectric systems incorporating proportional control.

It is understood that a group of German prosthetics experts, who visited Moscow in 1964, concluded that the Russian "Bioelectric Prosthesis" was in no way superior to the German pneumatic prosthesis (12).

The problem of objectivity is apparent. The author has been unable, as noted above, to make any extensive or formal first-hand evaluation of the Russian control system, although he has examined it on a number of occasions, and has conducted informal performance tests. However, from careful study of all available reports, and based upon experience with other myoelectric control systems and with the training of both patients and normal subjects, the following observations are submitted.

The Russian myoelectric prosthesis has been of unquestionable value in proving the feasibility of myoelectric control of prostheses, on a practical scale, outside the laboratory. The Russians are to be commended without reservation for making this system available outside Russia for evaluation, even though it was known to be in a relatively immature state of development and subject to certain criticism. If an assessment is made, not of the Russian hardware per se, but of the myoelectric control principle incorporated therein, it is felt that the system is unnecessarily wasteful of control sites. This is the only basic criticism of the system, aside from matters of technical development which are relatively unimportant. The topic of efficient utilization of control sites will be discussed in a later section of this paper.

Modified Russian (Montreal)

Since obtaining the manufacture and import rights for the Russian myoelectric prosthesis in 1964, the Department of Research of the Rehabilitation Institute of Montreal has directed considerable effort to the modification and improvement of the original equipment. Some progress is indicated in a paper published in November, 1965 (13), and the present status of this work is reported in the January 1967 issue of the Inter-Clinic Information Bulletin (14).

The modifications carried out by the Rehabilitation Institute of Montreal have primarily affected packaging of the control equipment. The latest package (14) has the surface electrodes and control electronics incorporated within the prosthesis, with a single cable leading to a flexible battery pack worn as a triceps cuff. A sketch of this arrangement is shown in Figure 2. The block diagram of the control system is identical to that of the Russian unit (Fig. 4).

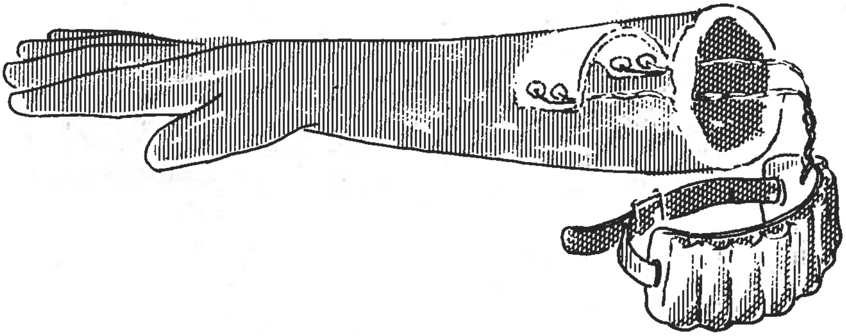

FIGURE 2.—Montreal modification of Russian system (prosthesis sketched for illustration only).

What is more important for the present discussion than the miniaturization of the electronic circuits and the improved packaging effected by the Rehabilitation Institute of Montreal, is the report of experience with the fitting of 15 amputees (14). The only serious problem reported (and it is emphasized by repetition) is involuntary operation of the prosthesis due to "external influences." This was noted by all patients.

British (London)

The first laboratory demonstration of a working myoelectric control system appears to be that reported by Battye, Nightingale, and Whillis of Guy's Hospital, London, in 1955 (2). The apparatus described in their paper was a one-channel system with on-off control of a terminal device in a normally open, voluntarily closed mode. By 1962 (15), a more sophisticated laboratory model had been constructed. This was a two-channel system employing the outputs from the biceps brachii and triceps muscles to provide on-off control of a pneumatic elbow flexion-extension unit. The system incorporated force and velocity feedback from the prosthesis to the control circuit, and a backlash generator which will be explained below. In 1965 (16), Dr. Bottomley reported a working prosthesis which used input signals from flexor and extensor muscle groups in the forearm to provide proportional control of an electrically driven hook. The apparatus was relatively large, and was still better suited to laboratory demonstration than to routine use by a patient. It has now been improved considerably, and a sketch of the most recent model is shown in Figure 3 with a block diagram, showing the operation of the control system, in Figure 5.

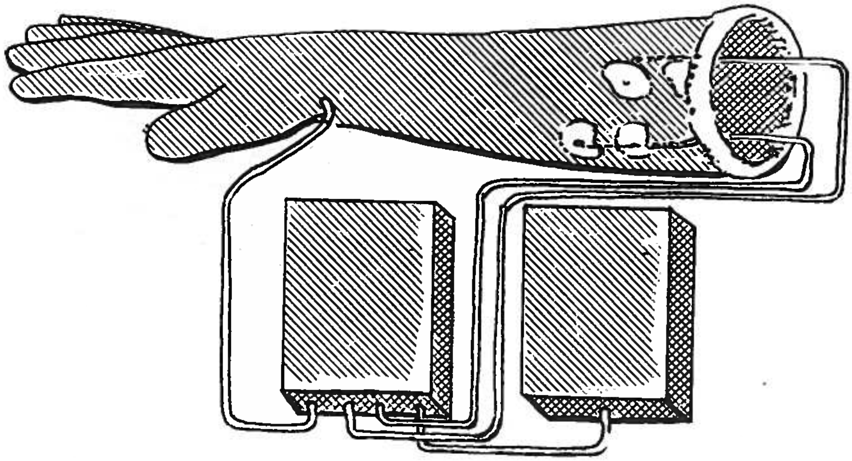

FIGURE 3.—British myoelectric control system (prosthesis sketched for illustration only).

With reference to Figure 5, it will be seen that the British control system differs from the Russian (Fig. 4) in a number of points. Most significant, perhaps, is the fact that this is a proportional, rather than an on-off control system. The velocity with which the terminal device opens or closes, and the force which it exerts upon an object, are dependent upon the myoelectric signal in a continuous manner. The second basic difference is that, in the British system, a single electrical control signal is derived from the output of two muscles. The myoelectric outputs from muscle A and muscle B, after processing, are combined in a mixer to produce an output signal proportional to the difference between the activity in muscle A and in muscle B. The purpose of this arrangement is to overcome the effect of cross talk; that is, to eliminate the confusion resulting from undesirable and inevitable simultaneous outputs from the two control sites. This it does successfully, although at the expense of a reduced dynamic range of output. Finally, the backlash generator is incorporated to render the control system insensitive to small changes in the myoelectric signal input. The width of the backlash region in this system is dependent upon the signal level, on the basis of Dr. Bottomley's observation (17) that unavoidable fluctuation in myoelectric activity exists and is proportional to the average level of this activity.

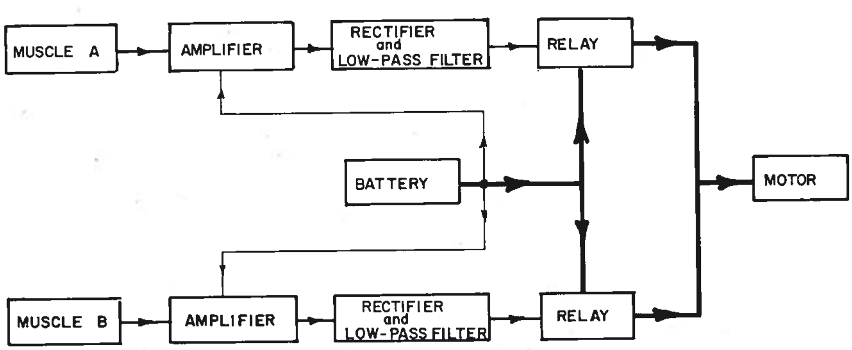

FIGURE 4.—Block diagram of Russian myoelectric control system.

The author has been unable to determine the extent to which this control system has been fitted to patients, or to obtain any comment on the success of these fittings. From brief personal trials of the 1964 version of the system, it is evident that the intended continuous control of force is, in fact, provided, and that this does permit certain activities which are impossible or improbable of success with the on-off control. The control system is relatively complex and consequently will be somewhat less reliable than a simpler system at the same level of development. It will be less efficient than an on-off system, chiefly because of the inevitabe losses in the output amplifier at moderate output levels (18, 19).

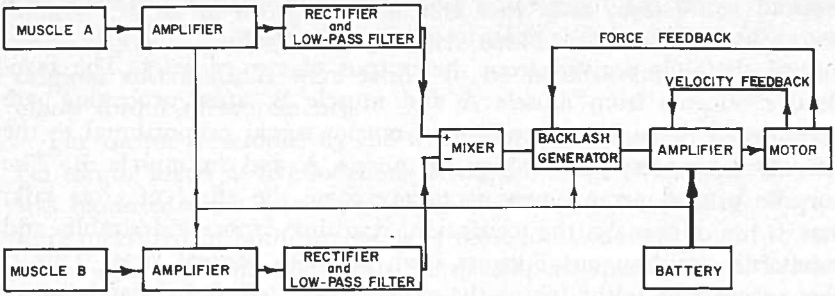

FIGURE 5.—Block diagram of British myoelectric control system.

Canadian (Fredericton)

The Bio-Enginering Institute of the University of New Brunswick is responsible for the design of a myoelectric control system in which only one muscle is required to provide on-off control of two functions (19, 20, 21, 22). A block diagram of this system is shown in Figure 6, and a sketch of the most recent package configuration is shown in Figure 8. The operation of the control system is best explained with reference to the block diagram, Figure 6, and the functional diagram shown in Figure 7. This three-state system will have both relays in the off position when the myoelectric input is very low (less than B in Fig. 7). If the myoelectric input lies between B and C in Figure 7, Function 1 will be activated; if the input is greater than level C, Function 2 will be activated. A slight time delay is incorporated into the control equipment, permitting the patient to move from the off state to the third (high level) state and vice versa without activating the intermediate state.

The purpose of this design was to develop a means of controlling more than one function from a single muscle, thus utilizing the output of that single control channel more efficiently. In order to obtain an assessment of this system with the least possible delay, no attempt was made to optimize the packaging prior to clinical trials. One unit, in a very crude form, was fitted successfully to an above-elbow amputee during the summer of 1965. Six additional units were fitted in Fredericton during the summer of 1966. Units have been provided to a number of hospitals and research establishments throughout Canada and the

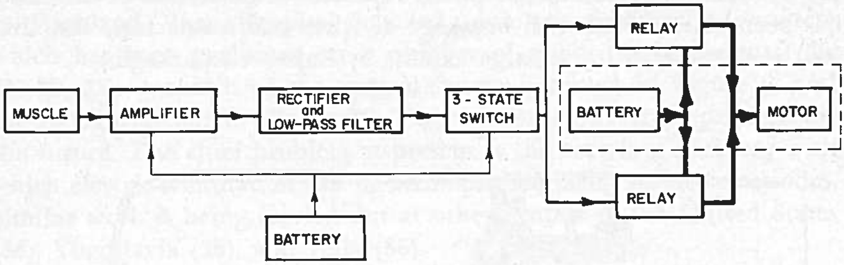

FIGURE 6.—Block diagram of Canadian three-state myoelectric control system.

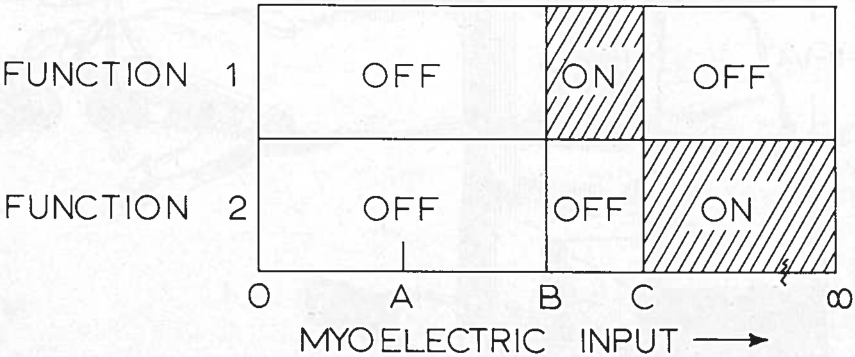

FIGURE 7.—Functional diagram of Canadian three-state myoelectric control system.

United States for evaluation, and one formal evaluation program has been established by the Committee on Prosthetics Research and Development of the U.S. National Academy of Sciences-National Research Council.

It will be noted that, in contrast to the three controls described previously, this control unit is not designed for use with a specific externally powered device. The motor and associated battery shown in Figure 6 may comprise any desired externally powered prosthetic or orthotic appliance, provided only that the motor current lies within the one ampere rating of the relay contacts. The control has been used primarily with prosthetic appliances designed by the Prosthetic Research and Training Unit of the Ontario Crippled Children's Centre, including an electric hook, an electric elbow unit, and an electric wrist rotation unit (23, 24, 25, 26).

Details of the clinical evaluations conducted by this Institute are included in a recent report (19), copies of which are available upon request. In brief, no patient has experienced difficulty in mastering the three-state control. Training periods have been short. No failures of the electronic equipment have been reported. A great deal of difficulty has been experienced with breakage of wires and connectors, and this has been remedied, to a large extent, by improved packaging.

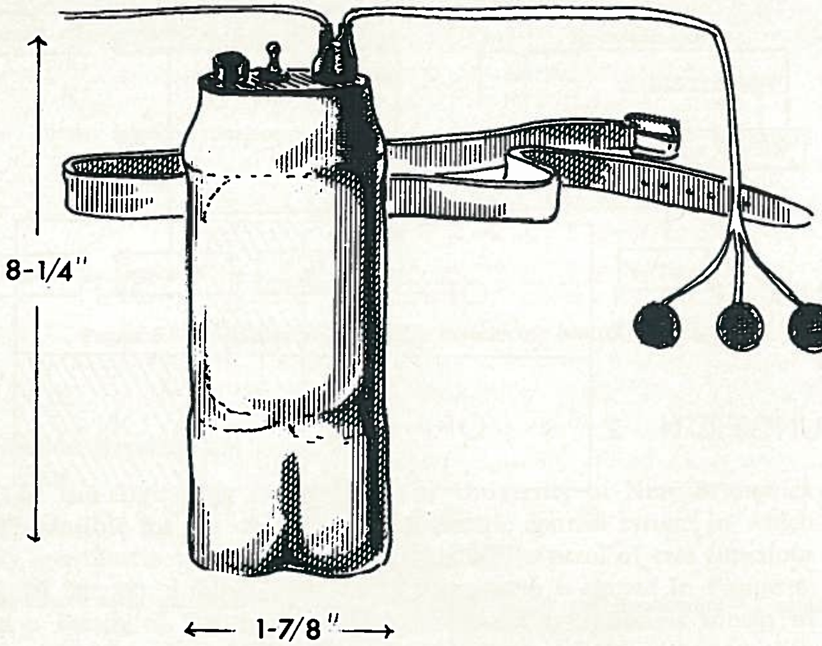

FIGURE 8.—Canadian three-state myoelectric control system.

From observation of the use of this equipment with electric hooks, particularly by young patients, it has been found desirable to provide, in addition, a two-state control, to permit use of a terminal device in a normally closed, voluntarily opened mode. Construction of such a unit, and redesign of the existing unit to improve performance and to reduce size, weight, and power requirements, are now being carried out.

Other Systems

In addition to the control systems described above, the following, which are not known to be in wide use or readily available, are mentioned for completeness. One of the more interesting of these is a myoelectrically controlled stimulator for paralyzed muscles. This work seems to have originated in a paper by Liberson in 1961 (27), which was followed in 1963 by nearly simultaneous and apparently independent publications from the U.S. Public Health Service Hospital, New Orleans (28), and from Highland View Hospital (29). The work at Highland View Hospital has led to a practical orthotic system which has been evaluated on a number of quadriplegic patients (30, 31, 32, 33). A sketch of the control system is shown in Figure 9, and the block diagram in Figure 10. This system shows great promise for the future. The chief problem at present is the very low efficiency with which electric stimulation can be accomplished using surface electrodes. Similar work is being carried out at other centers in the United States (34), Yugoslavia (35), and Italy (36).

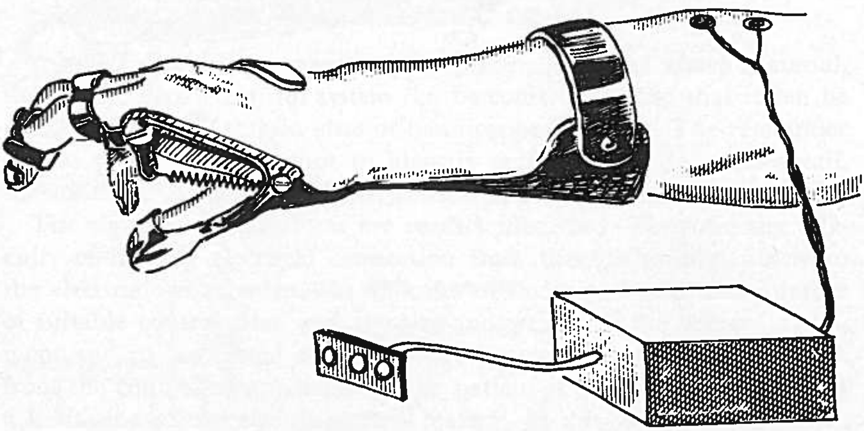

FIGURE 9.—Myoelectrically controlled orthosis (Case Institute of Technology).

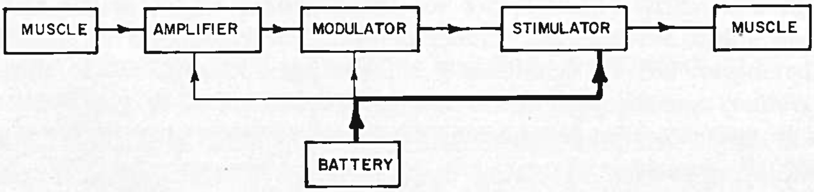

FIGURE 10.—Block diagram of myoelectrically controlled orthosis.

Several myoelectric prostheses for below-elbow amputees, similar in purpose to the Russian prosthesis, have been developed. One of the more complex was described by Horn in 1963 (37). It is understood that difficulty has been experienced in producing this rather complex prosthesis, which uses one myoelectric input and two mechanical inputs to provide continuous control of position and force in an artificial hand. A sketch of the system is shown in Figure 11. Stump rotation within the socket and force exerted by the stump against the socket provide the two mechanical inputs to the system. These control the rest position of the terminal device and the grasping force respectively, with the myoelectric signal operating in a position control servo system as illustrated in the block diagram of Figure 12.

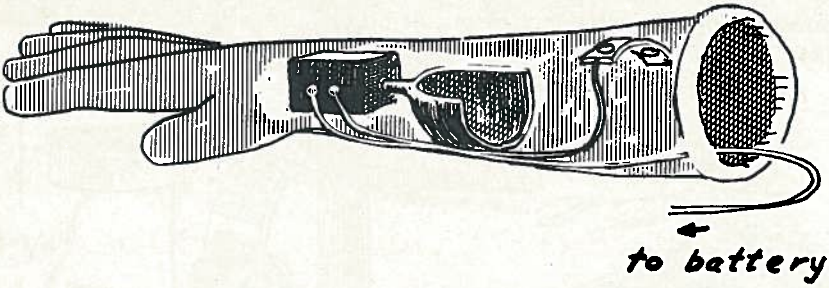

FIGURE 11.—Italian myoelectric prosthesis (prosthesis sketched for illustration only).

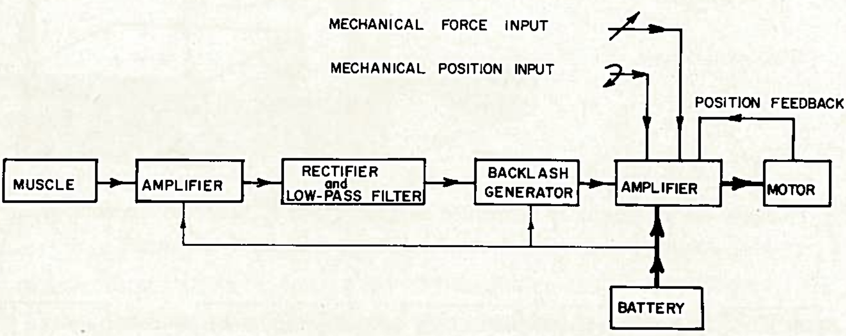

FIGURE 12.—Block diagram of Italian myoelectric prosthesis.

A myoelectric prosthesis similar to that proposed by Bottomley, but employing a stepping motor, is being developed at Manchester (38). It is understood that this device is still in a relatively early stage of development. Also, a prosthesis similar to the Russian myoelectric prosthesis has been developed in Austria (39). The author has no first-hand knowledge of the state of development or utilization of this system. A complex system using pattern recognition techniques to control a number of functions simultaneously has been reported by the Philco Corporation (40, 41). This development is being continued at the Moss Rehabilitation Hospital, Philadelphia (42).

A four-state control, similar in principle to the three-state control developed by the University of New Brunswick, has been designed at the Case Institute of Technology (43). The additional feature is a "dead zone" between the levels at which Function 1 and Function 2 are activated, facilitating rapid selection of the two functions. In the original model of this system, all thresholds are adjustable. Evaluation is now being carried out at the Highland View Hospital, Cleveland.

Research is also continuing in the Boston area on myoelectric control of externally powered prostheses. This work, which is an outgrowth of several graduate theses in the Department of Mechanical Engineering, Massachusetts Institute of Technology, is being carried on at M.I.T. and at Massachusetts General Hospital (44, 45).

LIMITATIONS OF MYOELECTRIC CONTROL SYSTEMS

It will be readily apparent to the reader, from the above material, that a myoelectric control system can be constructed and that it can be used, at least by a certain class of handicapped persons. The remainder of this paper is an attempt to identify and examine, in some detail, the inherent limitations of such control systems.

The significant limitations are readily identified. They are the difficulty of making electrical connection from the controlling muscle to the electronic equipment, the difficulty of finding an adequate number of suitable control sites, and the size and weight of the control equipment and its associated energy storage system. The need for feedback from the controlled apparatus to the patient is not properly classed as a limitation of myoelectric control systems, as this problem is common to all control systems for externally powered appliances.

Electrodes

The source of the control signal for a myoelectric system is a disturbance of the electric potential difference between the inside and outside of one or more muscle fibers. These fibers may be considered, for simplicity, to be imbedded in a more or less homogeneous conducting medium, and to be separated from any external control system by a thin electrically insulating membrane, the skin. Furthermore, the distance between the muscle fibers, from which a control signal is to be derived, and the nearest point on the skin surface, may be comparable to the distance from many other muscle fibers to that same point on the skin. An analysis of the variation in electric potential with propagation through body tissue, for the purpose of clarifying this particular situation, is contained in a recent graduate thesis (46), and it is expected that a summary of this work will be prepared for publication in the near future.

Some specific data from that thesis may be helpful to the present discussion. The myoelectric signal, whether from a single muscle fiber or from the normal (asynchronous) contraction of many muscle fibers, has its electrical energy distributed over a range of frequencies. Almost all the energy is contained within the range 20 to 300 Hz. This statement has been shown (46) to be valid not only for the potentials measured at the surface of the skin, as previously reported (47 and 48), but also for potentials measured with intramuscular electrodes in close proximity to the muscle fibers. Maximum signal power density occurs at a frequency lying typically between 50 and 100 Hz; that is, approximately at the commercial power mains frequency.

While the amplitude of the potentials measured close to a muscle fiber may be as high as several millivolts, this potential is attenuated as an exponential function of distance in accordance with the equation given below (46).

$$E_r \approx E_o \, \varepsilon^{-.17\sqrt{f}\, r}$$

where

E_r is the potential at a distance,
r centimeters radially from the fiber,
E_o is the potential at the fiber,
ε is the base of natural logarithms (2.71828), and
f is the frequency at which the potential is measured.

It will be seen that the high frequency components are attenuated more rapidly than the low frequency components of the signal, and that all components of interest are attenuated significantly in a distance of less than one centimeter.

Concerning electrodes, two choices exist. Either surface electrodes or electrodes in direct contact with the tissues under the skin may be used. For convenience, the latter will be referred to as percutaneous electrodes, even though, in the case of a totally implanted system, they would not in fact pass through the skin. All existing systems which have been fitted to patients use surface electrodes, despite the obvious disadvantage of such electrodes in respect of attenuation of the signal during its passage from the active muscle fibers to the surface of the body.

Surface electrodes may be merely metal disks in contact with the skin, with or without a conducting paste to improve contact. One of the desirable electrical characteristics of any electrode is low impedance between the signal source and the amplifier. This is achieved, with surface electrodes, only when a conducting paste or jelly is employed. Another desirable characteristic is freedom from generation of electric potentials due to physical movement. A high degree of stability has been achieved in electrodes developed by Day and Lippitt (49), now commercially available as Beckman Type 350059 Biopotential Skin Electrodes.

Because these electrodes are expensive, and because their use requires careful application of electrode paste and subsequent washing after use, they have not been accepted generally for use with myoelectric control systems. Rather, the tendency has been to employ very simple electrodes, either without any electrode paste or with a preliminary application of paste over a large area of the skin. While these techniques certainly reduce the nuisance of applying electrodes, they also, with equal certainty, make the control system susceptible to external electrical interference. Because the electrode-to-muscle impedance is very high, the input impedance of the amplifier must also be very high, and consequently the system impedance at the input terminals is high. This is the worst possible condition for coupling of electrical interference from external sources (20). The reader will recall the problem experienced by the Rehabilitation Institute of Montreal with undesired operation of prostheses due to "external influences." The Bio-Enginering Institute of the University of New Brunswick has employed Beckman electrodes exclusively, and has not experienced any problem with external electrical interference.

At the present time, efforts are being made to develop a surface electrode system which may be left in place for periods longer than one day. It is anticipated that problems of skin infection and/or irritation will be of primary concern, although the matter of a convenient and reliable electrical connector will also present difficulty. The "dry electrodes" recently developed by Spacelabs Incorporated (50) will be investigated, although it is understood that their impedance is relatively high. The ideal surface electrode, for use in myoelectric systems, would have good electrical stability and low impedance, and would be designed to permit convenient application and removal or continued use over periods of one week or longer.

Under certain circumstances, which will be elaborated upon below, it is essential that an electrode be in close proximity to one or more specific muscle fibers. For such applications, surface electrodes are not usable. Also, as noted above, the myoelectric potentials are seriously attenuated in their passage through body tissues, and much larger signals are available to electrodes inserted within the muscle. Consequently, there is considerable reason to be interested in percutaneous electrodes for myoelectric control systems, in addition to their very common use for clinical electromyography.

Excluding for the moment the matter of permanently implanted electronic equipment, the only electrodes in this class which are applicable to myoelectric control systems are wire electrodes, because of their flexibility. Two types have been used widely, insulated wires of approximately .001 in. diameter with a short portion of the tip deinsulated, and bare wires of approximately .003 in. in diameter. They may be inserted either in the muscle or subcutaneously. It is not difficult to insert either type of electrode using a hypodermic needle, and the two techniques are in common use (51, 52). The insulated wires were used initially for diagnostic purposes, and permit measurement of the electrical activity of a small portion of a muscle. The bare wire electrodes were developed for use in myoelectric control systems where a high degree of selectivity was not required (21).

Both wire electrodes suffer from three defects. First and most important, wire of this size is subject to breakage, and breakage of an electrode leaves the patient with an inoperative control system. Secondly, the insertion of these electrodes, while not difficult, is a procedure which is best done by trained personnel and is essentially impossible for the patient to perform by himself. Thirdly, there is a possibility of infection at the point where the wire passes through the skin, although this problem has been largely overcome (21). In addition, it is difficult to provide a suitable connector for use with such small wires. However, it is highly probable, in the author's opinion, that percutaneous wire electrodes will be employed by patients during a transitional period between the present universal adoption of surface electrodes and the ultimate adoption, at least in certain circumstances, of surgically implanted electronic equipment.

While considerations of implanted electronic equipment may not properly be classified under the heading of electrodes, the electrode problems associated with such equipment are of some interest. If small-area pickup from the muscle is required, it is probable that a wire electrode will be necessary. Most experimental implants have been made in soft tissue (53, 54). It is unlikely that sufficient stability will be achieved under these conditions to permit the use of electrodes on the surface of the implanted package. The alternative location for the implanted electronic hardware, within or attached to bone, also precludes the use of surface areas on the package for the pickup of highly localized myoelectric potentials. However, should the gross myoelectric signal from a relatively large area be desired, the use of such contact areas on the package may eliminate most difficulties with electrodes. Of course, an implanted transmitter and its associated external receiver would provide an excellent means of overcoming the barrier constituted by the skin.

Control Sites

It is unfortunate and inevitable that those patients with the greatest need for externally powered apparatus, and, consequently, for control facility, possess the fewest available control sites. This is as true of myoelectric control as of any other method of control. It is important to realize at the outset that control of a multifunctional externally powered prosthetic system exclusively by myoelectric control is not likely to be desirable. Myoelectric control will always be more costly and less reliable than a simple mechanical control system.

The proper place for myoelectric control, in the author's opinion, is as a supplement to other control means when it is impossible or impractical to meet all the patient's control needs by such means. This is not to discourage the use of myoelectric control for simple prostheses, at the present time, for the purpose of determining the feasibility of such systems and the aspects which need further development. However, it should be clearly understood that the purpose of such fittings is research and not optimum clinical handling of the patient.

For the amputee, it is probable that some muscle remnants exist which can be used as control sites. The necessary conditions are simply that they are not used for other purposes and that they are normally innervated. There is here an opportunity for the surgeon to make a significant contribution. He should employ any optional means available to render such muscle remnants as accessible as possible, and should immobilize the severed end where this technique is not otherwise undesirable. Indeed, research may lead to techniques for the production of additional control sites from available muscle tissue.

For the quadriplegic patient, it is possible to employ partially paralyzed muscles which are incapable of producing physical movement. It is also possible (55) to train a patient to use muscles, such as the auricularis, which have no useful function under normal circumstances.

In general, it is not difficult to train an individual to control the myoelectric output of one or several muscles. The problem of training has been overestimated by most research groups, and should not be considered a major factor in the application of myoelectric control systems. It is more difficult to control a large than a small number of muscles. The number of muscles which can be successfully trained may be primarily limited by the feedback channels employed for training.

Some of the most interesting developments in the provision of additional control sites at the present time concern the utilization of potentials from single motor units within the muscle. The occurrence of single motor unit potentials during voluntary contraction of muscle has been observed clinically from time to time. However, the present interest in such potentials for the control of prosthetic systems probably results from a publication by Basmajian in 1963 (56). This publication was followed by another by the same author in 1965 (57).

An exciting presentation by Pierce and Wagman at the Conference on the Control of External Power in Upper-Extremity Rehabilitation at Warrenton in 1965 (58) also dealt with the use of single motor unit potentials and the possibilities for using intracellular electrodes to provide control signals in myoelectric systems. The feasibility of single motor unit control has been demonstrated in research carried out at the Case Institute of Technology and Highland View Hospital (59, 60). Similar work has been initiated at the University of New Brunswick.

The significance of this research is not in the fact that only a single motor unit is involved, but rather in the possibility of using highly localized electrodes to obtain a large number of control sites within one muscle. Control sites separated by as little as ½ in. have already been shown to provide readily usable signals with negligible crosstalk, and it is probable that the spacing could be further reduced. Implementation of such systems on a reasonable scale is prevented, at the present time, almost solely by the lack of suitable electrodes.

Size and Weight

The size and weight of a myoelectric control system are of considerable importance in determining its usefulness to the patient. For any control system which is to be worn externally, it is perfectly feasible at the present time to reduce the size of the electronic circuitry to acceptable dimensions. The equipment shown in Figure 2 illustrates this point. However, for equipment which is to be surgically implanted within the body, the limitations on available size and weight will impose definite constraints upon the complexity of the control system, at least at the present time.

Any electronic control system requires a source of electric energy in addition to the requirements of the controlled appliance. If the control system is very complex, it is quite possible that the limiting factor in its acceptance will be the weight of additional energy storage required. At the present time, sealed rechargeable nickel-cadmium cells are commonly employed. A 12-volt battery, capable of supplying a load current of 10 ma. continuously for 10 hours, weighs approximately 3.2 oz. and occupies a volume of approximately 1.5 cu. in. New types of electric storage cells are being developed, which have considerably greater storage capacity per unit weight. However, these are understood to be prohibitively expensive at the present time.

A recurring topic of speculation is the possibility of employing either electrochemical or electromechanical transducers within the body to provide energy for the operation of implanted electronic equipment. To the author's knowledge, no practical results have been obtained. Implanted electronic equipment may be powered by wireless transmission of electric energy from outside the body. However, this transmission is quite inefficient, and necessitates the use of external energy storage of significant weight and volume. Of course, for the wheelchair-bound patient, energy storage is not a particularly serious problem, and it is probably for such a patient that the first applications of very complex electronic control equipment will be developed.

CONCLUSION

Myoelectric control of externally powered prosthetic and orthotic appliances has been shown to be feasible, and has been demonstrated in practice with large numbers of patients. Its primary usefulness, at least for amputees, is as a supplement to other simpler control means. The present state of the art represents a beginning, and only a beginning. The control method is of sufficient proven value to justify thorough investigation of all aspects, including particularly a solution to the electrode problem.

There is a great need for cooperation in this research. There is a need for more cooperation and less competition between bio-engineering research centers. There is a great need for increased involvement of medical research personnel and clinicians in cooperation with the bio-engineering groups.

There is a need for rapid evaluation of new ideas, and for immediate and comprehensive reporting of the results of clinical evaluations to research personnel. Also, the research personnel must be more willing to expedite the transition from idea to practice. Myoelectric control is not an abstract academic research topic to be pursued at leisure in an ivory tower. Rather, it is a topic of vital importance to a large class of handicapped persons, and its development should be treated as a matter of social urgency.

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