ELECTRICAL EXCITATION OF PARALYZED MUSCLE

J. T. Mortimer and P. H. Peckham

Summary

The underlying causes of three major problems encountered in functional stimulation of paralyzed muscle now appear to be understood and solvable. The problems are low contractile force, rapid fatigue and undesirable fluctuations in force during movement. The low contractile force results from disuse atrophy. This problem has been found to be rectified by a program of exercise brought about by electrical stimulation. To be effective, the exercise program must utilize stimulus frequencies which avoid rapid fatigue (below 15 Hz). Rapid fatigue results from stimulating the muscle at stimulus rates higher than 15 Hz and excitation of muscle fibers which are readily fatigable. Excitation of the muscle at frequencies greater than 15 Hz can result in transmission failure of the neuromuscular junction and inadequate blood flow to meet the demands of the working muscle. Application of electrical stimulus unavoidably results in excitation of white muscle fibers which charateristically have fast twitch times and are readily fatigable. Employment of the intramuscular electrodes, as opposed to surface electrodes, provides a possibility of avoiding both causes of fatigue. Changes in the induced contractile force during limb movement are largely a result of the relative motion between the skin surface and the nerve or motor point. This problem is circumvented by utilizing intramuscular electrodes. In line with these solutions, a system is proposed for electrical excitation of paralyzed muscle which minimizes fatigue during sustained contraction.

The successful development of systems employing electrical excitation of paralyzed muscle has been restrained by several problems. Three particularly difficult problems have been:

1. The force developed by the paralyzed muscle, which is electrically excited, is inadequate for functional uses (Doerr and Long /1/ and personal experience);
2. The muscle force developed by the electrically excited muscle decays too rapidly for functional use /2, 3/;
3. Erratic contraction result from relative movements between the surface electrode and the muscle motor point /4/.

The relative importance of each of these problems depends on the contractual demands placed on the muscle. The demand placed on the electrically excited muscle can take on two basic forms. The first is a

---

This research was sponsored by the Social and Rehabilitation Service, Grant Number 23-P-55207/5-02, of the Department of Health, Education, and Welfare, Washington, D. C.

contraction which results in gross motion of the limb and is phasic or short lasting in nature. The second is a contraction which results in a sustained submaximal force (or torque) and is tonic in nature. Experimentally, fatigue has been found to be considerably more of a problem in the development of tonic contractions than in the development of phasic contractions. The source of the above three problems now appears to be understood and techniques to overcome them have been developed.

Muscles sustaining an upper motor neuron lesion frequently remain inactive (unless they are subject to involuntary contractions). As a result of this inactivity, the muscles undergo a disuse atrophy similar to that seen in the immobilized limb. Following long term immobilization, a program of voluntary exercise is effective in restoring muscle strength. In the paralyzed muscle voluntary exercise is not possible; therefore, the exercise must be induced by other means, such as electrical stimulation. In this laboratory and elsewhere /5/ such a program is induced exercise has been found to be effective in restoring muscle forces to functional levels. Initial studies have shown that prehensile pinch can be increased from forces below functional levels to forces greater than functional levels in approximately ten weeks, with daily one-hour periods of induced exercise. An example of the results obtained from one patient participating in the induced exercise program is shown in Figure 1.

For the induced exercise program to be effective, the muscle must be contracting during the entire period of exercise; therefore, the stimulus frequency must be sufficiently low to avoid occlusion of a muscle blood flow or transmission failure at the neuromusclar junction. To ensure adequate blood flow, the stimulus frequency should be under 20 Hz for red muscle and under 5 Hz for white muscle /6/. To avoid transmission failure of the neuromuscular junction, the stimulus frequency should be below 15 Hz according to Krnjevic and Miledi /7/, or between 10 Hz and 20 Hz according to Kugelberg and Edström /8/.

The rapid decay in muscle force observed with electrical stimulation of muscle results from:

1. The use of relatively high stimulus frequencies (50 Hz);
2. Excitation of the muscle fibers which charateristically are easily fatigued (the white muscle fibers).

During maximal voluntary effort firing frequencies are on the order of 50 Hz. Also, during moderately strong contractions, blood flow is

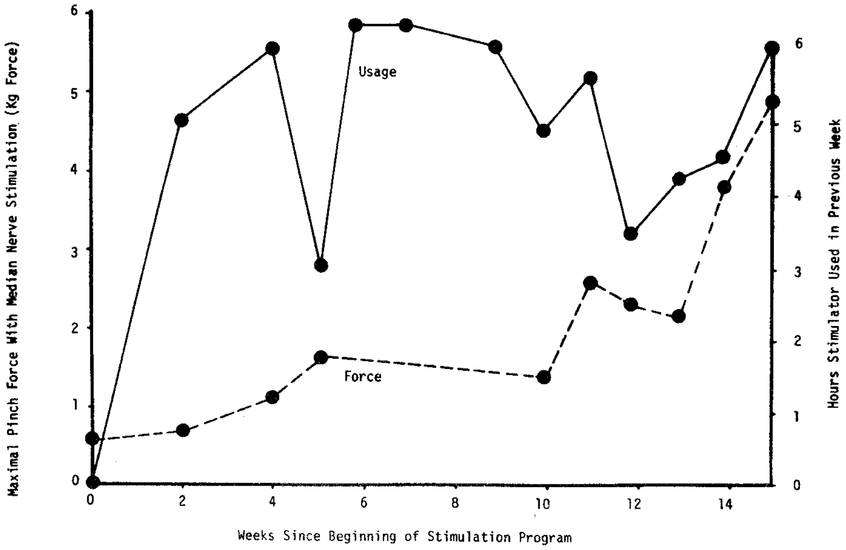

Fig. 1. The graph represents an increase in pinch force which resulted from a program of electrically induced exercise. The force is measured as the pinch force in palmar prehension in response to maximal electrical stimulation of the median nerve. Also graphed is the period of induced muscle exercise for the previous week.

impeded and may even cease during strong contractions (resulting from the increased intramuscular pressure) /9, 10, 11/. Therefore, electrical excitation of muscle at tetanic frequencies near 50 Hz would be expected to affect occlusion of the blood flow in the region of the muscle undergoing stimulation. Hence, the force decay in the electrically excited muscle would naturally follow that of a maximally contracting muscle. This behaviour would also hold for submaximal contractions (electrically induced) since no means is provided to replenish consumed energy stores in the ischemic portion of the muscle performing the work.

The second cause of the rapid muscle fatigue, which is at least as important as effects of "high" stimulus frequencies, is that the induced contraction is largely the result of stimulating white muscle fibers. In Table 1 are listed some of the important charateristics of red and white muscle fibers.

Table 1.

Red	White
low twitch tension	high twitch tension
low fusion frequency	high fusion frequency
aerobic metabolism	anaerobic metabolism
fatigue resistant	easily fatigued
small motor neuron	large motor neuron
∴ high electrical threshold	∴ low electrical threshold

The current theory of muscle fiber recruitment order during sustained voluntary contraction is that initially the smallest red fiber motor units are recruited. As the contractile force increases, large red units begin to fire, followed by the smaller white motor units; finally at maximal voluntary strength, the largest white units are recruited /12/. However, in the electrically excited muscle, the recruiment order is reversed; where large fibres are recruited before small fibres as the stimulus amplitude is increased. The first and most obvious source of fatigue is the relatively low electrical threshold of the large motor neuron innervating the large white motor units. As most muscles are a mixture of both red and white muscle, nerve stimulation will always recruit the white fiber group before the red fibre group. As a first order approximation, the muscle force can be described by the following equation:

$$F(t) = \Psi R(t) + \Omega W(t)$$

where, $F(t)$ is the muscle force as a function of time;
Ψ is the number of active fibers;
$R(t)$ is the fatigue charateristics of the red muscle fibers;
Ω is the number of active white fibers;
$W(t)$ if the fatigue charateristics of the white muscle fibers.

Since the twitch force of the white fibers is greater than the twitch force of the red fiber and, if Ψ is less than or equal to Ω, then $F(t)$ will be dominated by $W(t)$. Therefore, the forces which result from nerve stimulation will always be dominated by the charateristics of the white fiber component of the muscle. Further, histochemical observations in animal /8, 13/ and recruiment order studies in man /14/ indicate that the superficial portion of the muscle is dominated by white muscle fibres, and that the red fibers are located deep in the muscle (Fig. 2). Therefore, excitation of the muscle through surface stimulation will unavoidably result in forces which will be dominated by the white fibers. Only at the high stimulus intensities will the current density be sufficient in the deep portions of the muscle to begin recruiment of the red muscle fibers. To summarize, as a result of the superficial location of the white fibers and their relatively low electrical threshold to nerve stimulation, induced contractions will respond with the rapid fatigue charateristics of the white muscle fibers.

With the fatigue-resistant muscle fibers located deeper in the muscle, one might postulate that stimulation through intramuscular electrodes would be effective in exciting the red fibers without excessive excitation of the white muscle fiber. Testing this hypothesis, by employing the glycogen depletion techniques of Edstrom and Kugelberg /15/, revealed somewhat surprising results. Instead of exciting a circular portion of the muscle as might be expected, a pie-shaped section of the muscle was excited. An example of the results obtained from animals is shown in Figure 3. The apex of the pie is approximately at the electrode site and the pie-shaped area extends to the superficial portion of the muscle. The red fibers deeper in the muscle were excited; however, as the stimulated section widened toward the superficial portion of the muscle, the net result was that a greater proportion of white fibers were excited as comapred to the number of excited red fibers. Therefore, intramuscular stimulation of a muscle with superficial white fibers will have little advantages over direct nerve stimulation (with the electrode in the proximity of the motor nerve, proximal to nerve entry into the muscle).

The source of fatigue in the electrically excited muscle is most certainly the white muscle fiber group. Based on the previously mentioned studies, there appears to be no practical way to avoid excitation of this fiber type through physical positioning of the stimulating electrode. Therefore, a solution to this problem would be to alter the fatigue characteristics of the white fiber group to a more fatigue-resistant type. Based on the hypothesis that the muscle's metabolic characteristics and related fatigue resistance are governed

Fig. 2. Cross section of the tibialis anterior muscle of rat is stained for succinic dehydrogenase. The darker staining fibres are classified as red muscle fibers while the lighter staining fibers are classified as white. The superficial portion of the muscle is the lightest and the deeper portion is darker, indicating a high capacity for oxidative metabolism.

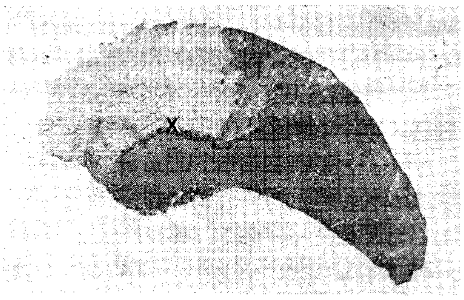

Fig. 3. Cross section of the tibials anterior muscle of rat is stained for glycogen (PAS stain). The glycogen has been depleted from the lightly stained area, indicating the portion of the muscle which had been activated by the intramuscular electrode position is marked by X.

by the working demands placed on it, a series of experiments /17/, were undertaken to study the effects of increased exercise. These experiments were designed to study the physiological changes (twitch time and fatigue index) and the histochemical changes (capacity for oxidative metabolism) which results from increased muscle exercise induced by electrical excitation of the muscle. In these experiments the tibialis anterior muscle of cat was excited electrically at 10 Hz for twenty-four hours per day. Thus far, studies performed on animals stimulated for more than 12 days reveal characteristics more like that of a red muscle than that of a predominantly white muscle (the tibialis anterior is essentially white). Muscles which have been chronically stimulated had contraction times similar to a red muscle which confirmed the earlier experiments of Salmons and Vrbova /16/. In addition, the muscle shows a concommitant change in fatigue resistance and has an increased capacity for oxidative metabolism. The increased capacity for oxidative metabolism is evidenced by an increased intensity in succinic dehydrogenase activity in the region of the muscle that has been chronically excited (marked by glycogen depletion, PAS stain) /13/. The net effect of these changes is to enable the fusion frequency to be approximately halved while increasing the fatigue resistance of the excited fibers. Decreasing the fusion frequency by a factor of two is a considerable decrease although not adequate by itself. Kugelberg and Edstrom /8/ found that stimulus frequencies above 10 Hz resulted in neuromuscular junction fatigue within a short period of time. Similar findings have been found in the rat diaphragm at a stimulus frequency of 14 Hz by Krnjević and Miledi /7/. Therefore, a further decrease in the stimulation frequency is necessary. To further drop the stimulus frequency while maintaining smooth contractile forces, the method of sequential stimulation can be applied /17/. This method utilizes several (N) small electrodes inserted into physically different portions of the same muscle. Application of a stimulus pulse to each electrode $360^{o}/N$ out of phase with the next electrode will result in a smooth contraction of the two muscle at the fusion frequency divided by N. If the muscle has the characteristics of a white muscle and N is four, the required stimulus frequency is approximately 10 Hz. If the muscle behaves like a red muscle and N is four, the stimulating frequency is approximately 5 Hz.

The third problem encountered was relative movement between the skin surface and the "motor point" of the stimulated muscle /18/. As the muscle moves during contractions, the "motor point" or lowest threshold point moves away from the electrode resulting in a decrease in muscle force. Crochetiere /18/ has developed methods to overcome this problem in surface stimulation; however, to avoid muscle fatigue, intramuscular electrodes will be required. Therefore, employing an intramuscular electrode which has very little relative motion as the muscle lengthens and shortens will overcome the problem. The Caldwell electrode /19/, a helically wound electrode (Fig. 4), has been found to be very effective in circumventing the problems associated with relative movement between the electrode and the muscle.

Employing intramuscular stimulation avoids one additional problem often encountered with surface stimulation, that is, uncomfortable sensations. The uncomfortable sensations arise from stimulation of receptors in the skin.

Summarizing, the previously posed problems facting electrical excitation of paralyzed muscle now appear to be solved. An exercise program, produced by electrical stimulation, has been found to be effective in restoring induced muscle forces to functional levels. Employing of intramuscular electrodes allows the possibility of avoiding ra-

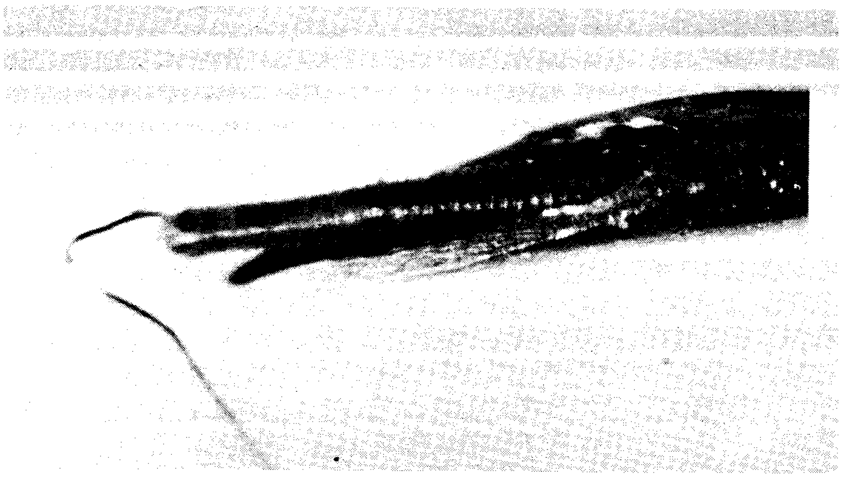

Fig. 4. The Caldwell electrode is loaded in a hypodermic needle. The helical coil is approximately 200 μ in diameter and is formed from 304 stainless steel, 28 μ in diameter.

pid fatigue and eliminates the problems associated with surface electrodes (relative movement and uncomfortable sensations). The fatigue problem can be avoided by sequential activation of several portions of the muscle and by conversion of the rapidly fatiguing muscle fibers to a type which will sustain activity at relatively low stimulus frequencies.

References

/1/ Doerr,G.M., Long, C., "Electrical Response and Electromyograms of Upper-Extremity Muscles in Quadriplegics", *Orthotics and Prosthetics*, Vol. **23**, **1969**, pp. 20-26.

/2/ Vodovnik, L., "Functional Stimulation of Extremities", *Advances in Electronics and Electron Physics*, Ed. L. Marton, Vol. 30, 1971, Academic Press, New York, pp. 282-297.

/3/ Vodovnik, L., "Information Processing in the Central Nervous System During Functional Electrical Stimulation", *Med. and Biol. Engrng.*, Vol. 9, 1971, pp. 675-682.

/4/ Long, C., "Normal and Abnormal Control in the Upper Extremities", Final Report to Social and Rehabilitation Services, Grant Number RD-2377-M; 1970.

/5/ Wilemon,W. K., Mooney, V., McNeal, D., Reswick, J., "Surgically Implanted Peripheral Neuroelectric Stimulation", Two Years' Experience at Rancho Los Amigos Hospital, Downey, Calif., 1970.

/6/ Folkow, B., Halicka, H.D., "A Comparison Between 'Red' and 'White' Muscle with Respect to Blood Supply, Capillary Surface Area and Oxygen Uptake During Rest and Exercise", *Microvascular Research*, Vol. 1, 1968, pp. 1-14.

/7/ Krnjević, K., Miledi, R., "Failure of Neuromuscular Propagation in Rats", *J. Physiol.*, Vol. 140, 1958, pp. 440-446.

/8/ Kugelberg, E., Edström, L., "Differential Histochemical Effects of Muscle Contractions on Phosphorylase and Glycogen in Various Types of Fibers: Relation to Fatigue", *J. Neurol., Neurosurg., Psychiat.*, Vol. 31, pp. 415-423, 1968.

/9/ Mortimer, J. T., et al., "Muscle Blood Flow in the Human Biceps as a Function of Developed Muscle Force", *Arch Surg.*, Vol. 103, Sept., 1971.

/10/ Tønnesen, K.H., "Blood Flow Through Muscle During Rythmic Contraction Measured by X_e^{133}, *Scandinav. J. Cli. & Lab. Investigation*, Vol. 16, 1964, pp. 646-654.

/11/ Lassen, N.A., Kampp, M., "Calf Muscle Blood Flow During Walking Studies by the X_e^{133} Method in Normals and in Patients with Intermittent Claudication", *Scandinav. J. Clin. & Lab. Investigations*, Vol. 17, 1965, pp. 447-453.

/12/ Henneman, E., Olson, C.B., "Relations Between Structure and Function in the Design of Skeletal Muscles", *J. Neurophysiology*, Vol. 28, 1965, pp. 581-598.

/13/ Peckham, P.H., Mortimer, J.T., VanDerMeulen, J.P., "Physiological and Metabolic Changes in White Muscle of Cat Following Electrically Induced Exercise", submitted for publication,1972.

/14/ Calmann, H.P., "Activity of Single Motor Units During Isometric Tension", *Neurology*, Vol. 20, 1970, pp. 254-260.

/15/ Edström, L., Kugelberg, E., "Histochemical Composition, Distribution of Fibers and Fatigability of Single Motor Units", *J. Neurol., Neurosurg, Psychiat.*, Vol. 31, 1968, pp. 424-433.

/16/ Salmons, S., Vrbova, G., "The Influence of Activity on Some Contractile Characteristics of Mammalian Fast and Slow Muscles", *J. Physiol.*, 1969, Vol. 201, pp. 535-549.

/17/ Peckham, P.H., VanDerMeulen, J.P., Reswick, J.B., "Electrical Activation of Skeletal Muscle by Sequential Stimulation", *The Nervous System and Electrical Currents*, Ed. N. Wulfson & A. Sances, Jr., Plenum Press, 1970, pp. 45-50.

/18/ Crochetiere, W.J.,"On the Use of Electrically Stimulated Muscle as a Controlled Actuator of a Limb", Ph. D. Thesis, and Report No. EDC 4-67-17, Case Institute of Technology, 1967.

/19/ Caldwell, C.W., "A High Strength Platinum Percutaneous Electrode for Chronic Use", Ph. D. Thesis and Report No. EDC 4-70-30, Case Western Reserve University, Cleveland, Ohio, 1970.