Proceedings of the Eighth International Symposium on ECHE, 1984, Dubrovnik

RECRUITMENT PROPERTIES OF MONOPOLAR AND BIPOLAR EPIMYSIAL ELECTRODES

P.A. Grandjean' and J.T. Mortimer
The Applied Neural Control Laboratory
Department of Biomedical Engineering
Case Western Reserve University
Cleveland, Ohio 44106, U.S.A.

ABSTRACT

Physiological properties of electrically stimulated muscle were studied as a function of stimulus current, electrode position, and muscle length, using monopolar and bipolar electrodes placed on the surface of the muscle. The dependence of recruitment (force - stimulus amplitude relationship) on muscle length was minimal for a monopolar electrode positioned close to nerve entrance or 5 mm proximal to the motor point of the muscle. The selectivity of stimulation (minimizing spread of the stimulation to adjacent muscles) was best for an electrode placed close to the nerve entrance. The recruitment rate was highest for electrode positions that had the greatest selectivity. The recruitment rate was also observed to decrease with decreasing pulse width for both monophasic and biphasic stimuli. The decrease was larger with biphasic pulses when the delay between phases was zero.

Placing an anode and a cathode along the length of the muscle and on the side opposite to nerve entrance resulted in better selectivity at the low end of the recruitment range. This electrode configuration also exhibited a lower recruitment gain than was obtained for a monopolar electrode in the same position. Much larger stimulus currents were required for bipolar electrodes than for monopolar electrodes.

Examination of tissues surrounding the electrodes 30 days after implantation showed that the electrodes were encapsulated in the fascial layer. Slightly larger dependence on muscle length and lower selectivity of stimulation were measured after encapsulation than were measured in the acute experiments.

INTRODUCTION

Electrical stimulation of neural tissues can be used to restore control over absent or abnormal body functions. In our laboratory, multistrand stainless steel (316L) intramuscular (IM) electrodes have been employed to activate paralyzed muscles of the upper-extremities [6,7]. The IM electrodes perform well for laboratory and preliminary clinical tests, but present three major disadvantages for long-term patient utility: repeated bending and flexing during muscle contractions eventually result in breakage [8], the recruitment characteristics (relationship between stimulus amplitude or pulse width and evoked force) vary with electrode position, and muscle length [2], and may also vary with time due to change of the electrode position relative to nerve branches [9]. Some of the problems associated with length variability may be remedied with closed-loop control [3]. However, the controller will be more reliable if the length dependence of recruitment is minimized or eliminated [4].

The lifetime of the electrode and/or its lead may be the most important limitation in the development of motor prostheses. An electrode positioned on the surface of the muscle epimysium will be subjected to much less bending during muscle shortening than the IM electrode placed in the belly of the muscle. Since the bending is less, the expected lifetime of an epimysial electrode and lead could be expected to be greater than that of the IM electrode. Surgical placement of an epimysial electrode could be accomplished easily for many muscles being used for hand-arm control and it should be well suited for use with an implantable stimulator. An evaluation of the recruitment characteristics of this electrode is required before further clinical investigation.

METHODS

Acute experiments: Fifteen adult cats were studied using the Soleus muscle (5 cats), or the Tibialis Anterior (TA) and the Extensor Digitorum Longus (EDL) muscles (10 cats). The animal were anesthetized with intramuscular injection of ketamine hydrochlorine (25 mg/kg) with atropine sulfate (0.03 mg/kg) to reduce salivation. The cephalic vein was cannulated, and anesthesia was maintained with sodium pentobarbital administred i.v. as needed in 5 to 10 mg increments. The animals were intubated and maintained on a respirator (Harvard Apparatus Co) throughout the data collection procedure at rates and volumes indicated by the manufacturer to be appropriate to their respective body weights. Surgical techniques used to expose the Soleus muscle were similar to those described by Crago et al. [2]. For TA and EDL preparations, the distal portion of the TA tendon was exposed and maximal physiological length was marked by a suture in the tendon and a stationary metal pin placed in the distal tibia. The tendon of TA was freed at the most distal point and attached to a stiff cable. EDL maximal physiological length was marked by a suture in the tendon placed 15 mm distal from the metal pin. Care was always taken not to interfere with blood supply to the muscles. The common peroneal nerve was cut 4 cm proximal to its insertion into muscle , and a cuff electrode was placed around the distal portion for whole nerve stimulation at supramaximal amplitudes. The hindlimb was secured in a frame with clamps on the distal and proximal ends of the tibia. The distal tendons of Soleus or TA and EDL were attached to rigid force transducers. EDL was set at 6 mm less than its maximal physiological length for all experiments. The temperature of the limb was maintained between 35 and 38 degrees C by radiant heat.

Epimysial electrodes (5x3 mm) were made of 316L stainless steel with a Dacron reinforced silicone rubber (10x8 mm). Monopolar and bipolar electrode configurations were studied

(Fig.1). A monopolar electrode was sutured to the surface of the Soleus (on the same side as nerve entrance) or, in experiments involving the stimulation of the Tibialis Anterior, to the surface of the muscle, either on the side of nerve entrance or on the side opposite to nerve entrance. The indifferent electrode, for monopolar excitation, was always a 22 gauge hypodermic needle , 5 cm long, placed in the subcutaneous space along the midline of the back. Two electrodes were sutured to the surface of the TA (opposite to the side of nerve entrance) for bipolar electrode activation. The cathode was placed at the motor point of the TA, and the anode was placed distal or proximal to it. The distance (D) between cathode and anode varied from 4 mm to 20 mm. Electrode positions were measured with respect to the nerve entrance into the muscle (when the electrode was on the side of nerve entrance), or relative to the motor point of the muscle (when on the side opposite to nerve entrance). All measurements, unless otherwise indicated, were made when the muscle was at maximal physiological length. The motor point was designated as the point of lowest electrical threshold for superficial muscle fiber activation. It was located using a 2 mm diameter circular metal probe, and was always a unique position on the muscle surface. Isometric evoked forces were measured as a function of stimulus parameters (amplitude and duration), muscle length, and electrode position on the surface of the muscle. Forces for the given muscle length were normalized to the maximal force obtained with supramaximal nerve stimulation, applied through a bipolar cuff electrode. Nerve stimulation was performed before and after each set of measurements to take into account changes in maximal force. Muscle length (L) was measured with respect to its maximal physiological length (e.g. L=-4mm indicates that muscle length is 4 mm less than maximal physiological length).

Stimuli were rectangular, regulated current monophasic (cathodic) and rectangular balanced-charge biphasic single pulses, 300, 100, 50, and 30 us wide. The delay between primary (cathodic) and secondary (anodic) pulses for biphasic stimulation varied from 0 to 80 usec.

The selectivity of activation was evaluated by measuring the evoked force in the EDL in response to a stimulus applied to TA (electrode placement shown in Fig.1).

Chronic experiments: Two monopolar electrodes (5x3 mm, lead length = 100 mm) were aseptically sutured on the TA of four adult cats. One electrode was placed between the TA and EDL, and the other was placed on the superficial surface, slightly proximal to the motor point. After 30 days of implantation with no stimulation applied, acute measurements as previously described were performed. Prior to surgery, radiographs of each leg were made in order to locate electrodes and leads. The end of the electrode lead was dissected with care to minimize perturbation of the electrode. At the end of the measurements, the rear leg muscles and tibia were removed and fixed in 10% buffered formalin with TA and EDL held at maximal physiological length. Following fixation, electrodes were careful removed and 16 mm sections of muscles were cut and stained with hematoxylin and eosin

RESULTS

Effect of electrode position: The recruitments characteristics of a monopolar electrode placed on the side of nerve entrance into the muscle had a sigmoidal shape. Inscreased current threshold and increased length dependence were observed as the electrode was moved away from the point of nerve entrance into the muscle. The recruitment rate also decreased as the electrode moved away from the nerve entrance. In Figure 2a are plotted the recruitment characteristics for three muscle lengths obtained with an electrode placed on the Soleus close to the nerve entrance (distally). All 3 cats studied showed similar behavior. Recruitment characteristics were measured for different electrode positions distal to the nerve entrance. The effect of electrode position on the recruitment was evaluated by plotting the normalized forces developed by stimuli of equal magnitude at L = -4 mm against those developed at L = -12 mm (Fig.2b). This procedure described by Crago et al. [2], eliminates the length-tension dependence of force from data analysis and enables easy visualization of length dependence of recruitment. Deviation from a 45 degree line indicates a length dependence of the recruitment characteristics.

The recruitment characteristics of a monopolar electrode placed on the side opposite to nerve entrance into the muscle show a more gradual recruitment rate than that measured with a similar electrode on the side of nerve entrance. The length dependence increases as the electrode moves awy from the motor point of the muscle. In Figure 3a are shown the recruitment characteristics obtained with a monopolar electrode 5 mm proximal to the motor point of Tibialis Anterior (side opposite to nerve entrance into the muscle), and how muscle length affected the recruitment. The muscle length dependence of the recruitment was measured for different electrode positions distal and proximal to the motor point. It was found to be the lowest for an electrode slightly proximal to the motor point (Fig.3b). All cats studied showed similar behavior, although the magnitude of muscle length dependence and recruitment characteristics varied from one animal to another. The point of least muscle length dependence was always at a point slightly proximal to the motor point (less than 5 mm).

The recruitment rate for an electrode placed on the side of nerve entrance to the TA (between TA and EDL) was found to be similar in all aspects to that reported for the Soleus in the three cats studied.

Selectivity of stimulation: Spread of stimulus current sufficient to induce adjacent muscle (e.g. EDL) contractions when TA is desired could be observed in all cases studied. Generally, the threshold of stimulation of adjacent muscles was higher than the muscle with the electrode, but the threshold was lower than the current required to fully activate the intended muscle. The degree of adjacent muscle activation increased as the electrode was moved farther from the nerve entrance. In Figure 4 are shown the curves obtained by plotting the evoked force in the EDL versus the force evoked in the TA; stimuli were applied to TA with monopolar epimysial electrodes placed close to the motor point of TA or close to nerve entrance into TA, with a bipolar electrode (discussed below), and with an intramuscular electrode. The deinsulated tip of the IM electrode (10 sq.mm) was placed 10 mm proximal to motor point and 5 mm below the superficial surface of the muscle. The selectivity of stimulation measured for both the monopolar epimysial electrode placed close to the motor point on the side opposite to nerve entrance of TA and the intramuscular electrode are similar: 25% of the maximum force of TA could be evoked without evoking a force in EDL. The selectivity of stimulation was markedly better with the electrode placed between the TA and EDL, and close to the nerve entrance into TA: 90% of TA force could be evoked before measurable force in EDL was observed.

Effect of pulse width: Recruitment rate was found to be dependent on the stimulus pulse width and on the delay between the cathodic and anodic pulses. The effect of pulse width on the recruitment rate was measured using Soleus preparation with regulated current cathodic monophasic and balanced-charge biphasic pulses. The recruitment rate decreased with decreasing pulse width. An additional decrease could be obtained using biphasic pulses. As the delay between primary and secondary pulses was decreased, the slope of the recruitment curve decreased. These findings agree with those reported for stimulation with nerve cuff electrode [5].

Effect of distance between cathode and anode: Recruitment characteristics for bipolar activation were found to be dependent on the distance (D) between anode and cathode. Recruitment rate was found to be lower with this electrode configuration than with a monopolar electrode placed in a similar position. Recruitment characteristics for a bipolar electrode placed on the side opposite to nerve entrance into TA are shown in Figure 5 for two distances between anode and cathode. Also shown is the recruitment characteristics abtained with the same cathode used in the monopolar mode. For D = 4 mm, only a small number of muscle fibers were recruited at the highest stimulus amplitude (30 mA). As the distance D increased to 20 mm, more fibers could be recruited, and the maximum force of the TA could be evoked with a current of 30 mA.

Selectivity of stimulation with bipolar electrode: Bipolar stimulation was found to be more selective than monopolar activation for the lower half range of forces developed by TA. In Figure 4 is shown the result obtained with a bipolar electrode (D = 20 mm) placed on the side opposite to nerve entrance (TA). The cathode was at the motor point. The TA could be activated up to 50% of the nromalized force before evoking a force in EDL. The selectivity, however, strongly decreased as more TA motor units were recruited. This configuration was less selective than a monopolar electrode placed at the motor point for the upper range of forces from TA.

Chronic implants: Examination of the implant site 30 days after implantation revealed that the encapsulation layer around the electrode was always incorporated into the fascia and that the electrodes did not move with the muscle, as had been the case with the acute experiments. Encapsulation of the electrodes placed close the motor point was thick, especially on the Silastic backing side of the electrode (1-2 mm). The electrode was loose within the encapsulation pocket. The encapsulation of the electrodes between TA and EDL was always thinner. These observations were consistant for each of the four animals.

The recruitment dependence on muscle length was slightly greater, and the selectivity of stimulation was lower than anticipated from acute experiments for similar electrode positions. In Figure 6a is shown the recruitment length dependence obtained with monopolar electrodes placed in the vicinity of the motor point of TA and between TA and EDL, close to nerve entrance into TA. The dependence is moderate but higher tahn measured in acute preparations for similar electrode positions.

In Figure 6b is plotted the selectivity obtained for the two electrode positions. Compared with results reported in Figuire 4, selectivity is slightly lower for both electrode positions.

DISCUSSION

This study of the relationship between recruitment and electrode position provides insight into the properties that might be expected from the motor prostheses that employ epimysial electrodes. The anatomical configuration of the three muscles evaluated in this study (Soleus, Tibialis Anterior, and Extensor Digitorum Longus of cats) have many similarities with the muscles that might be employed in these devices. In these studies the recruitment characteristics have been found to be dependent on the location of the electrode. Two locations (the motor point and a site very close to the point of motor nerve entrance into the muscle) have been identified that exhibit recruitment properties which are considered important for motor prostheses. Both of these locations are characterized by having a high density of motor nerve fibers near the electrode or close to the surface of the muscle and near the electrode. The recruitment propertiues of these two locations are sufficiently different that they will be discussed separately.

The results of our study for electrodes placed near to the site of motor nerve entrance into the muscle are summarized in graphical form in Figure 7a. Electrodes positioned closest to the nerve required the least stimulus strength to effect excitation, and the length dependence of recruitemnt was also least. The relatively low stimulus level required to effect muscle excitation, when the electrode was positioned close to the nerve , accounts for the localization of the stimulus to one muscle, even though the electrode was in close contact with an adjacent muscle. At electrode locations close to the nerve, the recruitment rate and the relative gain (the recruitment rate normalized to the threshold current) were the highest. The rapid rate of recruitment may be reduced by using narrow biphasic stimulus pulses, as described by Gorman and Mortimer [5]. As the electrode was moved more distal to the site of motor nerve entrance, larger stimulus amplitudes were required and greater length dependence of recruitment was emcountered. The realtive gain and recruitment also decreased. Electrodes positioned close to the nerve, in general, will provide more desirable properties than those further from the nerve, unless the high relative gain makes the motor prostheses difficult to control. If the relative gain is excessively high, an electrode positioned close to the motor point, as described in the next paragraph, should be considered.

The results of our studies for electrodes positioned close to the motor point are summarized in graphical form in Figure 7b. The sensitivity of any one property was found to be relatively small for changes in electrode position near the vicinity of the motor point. The ability to activate the desired muscle to near maximumlevels, without exciting neighboring muscles, was found to be difficult, as indicated by the value of 0.6 for the selectivity rather than a value closer to 1.0. Using a bipolar electrode rather than a monopolar electrode improved the selectivity at the lower end of the recruitment scale, but showed poorer selectivity at the higher end of scale. The required stimulus for maximal activation may be reduced by increasing the distance between the anode and cathode. Increasing the separation improves the electric field penetration, since it varies as the cube root of the electrode separation [1]. The point of optimal location for an epimysial electrode is judged to be a position that is slightly proximal to the motor point.

The findings from the implant experiments that the electrode encapsulation was encorporated in the fascial layer overlaying the muscle has imnportant implications for the extrapolation of these results to human use. The effect of the encapsulation will be to move the electrode away from the "optimal" location, which will result in decreased selectivity, recruitment rate, and relative gain. Increased stimulus amplitude will be required and increased length dependence can be expected. The increase in length dependence of recruitment will depend on the motion of the motor point relative to the fascial layer. If there if little relative motion, the increase may not be significant. In the cat TA, the motor point is located at the proximal end of the muscle, and there is little relative motion between the fascial layer and the muscle during muscle contraction. If there is substantial relative motion between the muscle and fascial layer, the length dependence of recruitment may be severely degraded as the electrode becomes encapsulated.

Acknowledgements: The authors express their appreciation to Drs P.H. Peckham and P.E. Crago for time and suggestions they gave during this study, Dr. U. Roessmann for assistance in the histological examination, K. Jackson and L. Fay for fabrication of the electrodes, and the staff and students of the Applied Neural Control Laboratory for their assistance.

References:

[1] Comte, P.A., Monopolar versus bipolar stimulation. Applied Neurophysiology 45:156, 1982.
[2] Crago, P.E., P.H. Peckham, and G.B. Thorpe. Modulation of force by recruitment during intramuscular stimulation. IEEE Trans. BME 27:679, 1980.
[3] Crago, P.E., J.T. Mortimer, and P.H. Peckham. Closed-loop control of force during electrical stimulation of muscle. IEEE Trans. BME. 27:306, 1980.
[4] Crago, P.E. Control of movements by functional neuromuscular stimulation. IEEE Engineering in Medicine and Biology Magazine. vol.2, 3:32, 1983.
[5] Gorman, P.H. and J.T. Mortimer. The effect of stimulus parameters on the recruitment characteristics of direct nerve stimulation. IEEE Trans. BME 30:407, 1983.
[6] Peckham, P.H. and J.T. Mortimer. Restoration of hand function in the quadriplegic through electrical stimulation. Functional electrical stimulation: New York, Dekker, 1977, 83.
[7] Peckham, P.H., E.B. Marsolais, and J.T. Mortimer. Restoration of key grip and release in the C6 quadriplegic through functional electrical stimulation. J. Hand Surgery 5:462, 1980.
[8] Peckham, P.H., G.B. Thorpe, and E.B. Marsolais. Percutaneous intramuscular excitation of paralyzed skeletal muscles: electrode reliability. Proc. 4th Annual Conf. on Rehabilitation Engr: Washington D.C., 1981, 229.
[9] Trnkoczy, A. Variability of electrically evoked muscle contraction with special regard on closed-loop controlled orthosis. Ann. of BME 2:226, 1974.
[10] van den Honert, C. and J.T. Mortimer. The response of the myelinated nerve fiber to short duration biphasic stimulation currents. Ann. Biomed. Engr. vol. 7, 117, 1979.

' present address : Medtronic B.V.
Research and Support Center
Kerkrade, Holland

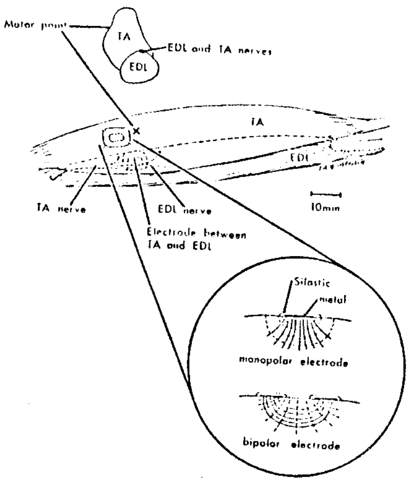

Figure 1: Anatomy of cat leg showing the proximity of Tibialis Anterior and Extensor Digitorum Longus and the epimysial monopolar and bipolar electrodes.

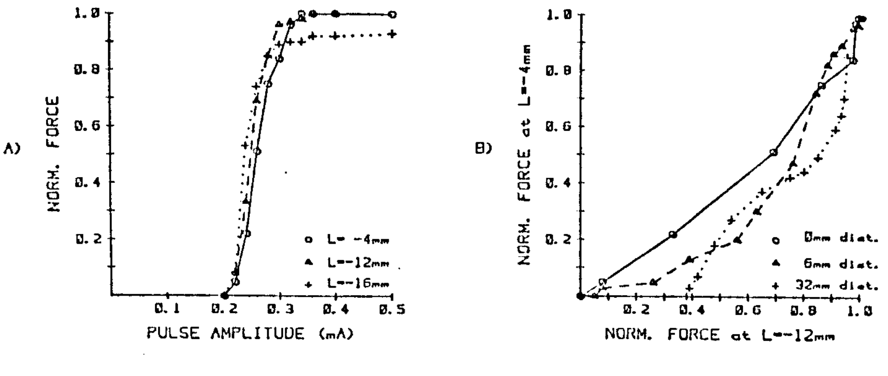

Figure 2: Recruitment characteristics for 3 muscle lengths (A) and length dependence for 3 electrode positions (B) obtained with a monopolar epimysial electrode placed on the Soleus (side of nerve entrance). Muscle lengths (L) are given with respect to the maximal physiological length. Electrode positions are given with respect to the nerve entrance into the muscle. Normalized forces in (B) at L=-4mm are plotted versus normalized forces at L=-12mm (developed by equal stimuli). Stimuli were 100 us monophasic current pulses.

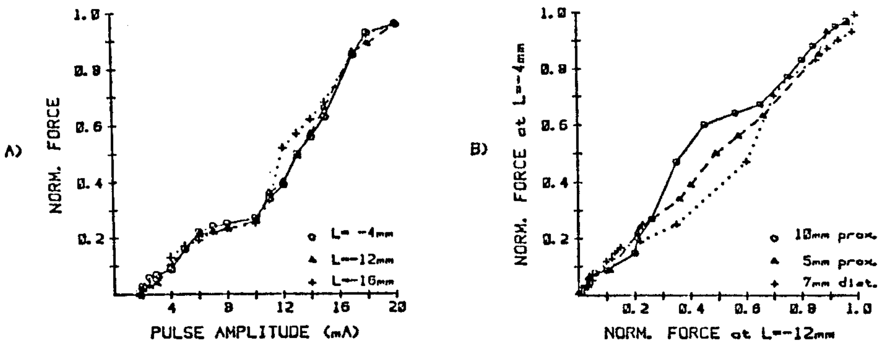

Figure 3: Recruitment characteristics for 3 muscle lengths (A) and muscle length dependence for 3 electrode positions (B) obtained with a monopolar epimysial electrode placed on the side opposite to nerve entrance of Tibialis Anterior. Electrode position is given with respect to the motor point and was 5 mm proximal in (A). Length dependence was minimal for an electrode slightly proximal to the motor point. Stimuli were 100 us monophasic current pulses.

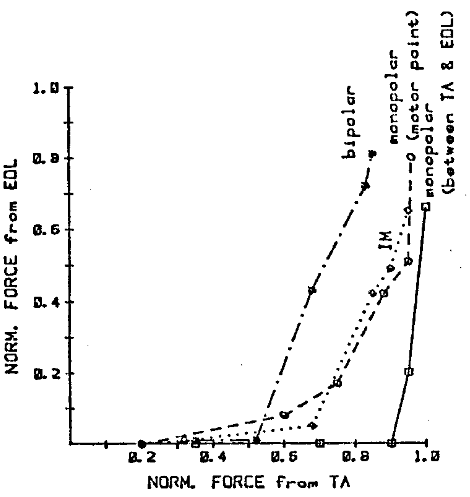

Figure 4: Selectivity of stimulation obtained with a monopolar epimysial electrode close to motor point (---), a monopolar epimysial electrode close to nerve entrance between TA and EDL (——), a bipolar epimysial electrode with cathode at motor point of TA and anode 20 mm proximal (-•-), and an intramuscular electrode placed 10 mm proximal to the motor point and 5 mm under muscle surface of TA (...).

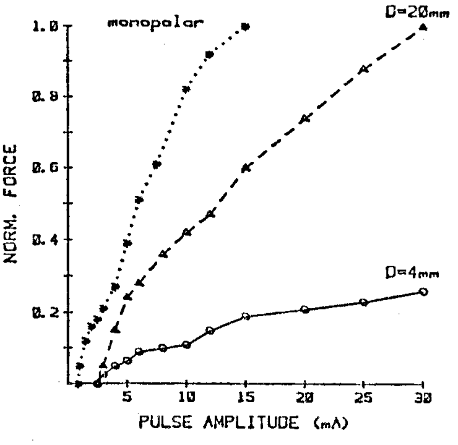

Figure 5: Recruitment characteristics of bipolar epimysial electrodes for 2 distances between cathode and anode. Cathode was placed at the motor point of TA, anode was proximal to it. Also shown is the recruitment characteristic of a monopolar epimysial electrode placed at the motor point of TA. Larger D allowed recruitment of all fibers. Recruitment rate was lower for bipolar configuration than for monopolar. However, stimulus amplitudes were larger. Stimuli were 300 us monophasic current pulses.

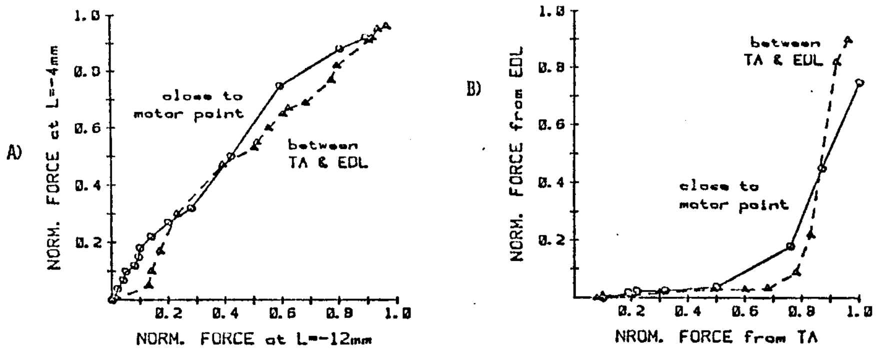

Figure 6: Length dependence of recruitment (A) and selectivity of stimulation (B) after 30 days of implantation obtained with 2 monopolar epimysial electrodes placed close to motor point of TA (——) and close to nerve entrance of TA (between TA and EDL) (---). Stimuli were 100 us monophasic current pusles.

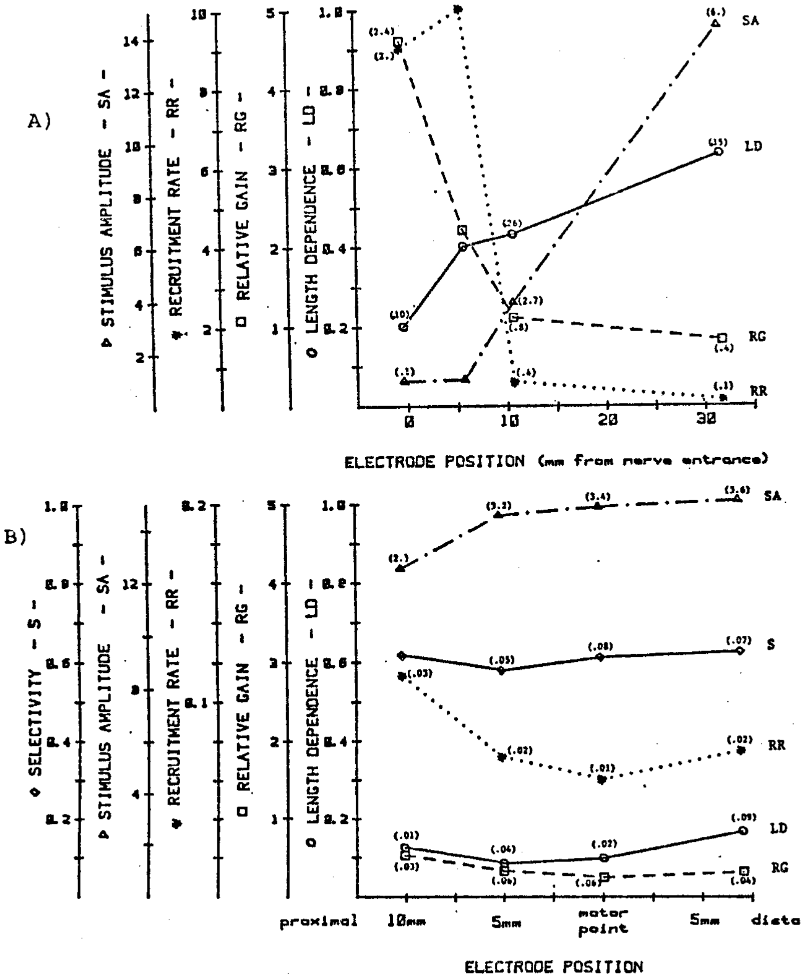

Figure 7: Variations of characteristics of monopolar electrodes with electrode position:

(A) electrode on side of nerve entrance of Soleus

(B) electrode on side opposite to nerve entrance of Tibialis Anterior

The length dependence (LD) is calculated as the area included between the unity slope line and recruitment curves of Fig.2 and 3, normalized to the area included between the unity line and the x-axis. This latter surface equals the maximum possible muscle length dependence.

The recruitment rate (RR) is the average slope of the curve normalized force vs stimulus amplitude measured between F=80% and F=10%, PW = 100 us.

The relative gain (RG) is the recruitment rate with the current normalized to the threshold current and is calculated in the following way:

$$RG = (\Delta F)/(\Delta I/Ith)$$

where $\Delta F = F2 - F1 = 0.8 - 0.1$; $\Delta I = I(F2)-I(F1)$
and Ith = current threshold = $I(F=0.1)$.

The stimulus amplitude (SA) is the current magnitude required to evoke 80% of the maximal muscle force.

The selectivity of stimulation (S) is defined here as the normalized force evoked in TA for 10% force evoked in EDL.

Number between parentheses are standard errors calculated for 3 animals in (A) and 5 animals in (B).