Selective Control of Muscle Activation with a Multipolar Nerve Cuff Electrode

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***Abstract*— Acute experiments were performed on adult cats to study selective activation of medial gastrocnemius, soleus, tibialis anterior, and extensor digitorum longus with a cuff electrode. A spiral nerve cuff containing twelve "dot" electrodes was implanted around the sciatic nerve and evoked muscle twitch forces were recorded in six experiments. Spatially isolated "dot" electrodes in four geometries: monopolar, longitudinal tripolar, tripolar with four common anodes, and two parallel tripoles, were combined with transverse field steering current(s) from an anode(s) located 180° around from the cathode(s) to activate different regions of the nerve trunk. To quantify the degree of selectivity, a selectivity index was defined as the ratio of the force in one muscle to the force in all four muscles in response to a particular stimulus. The selectivity index was used to construct recruitment curves for a muscle with the optimal degree of selectivity. Physiological responses were correlated with the anatomical structure of the sciatic nerve by identifying the nerve fascicles innervating the four muscles, and by determining the relative positions of the electrodes and the nerve fascicles. The results indicated that the use of transverse field steering current improved selectivity. We also found that tripoles with individual dot anodes were more selective than tripoles with four common dot anodes. Stimulation with two parallel tripoles was effective in activating selectively fascicles that could not be activated selectively with only a single tripole. The multipolar cuff proved an effective method to control selectively and progressively the force in muscles innervated by fascicles that were well defined at the level of the cuff.**

I. Introduction

CUFF-TYPE electrodes capable of activating selectively regions of a nerve trunk offer an expanded range of opportunities for the development of motor prostheses. These electrodes offer enhanced reliability, greater ease of implantation, and occasion to consider control strategies that are limited by the ability to localize the electric field to discrete regions of a large nerve trunk, rather than by the practical number of electrodes and leads that can be physically tolerated by a patient.

Restoration of motor function in spinal cord-injured patients by electrically activating the motor nerves serving paralyzed muscles requires the control of a large number of different muscles. Up to thirty-two muscles are activated for rehabilitation of locomotion in paraplegics and hemiplegics [9], and up to eight muscles are activated to restore hand grasp to quadriplegics [14]. In both cases investigators expect that even more muscles will be activated in future systems as the demand for refined control increases. Present motor prostheses use at least one electrode to activate each muscle. Implanted epimysial electrodes or coiled wire intramuscular electrodes require an extensive surgical implant procedure and maintenance of a large number of electrodes. Problems with breakage and movement of coiled wire intramuscular electrodes [8] occur because of the large stresses they experience during limb position changes and when crossing tissue planes. Additionally, both intramuscular [4] and epimysial electrodes [6] suffer from recruitment properties that depend on muscle length. Stimulation through cuff electrodes placed around the nerve has the advantages that it may not suffer from length dependent recruitment properties, the electrodes need not withstand the mechanical stresses experienced by intramuscular electrodes since nerve electrodes can be positioned in regions of relatively low stress, and lower excitation thresholds reduce system power requirements [13].

Caldwell [3] reported electromyographic studies indicating selective activation of the gastrocnemius and tibialis anterior muscles of the rabbit using eight wire electrodes around the sciatic nerve. McNeal and Bowman [10], using a rigid cuff-type electrode, showed that the ankle flexors and extensors could be activated selectively if the electrodes were in snug contact with the nerve. However, the results were dependent on the position of the electrodes which could not be precisely controlled. Until recently, snug-fitting nerve cuffs were not considered safe [1]. There are now two electrode designs available that provide snug contact between the electrodes and the nerve trunk without causing neural damage, the CWRU Spiral [11], [12] and the Huntington Helix [2].

Sweeney, *et al.* [17] reported on the results of a preliminary set of experiments designed to explore the efficacy of a single tripolar electrode with a "steering" anode in selectively activating a single fascicle of a multifascicular nerve trunk. With the position of the tripole carefully selected they demonstrated a significant improvement in selectivity of a peripheral fascicle with transverse current from the steering anode. The study demonstrated that the subthreshold transverse current restricted the region of excitation to the periphery of the nerve trunk. In this paper we report on an investigation of selective activation using a 12-electrode spiral nerve cuff that was placed without prior reference to locations of specific fascicles.

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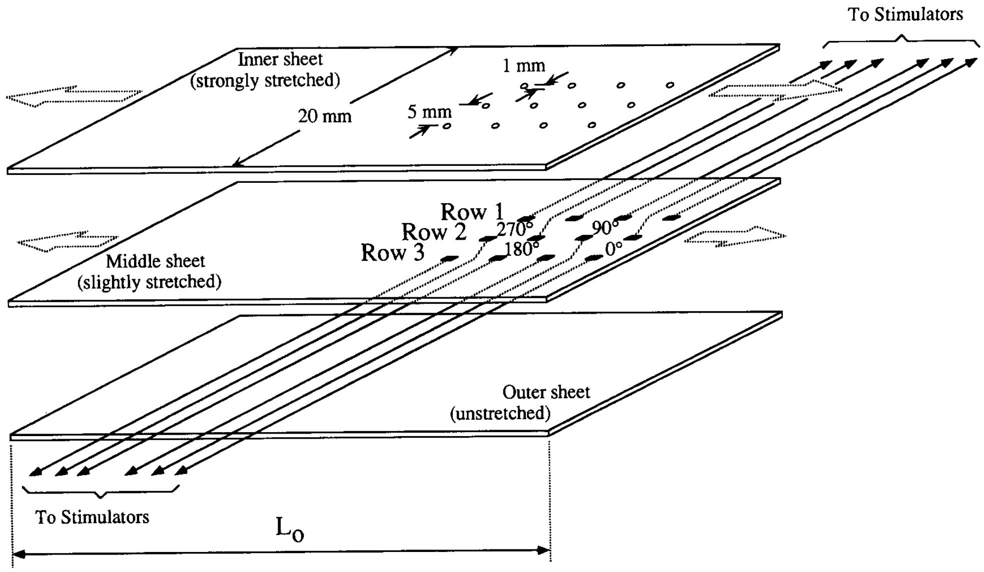


Fig. 1. Fabrication of multipolar spiral nerve cuff electrode. Twelve 1 mm × 2 mm platinum foil electrodes, spot-welded to stainless steel multistrand lead wires, were inserted through three rows of four perforations made in the middle sheet of 50 μm thick silicone rubber. The electrodes were organized in four tripoles labeled from 0° to 270° according to their eventual position around the nerve in the curled cuff. After being stretched, the intermediate sheet was bonded to the unstretched (outer) sheet with the lead wires between the layers and oriented perpendicularly to the direction of stretch. The resulting bi-layer was then bonded to a third (inner) stretched sheet. Circular windows, 1 mm diameter, were cut to expose the electrodes, and the cuff was trimmed according to the desired dimensions.

We combined spatially isolated electrodes and transverse field steering currents to test the performance of the nerve cuff in the selective and progressive control of force in four muscles innervated by the sciatic nerve. Experiments were also undertaken with the goal of optimizing the number and spatial arrangement of stimulating electrodes within the cuff. Preliminary results of this study have been previously reported [7].

II. Methods

A. Electrode Design and Fabrication

Spiral nerve cuffs were fabricated by modifying the method of Naples *et al.* [12] to create a trilayer silicone rubber cuff that included four longitudinal tripoles of recessed 1-mm-diameter platinum dot electrodes, each with a separate lead (Fig. 1). The design allowed implementation of a tripolar electrode configuration (cathode between two anodes) at four locations every 90° around the circumference of the nerve trunk, and use of transverse field steering current from a dot electrode located 180° around the trunk from the cathode of the tripole (Fig. 2).

Three rows of four perforations were made in a 50μm thick sheet (middle sheet in Fig. 1) of silicone rubber (SCIMED Surgical, Minneapolis, MN) using a 23-gauge hypodermic needle. The rows were spaced 5 mm apart and the distance between perforations in each row was between 2.0 and 2.75 mm, depending on the intended final inside diameter of the cuff (2.5 to 3.5 mm). Teflon® insulated multistrand 316L stainless steel wires (Cooner Wire Co., Chatsworth, CA) were spot-welded to 2 mm by 1 mm pieces of 35 μm thick platinum foil (Johnson Mathey, Pittsburgh, PA) and were passed through each perforation until all the electrodes lay flat on the silicone rubber sheet. The position of each electrode in the array was thus determined by the position of the perforation and was maintained during the remainder of the fabrication process.

The middle sheet, with the platinum electrodes facing downward, was clamped at both ends leaving length $L_m = 155/\sqrt{(1 + (1.3/d))}$ between the clamps, where d is the intended internal diameter of the cuff. The sheet was then stretched to length $L_o = 155$ mm between the clamps, and bonded to a second 50 μm thick unstretched sheet (outer sheet in Fig. 1) of silicone rubber as described by Naples *et al.* [12]. The lead wires ran between the two sheets and were oriented perpendicularly to the direction of stretch. A third 50 μm thick silicone rubber sheet (inner sheet in Fig. 1) was clamped at both ends at length $L_i = L_m^2/L_o$ and stretched to length L_o between the clamps. The proportion of stretch of the inner layer with respect to the middle layer was thus equal to the proportion of stretch of the middle layer with respect to the outer layer. The bilayer of the outer and middle sheets containing the electrodes, maintained at length L_o, was then bonded to the stretched inner sheet. Circular windows, 1 mm in diameter, were cut in the inner layer using a sharpened section of hypodermic tubing to expose the electrode surfaces, yielding electrodes that were recessed by 50 μm below the inner surface of the cuff. The recession creates a more uniform current density across the surface of the electrode [15], which will help to minimize corrosion at the edges of the electrodes [16] in applications requiring chronic stimulation. The cuff, with the 12 leads, was cut out and trimmed to a width of 20 mm, leaving 5 mm between each external rows of electrodes

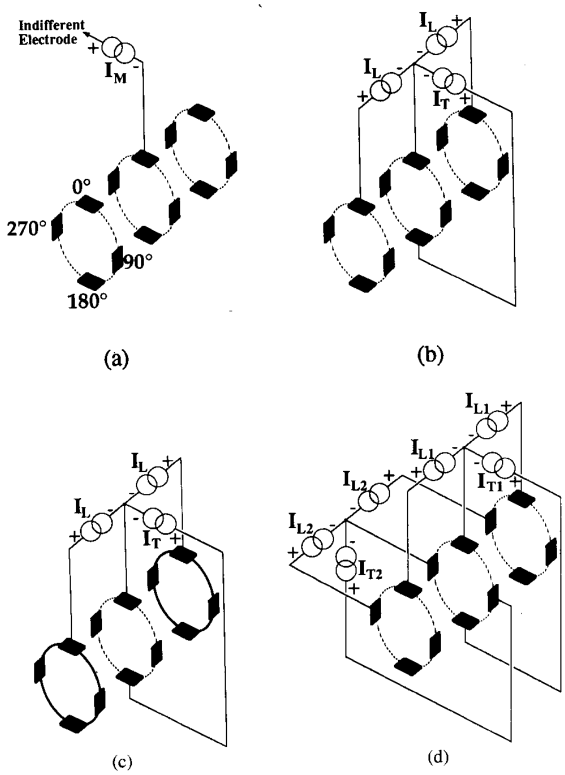


Fig. 2. The four electrode configurations investigated in this study. In each configuration, the 12 electrodes are represented in a perspective view according to their position inside the cuff around the nerve trunk. a) Monopolar configuration: one of the electrodes from the central row served as the cathode and a subcutaneous hypodermic needle served as the anode. b) Longitudinal tripolar configuration with an opponent steering anode: I_L refers to the intensity of the longitudinal current and I_T to the transverse or steering current. c) Tripolar configuration with steering and common anodes: the four electrodes in each external row were connected together to simulate a band anode at each end of the cuff. d) Adjacent tripoles with steering: the configuration of 2b was duplicated for two adjacent tripoles.

and the ends of the cuff. The length of the unrolled cuff was trimmed to between 32 and 50 mm, depending on the diameter of the nerve trunk, to provide two full wraps of the cuff around the nerve trunk. The 12 leads were gathered in a common connector and checked for possible short- or open-circuit conditions and for insulation failure. The diameters of the cuffs were between 2.5 and 3.5 mm to fit the range of diameters measured for the cat sciatic nerve [D. G. Atzberger and J. T. Mortimer, unpublished results].

B. *Experimental Procedure*

Acute experiments were performed on six adult cats. Animals were anesthetized with an I.M. injection of ketamine hydrochloride (30 mg/kg) and atropine (0.044 mg/kg). A venous catheter was installed and I.V. injections of sodium pentobarbital were delivered as needed to maintain the proper level of anesthesia. The animal was intubated and body temperature was monitored and maintained at $38.5(\pm 1)$°C with a heating pad. The medial gastrocnemius (MG), soleus (Sol), tibialis anterior (TA), and extensor digitorum longus (EDL) muscles of the right hindlimb were surgically isolated. Small needles were inserted in a bone lying near the distal tendon of each isolated muscle to serve as landmarks. A piece of suture material was inserted in the tendon of each muscle at the level of the needle to mark its maximum physiological length, and the four tendons were transected. The right sciatic nerve was mobilized for approximately 4 cm just proximal to its branching point into tibial and common peroneal components. Sciatic nerve diameter was determined by measuring its circumference with a piece of Prolene® suture [11]. A cuff was selected that provided a cuff-to-nerve diameter ratio of approximately one and installed with its distal end lying approximately 1 cm proximal to the branching point of the sciatic nerve. A cuff-to-nerve diameter ratio of one has been found safe in chronic animal studies [11], and ensured that the tripoles of the cuff were aligned at 90° intervals around the nerve trunk. The animal was placed in a stereotaxic frame and the right hindlimb was immobilized in a slightly flexed position by fixing the knee and ankle joints. The four muscle tendons were attached to adjustable rigid force transducers and set at their maximum physiological lengths by positioning each tendon suture beside its corresponding bone landmark. Each force transducer was an aluminum proof ring with four semiconductor strain gauges oriented in a bridge configuration to measure the linear strain. After amplification, signals from the force transducers were recorded on strip-chart paper. The temperature of the muscle preparation was maintained using radiant heat, and the exposed tissues were regularly soaked with body temperature saline.

C. *Stimulation and Recording*

Six regulated-current stimulators, designed and fabricated in our laboratory, were optically coupled to a switch box that allowed rapid setting of the selected electrode configuration, and display of every stimulation pulse for confirmation of pulse duration and amplitude. Monophasic rectangular 10 μs pulses were used for all currents. The pulse width was chosen to maximize the threshold differences between nerve fibers of different diameter [5]. When an electrode configuration required two or more stimulators all current pulses were in phase.

In the first configuration, monopolar stimulation (Fig. 2(a)), one of the four electrodes in row 2 (see Fig. 1) acted as the cathode and a subcutaneous hypodermic needle served as the anode. In the second configuration, tripolar stimulation with an opponent steering anode, three stimulators were used; one of the four tripoles was connected to two stimulators, and the central electrode in the opponent tripole (lying 180° around the nerve trunk) was connected as an anode to a third stimulator (Fig. 2(b)). The current I_L that passed between each external anode and the central cathode in a tripole was equal and was referred to as the *longitudinal current.* The *transverse current*, I_T, was passed from the opponent anode to the cathode of the longitudinal tripole. Following Sweeney *et al.* [17], the electric field modification induced by using a nonzero transverse current was referred to as the *steering effect*. In the third configuration, tripolar stimulation with steering and common anodes, the stimulator connections were identical to those used in tripolar stimulation with an opponent steering anode, except that the four dot electrodes in each external row were connected together (Fig. 2(c)). This configuration was intended to simulate the use of two band anodes. Using a cuff with two band, rather than eight dot, anodes would simplify electrode fabrication and reduce the number of external leads from twelve to six. In the fourth configuration, adjacent tripoles with steering, connections used in tripolar stimulation with an opponent steering anode were duplicated using a second group of three stimulators connected to a second tripole and its respective steering anode (Fig. 2(d)). The longitudinal current was always equal in both tripoles of the adjacent pair. This configuration was used to simulate intermediate positioning of four additional tripoles located at 45 °, 135°, 225°, and 315° in the cylindrical coordinate system of the cuff. Recruitment curves for the four muscles were collected using all four tripoles with each electrode configuration.

Successive isometric muscle twitches were evoked by trains of four to five pulses, at a frequency between 0.15 and 0.3 Hz. The responses of the muscles to electrical stimuli were evaluated by determining the mean evoked twitch force. With the exception of very small responses (lower than 5 percent of the maximum force), for which a twitch was elicited only by the first stimulus, the amplitude of successive twitches was steady and did not vary by more than 10 percent. No facilitation in successive responses evoked at this frequency was observed. Rest periods of at least 20 s were allowed between successive bursts of stimuli. Using each of the four tripoles, recruitment curves were recorded by changing either the monopolar current amplitude (I_M in Fig. 2(a)) or the longitudinal current amplitude (I_L in Fig. 2(b)) to elicit muscle forces between zero and maximum force. When an electrode configuration used field steering up to six values of steering current, I_T, in a range from 0 to a value that was beyond the transverse threshold for excitation, were tested. For each value of transverse current the longitudinal current was varied from below threshold to supramaximal for the four muscles studied. Thresholds were assessed by the appearance of a just detectable contraction of any of the four muscles (in the range of 0.1 to 0.2 N). The transverse threshold current was determined by passing current between the opponent electrode in row 2, used as an anode, and the cathode of the longitudinal tripole, also in row 2.

D. Data Analysis

Values of evoked twitch force were normalized to the maximum value of twitch force to evaluate the relative efficacy of each stimulating condition in the selective activation of the different muscles. Maximum twitch forces varied as a function of time during the length of an experiment (12–16 hours), however, no systematic trend in the evolution of muscle force was observed. For a specific electrode configuration the mean value of these changes (percentage increase of the highest value of maximum force with respect to the lowest value of maximum force) remained below 20 percent. Considering responses to all of the electrode configurations used during an experiment, for a given muscle the changes varied from 0 to 60 percent. Changes in maximum force associated with different electrode configurations were likely due to alterations in the activation patterns of the nerve fibers innervating a given muscle.

The maximum values of evoked force measured in the different muscles were approximately 5 N for Sol and EDL, 10 to 15 N for TA, and greater than 50 N for MG (the maximum force for MG was out of the amplifier's calibrated range, and only relative forces were measured with the decalibrated amplifier). Although efforts were made to ensure that the stereotaxic frame was rigid, the large forces generated by the MG could flex the frame enough to influence the forces measured from the other muscles. The EDL muscle, which was attached to a force transducer just below the MG force transducer, appeared to be the most affected by crosstalk. In the worst cases crosstalk resulted in a 40 percent decrease in the measured force for the EDL; however, this had no significant effect on the conclusions presented here.

In all animals but the first, three to five recruitment curves were collected with the monopolar configuration (Fig. 2(a)) at the beginning and end of data acquisition, and at intermediate time intervals of between 3 and 5 hours. Recruitment curves collected with the monopolar configuration were considered to be standard tests to evaluate muscle responses, and they were used as a measure of variation of maximum twitch force over time. Accordingly, all data collected during the time interval between two successive monopolar recruitment stimulations were normalized by dividing the response of each muscle by the mean of its two maximum forces measured at the beginning and end of the time interval using the monopolar configuration. In the first animal, twitch forces were normalized by the maximum values evoked by each of the four tripoles.

Two- and three-dimensional graphs of normalized twitch force versus current amplitude were constructed to compare either the responses of the four muscles to the same stimulating condition or the responses of a single muscle to different stimulating conditions. These graphs allowed a qualitative evaluation of selective muscle activation by comparison of relative muscle forces elicited by a specific electrode configuration. Using these graphs, however, it was difficult to determine the stimulating condition (current amplitude and electrode configuration) that yielded the maximum selectivity of a muscle over a given range of forces. To quantify the activation by a specific stimulating condition of a single muscle, M_i, among a set of N muscles a selectivity index, S.I., was defined as the ratio between the normalized force exhibited by that muscle, FM_i, and the sum of the normalized forces elicited in all N muscles.

$$\text{S.I.}\,(i, \text{stimulating}, \text{condition}) = \frac{FM_i}{\sum_{j=1}^{N} FM_j}$$

Graphs of the selectivity index versus normalized force were constructed to determine the stimulating condition that allowed

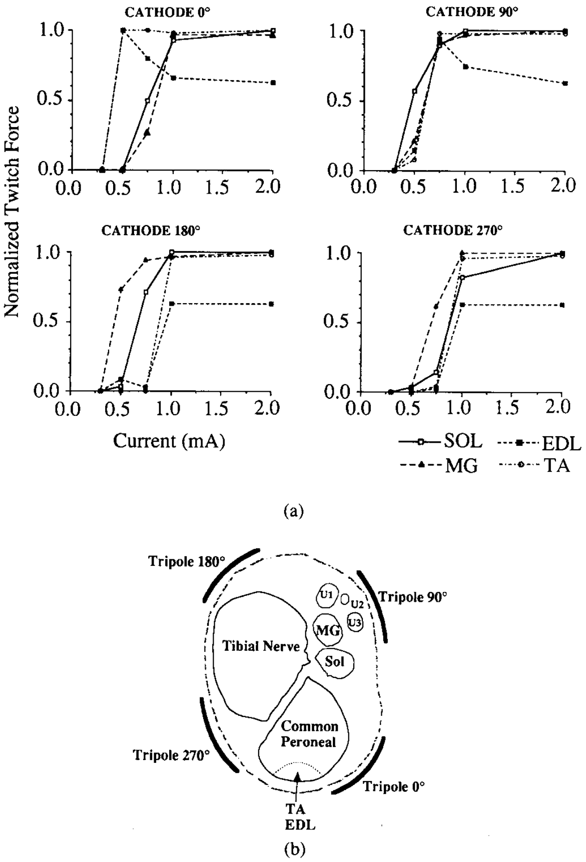


Fig. 3. Interpretation of monopolar recruitment curves with topographical data. a) Recruitment curves of normalized twitch force as a function of current amplitude for the 4 studied muscles collected using the monopolar configuration with each of the four central electrodes (Fig. 2(a)). b) The fascicular organization of the sciatic nerve traced from a stained section taken at the middle of the cuff showing the relative locations of the electrode contacts and fascicles. MG = medial gastrocnemius, Sol = soleus, EDL = extensor digitorum longus, TA = tibialis anterior, and U1, U2, and U3 were unidentified fascicles (Cat #924).

the most selective activation of a muscle over a full range of forces.

E. Histological Procedures

At the end of each experiment the animal was perfused to facilitate identification of the electrode positions with respect to each fascicle. The chest was opened and the pericardium cut away. Heparin sodium (1500 units) was injected into the left ventricle and allowed to circulate for 2 min. The aorta was then cannulated through an incision made in the left ventricle, and the right atrium was cut to provide an exit point for the perfusates. A liter each of warm saline (39°), warm glutaraldehyde (3.5% in 25 mM sodium cacodylate buffer), cold glutaraldehyde (5°), and cold paraformaldehyde (1% in 25 mM sodium cacodylate buffer) was perfused into the aorta by means of a peristaltic pump.

The position of the cuff was marked by inserting two or three pieces of suture material aligned with the tripoles at both ends of the cuff into the outer layer of the epineurium. The tibial and common peroneal nerves were identified, and the terminal branches innervating the MG, Sol, TA, and EDL were dissected from the muscles proximally toward the cuff and identified using pieces of suture. The sciatic nerve was then excised from 10 to 15 mm proximal to the cuff to the end of the four terminal branches, and the cuff was removed. Three sections of the sciatic nerve corresponding to proximal and distal ends of the cuff and to the middle of the cuff were cut for histological preparation. From these samples, 1 μm thick sections were cut and stained with Masson's trichrome, hematoxyline and eosin, and crimbring myelin stains. The terminal branches of the MG, Sol, EDL, and TA were carefully dissected toward the section made at the distal end of the cuff, and their corresponding fascicle or position in all three nerve sections was assessed using a surgical microscope and recorded on videotape.

III. Results

A. Influence of Electrode Configuration

1) Monopolar stimulation: Three to five recruitment curves were recorded during each experiment using the monopolar configuration (Fig. 2(a)). A typical example is shown in Fig. 3. These results show a single group of monopolar recruitment curves (among three) for one animal. The recruitment of the four muscles is in good agreement with the position of each electrode, except perhaps MG whose activation by the cathode in position 90° may have been impaired by the presence of the three smaller unidentified fascicles (U1, U2, U3). The twitch force amplitude of EDL appears to decrease when the stimulus amplitude is increased using the 0° and 90° electrodes, and with electrodes 180° and 270 °, the force of the EDL did not reach its maximum value. In both cases this phenomenon occurred when the force exerted by the MG became significant, indicating that it was the result of crosstalk as discussed in Sec. II.

2) Tripolar stimulation with transverse steering current: Three-dimensional graphs of normalized twitch force as a function of transverse current amplitude and longitudinal current amplitude (Fig. 2(b)) were constructed to examine the effects of modulating both currents. The results from one animal are shown in Fig. 4. By stimulating with different tripoles at different locations around the nerve trunk it was possible to control the recruitment order of the four muscles. In this example TA was preferentially activated using tripole 0° (Fig. 4(a)), Sol was preferentially activated using tripole 90° (Fig. 4(b)), and MG was preferentially activated using tripole 180° (Fig. 4(c)). No muscle was selectively activated using tripole 270 ° (Fig. 4(d)). The changes in recruitment order were consistent with the relative locations of the tripoles with respect to the different fascicles illustrated for the same animal in Fig. 3(b). As discussed in the section devoted to the quantification of selectivity, the bold arrows in Fig. 4(a), (b), and (c) indicate the path up the recruitment surface that maximizes selectivity (i.e., S.I. maximized) of a specific muscle.

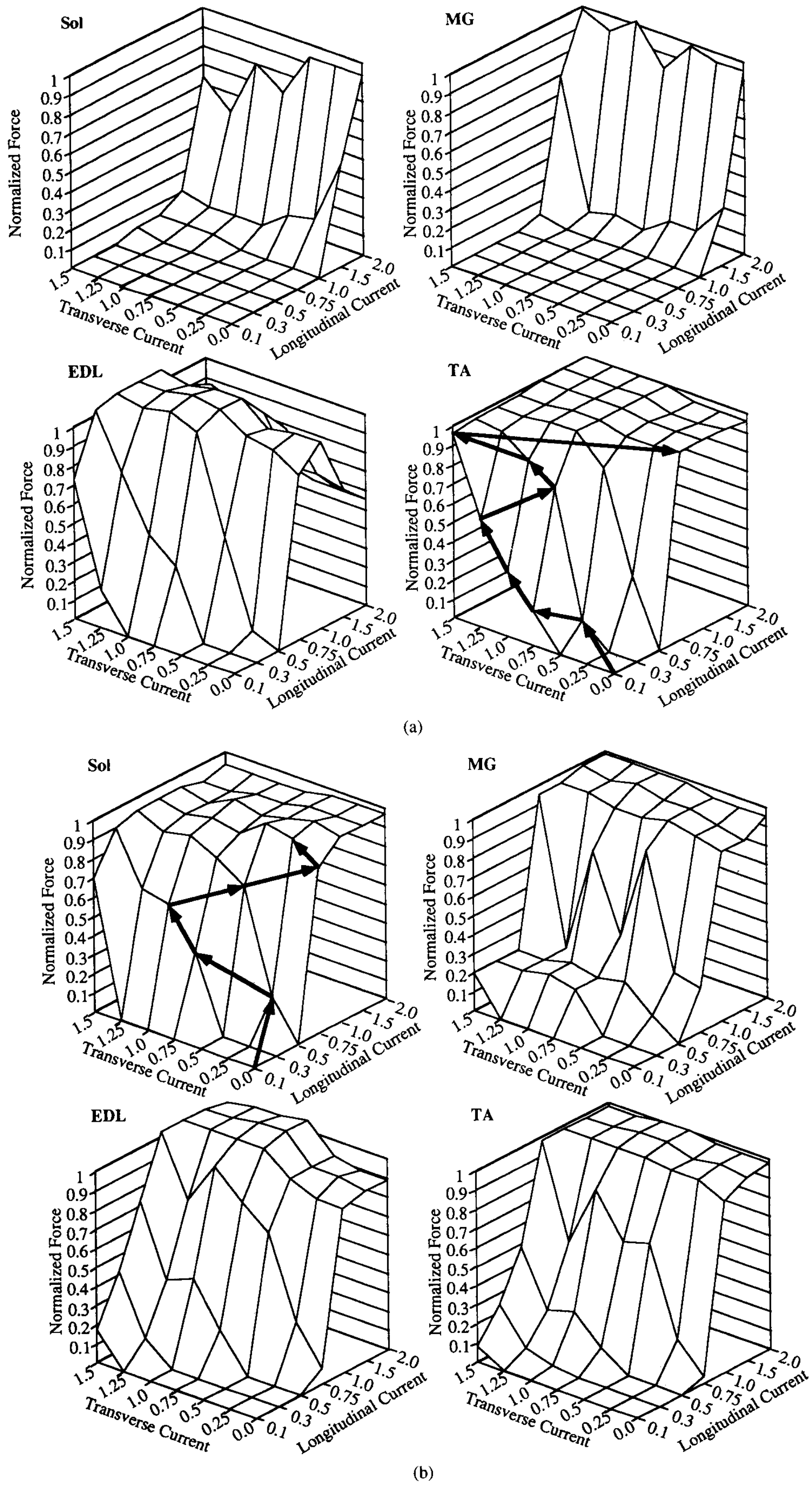
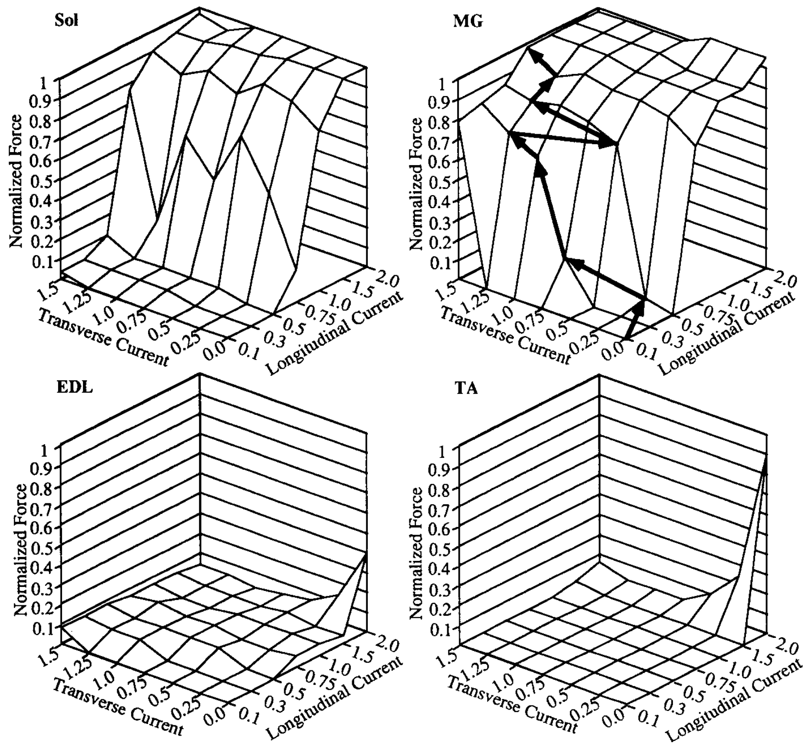
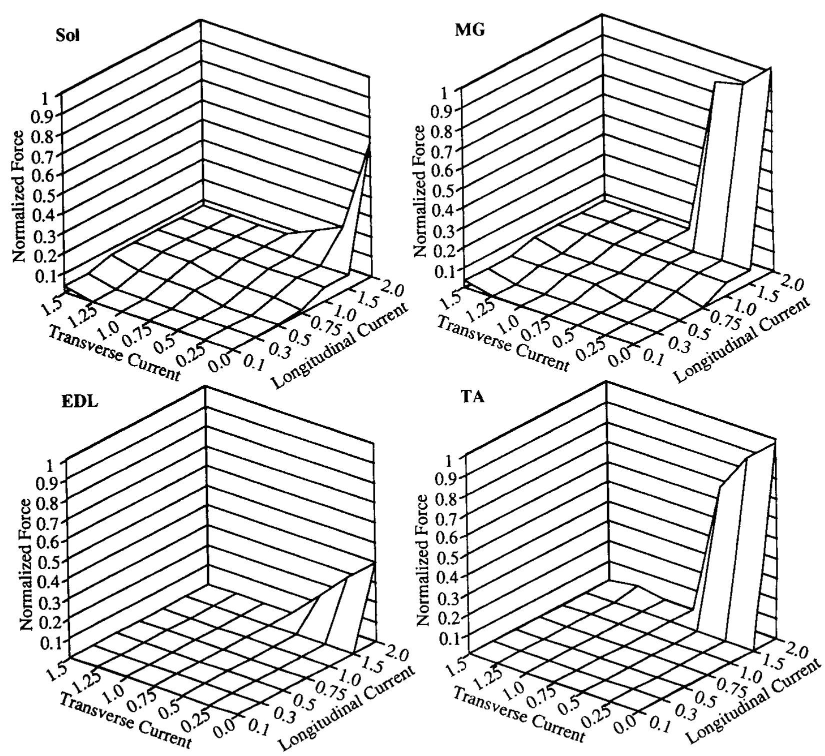


Fig. 4. Example of recruitment by modulation of the longitudinal and transverse current amplitudes. Three dimensional recruitment surfaces show normalized twitch force as a function of both longitudinal and transverse current amplitudes from the tripolar electrode configuration (Fig. 2(b)). All currents are in mA. (a) Tripole 0°: Tibialis anterior was preferentially activated. (b) Tripole 90°: Soleus was preferentially activated.



(c)



(d)

Fig. 4. (cont.) (c) Tripole 180 °: Medial gastrocnemius was preferentially activated. (d) Tripole 270°: no muscle was selectively activated with this tripole. As explained in the section of the results devoted to the quantification of selectivity, the bold arrows show the recruitment path for maximum selectivity of TA, Sol, and MG in (a), (b), and (c), respectively (Cat #924).

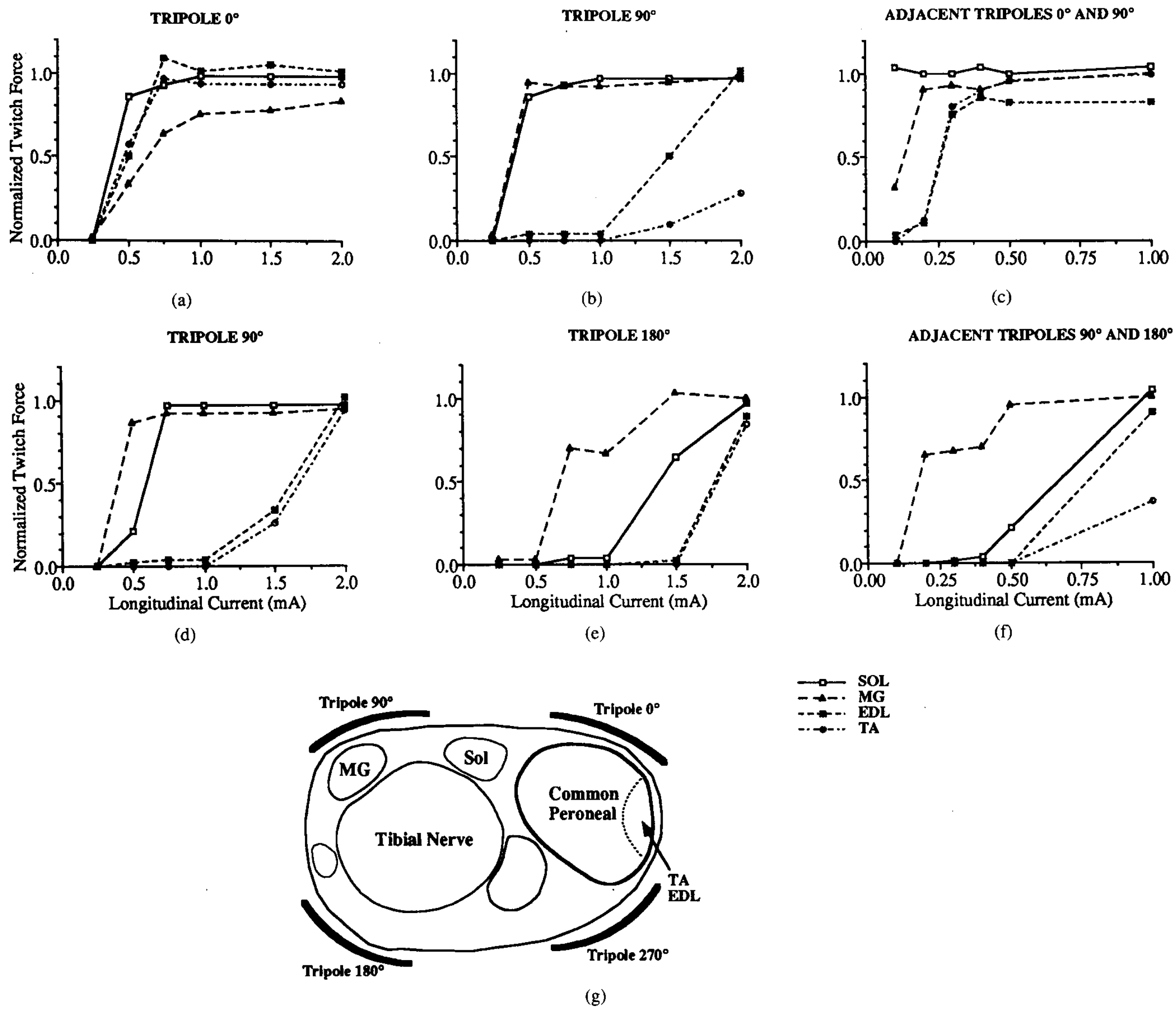


Fig. 5. Examples of improvement of selectivity using adjacent tripoles. Refer to Fig. 2(d). Recruitment curves collected using a) triple 0° with $I_T = 0.5$ mA, showing no selective activation, b) tripole 90° with $I_{T2} = 0.6$ mA showing activation of both Sol and MG, and c) tripole 0° with $I_{T1} = 0.5$ mA and triple 90° with $I_{T2} = 0.6$ mA showing selective activation of Sol with adjacent tripoles. Recruitment curves collected using d) tripole 90 ° with $I_T = 0$ mA showing activation of both Sol and MG, e) tripole 180° with $I_T = 1.0$ mA showing limited degree of selective activation of MG, and f) tripole 90° with $I_{T1} = 0$ mA and tripole 180° with $I_{T2} = 1.0$ mA showing improved selectivity of MG with adjacent tripoles. g) The fascicular organization of the sciatic nerve traced from a stained section taken at the middle of the cuff showing the relative locations of the electrode contacts and fascicles (Cat #933).

Muscle force could be controlled by modulating either the transverse or longitudinal current amplitude, but the selectivity of muscle activation was dependent on the chosen sequence of stimulating conditions. As an example, consider the activation of soleus in Fig. 4(b). Without steering (transverse current = 0), the activation of Sol was limited to only one point ($I_L = 0.75$ mA) for which force of Sol is higher than the forces of the other three muscles. The influence of steering on selective activation can be demonstrated by comparing recruitment curves without steering current to those with a nonzero value of transverse current. With the addition of steering current (e.g., $I_T = 0.25$ or 0.5 mA), it was possible to recruit Sol over 100 percent of its force range with less than 30 percent force from the TA, EDL, and MG. The steering current could also be used to recruit directly force from a given muscle. Considering the family of recruitment curves obtained by varying the transverse current magnitude for fixed values of the longitudinal current (e.g., $I_L = 0.3$, 0.5, or 0.75 mA), a more selective activation of Sol was possible. In general, to achieve maximal selectivity for a given muscle over a full range of forces, it was necessary to modulate the amplitude of both the longitudinal and transverse currents.

3) Tripolar stimulation with common anodes: In four cats the performance in selective activation achieved with tripolar stimulation (two dot anodes, Fig. 2(b)) was compared to that achieved using tripolar stimulation with common anodes to approximate a band-type anode at each end of the cuff (Fig. 2(c)). Recruitment curves were recorded by modulat-

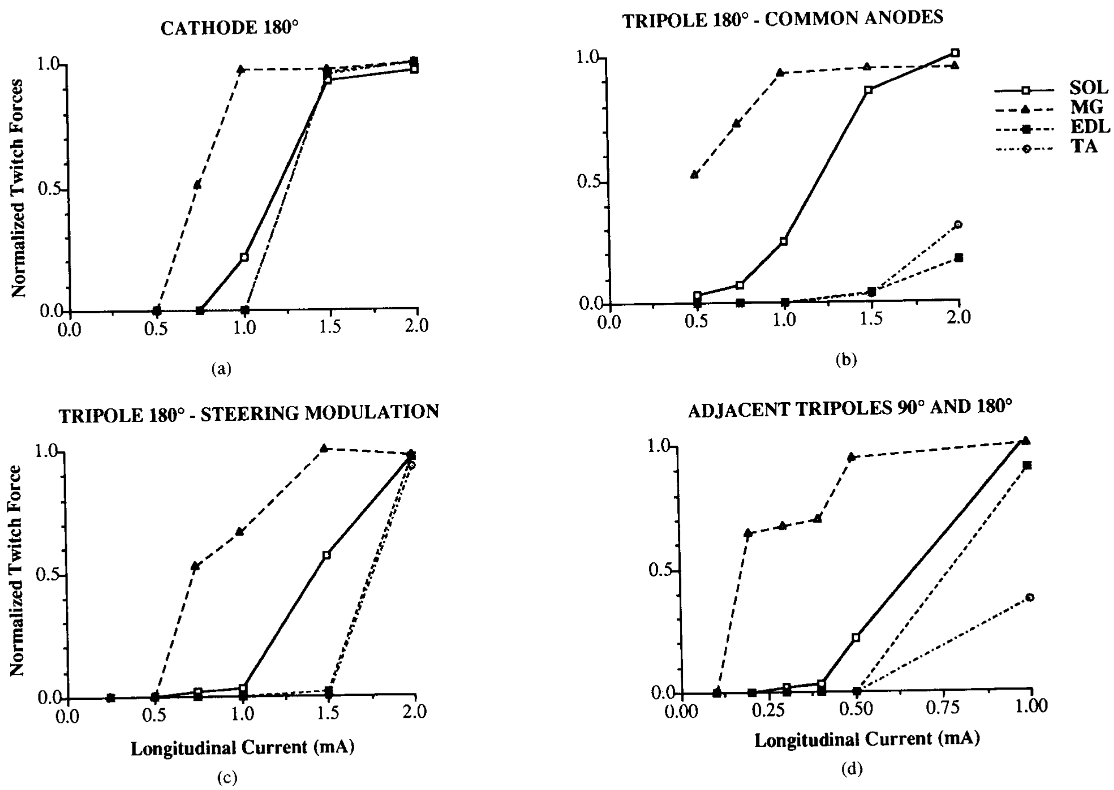


Fig. 6. Example of similar performance in selective activation using different electrode configurations. Recruitment curves of normalized twitch force as a function of longitudinal current amplitude showing some selectivity in MG activation. a) Monopolar configuration using cathode 180°. b) Tripolar configuration with common anodes using tripole 180° with $I_T = 2.0$ mA. c) Tripolar configuration using tripole 180° with $I_T = 0.5$ mA. d) Adjacent tripoles configuration using tripole 90° with $I_{T1} = 0$ mA and tripole 180° with $I_{T2} = 1.0$ mA (Cat #933).

ing the longitudinal current under four different stimulating conditions: two dot anodes with no transverse current, two dot anodes with transverse current, common anodes with no transverse current, and common anodes with transverse current. The value of transverse current was chosen just below the transverse threshold for each of the four tripoles to maximize the *steering* effect. The selectivity index for each point was computed to compare quantitatively the different stimulating conditions. Graphs of S.I. as a function of the normalized twitch forces were plotted for the results of each stimulating condition.

Among all of the data collected with these four electrode configurations, there were eighteen cases (distributed among twelve muscles in four cats) in which a single muscle was selectively activated (i.e., the value of the selectivity index for that muscle was greater than 0.5 over the full force range). In six of the eighteen cases (33 percent), selective activation of a given muscle over a full range of forces required use of both the two-dot-anodes configuration and the common-anode configuration. The three cases (17 percent), the two configurations yielded identical results. In seven cases (39 percent), the two-dot-anodes configuration provided better selectivity than the common-anode configuration, and in two cases (11 percent) the common-anode configuration provided better selectivity than the two-dot-anodes configuration. No changes in this pattern were observed with and without steering current. Thus in 72 percent of the cases considered here, the two-dot-anodes configuration was required to avoid any decrease in the level of selective activation.

4) Stimulation with adjacent tripoles: In three cats the performance of stimulation with adjacent tripoles (two tripoles in parallel, Fig. 2(d)) was investigated. Recruitment curves were collected by modulating the longitudinal current in both tripoles (the magnitude of the longitudinal current was always the same for each of the adjacent tripoles) with four different steering current configurations: no steering, subthreshold steering current from the opponent anode of one tripole, subthreshold steering current from the opponent anode of the other tripole, and subthreshold steering current from the opponent anodes of both tripoles.

When combined with field steering, the adjacent tripolar configuration was effective in activating fascicles that could not be activated selectively using a single tripole. In certain cases, as illustrated in Figs. 5(a) and (b), it was not possible to isolate a specific muscle (Sol in this case) using a single tripole with steering. However, when two tripoles were combined, selective activation of the Sol was possible (Fig. 5(c)). Use of two tripoles was also effective in enhancing the selectivity

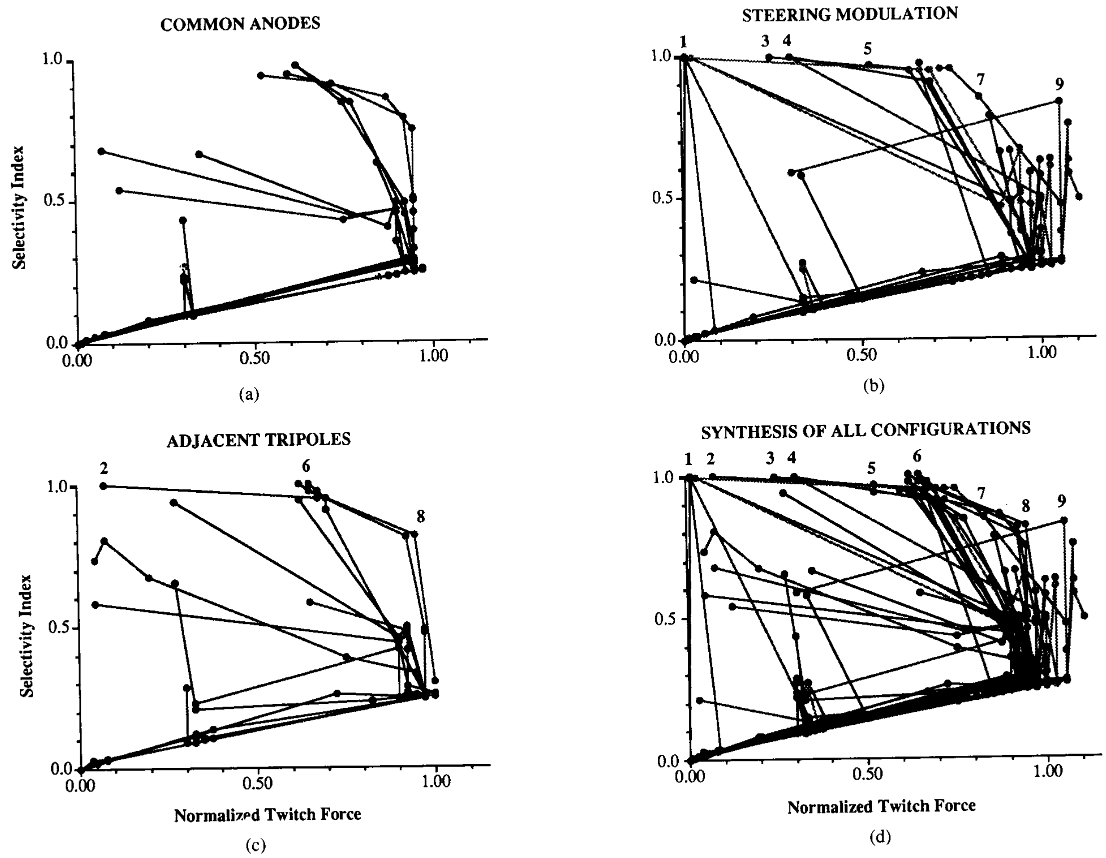


Fig. 7. Quantification of selectivity. Graphs of S.I. as a function of normalized twitch force of MG computed for all stimulating conditions chosen with different electrode configurations. In these graphs, each point corresponds to specific intensities of the longitudinal and transverse current(s), and the lines connect points common to a single recruitment curve. a) Tripolar configuration with common anodes and steering. b) Tripolar configuration with steering. c) Adjacent tripolar configuration. d) Superposition of all data points collected with the three previous electrode configurations. Points 1 and 9 in (d) constitute a selection of data points corresponding to the highest value of S.I. over the full range of MG forces. These points are identified in graphs (b) and (c) according to the electrode configuration with which they were collected. The electrode configurations and stimulus currents for each point are given in Table I. (Cat #933).

of a given muscle as seen when comparing the activation of MG with single tripoles (Figs. 5(d) and (e)) and with two adjacent tripoles (Fig. 5(f)). These results were consistent with the location of the electrodes with respect to the fascicles (Fig. 5(g)).

B. Quantification of Selectivity

When considering the results of all electrode configurations, it was difficult to determine the electrode configuration that yielded the most selective activation of a given muscle. This problem is illustrated in Fig. 6 when considering the most selective activation of MG using four different electrode configurations: monopolar, tripolar with steering, tripolar with steering and common anodes, and adjacent tripolar with steering. The locations of the electrodes with respect to the fascicles are shown in Fig. 5(g).

To quantify the degree of selectivity of a muscle under different conditions the selectivity index was computed as described in Sec. II. The graphs in Figs. 7(a), (b), and (c) show the S.I. for MG plotted as a function of the normalized twitch force evoked using three different electrode configurations. In these graphs each point corresponds to specific intensities of the longitudinal and transverse current(s), and the lines connect points common to a single recruitment curve. The data from these three graphs were superimposed, as shown in Fig. 7(d), to determine the maximum selectivity of MG using all of these configurations. The path of maximal selectivity was determined by choosing the points that corresponded to the highest value of S.I. over the full range of MG forces. These points are labelled 1 through 9 in Fig. 7(d), and the corresponding normalized forces are plotted in Fig. 8(a) as a function of the stimulating condition that elicited them. The electrode configurations and stimulus currents used for each of these points are given in Table I. The stimulating conditions corresponding to the nine points that yielded maximal selectivity of MG required two different electrode configurations: tripolar with steering for points 1, 3, 4, 5, 7, and 9, and adjacent tripolar with steering for points 2, 6, and 8.

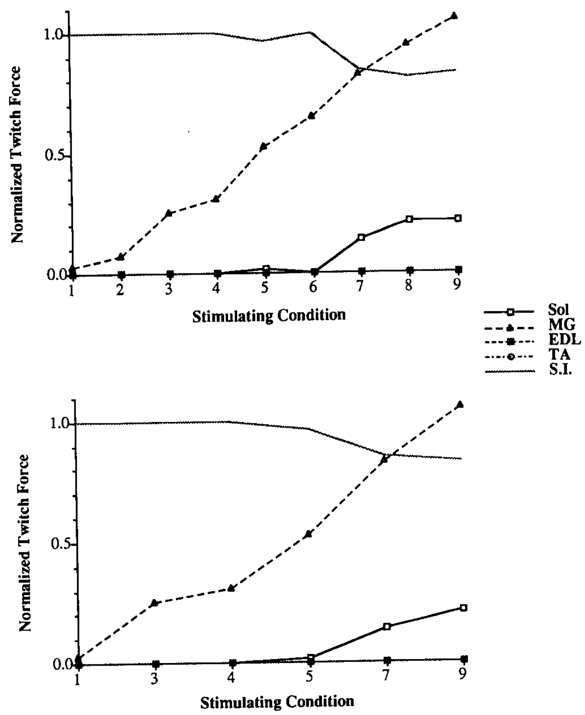


Fig. 8. Most selective recruitment of MG with different electrode configurations. Compound recruitment curves reconstructed with the 9 data points selected in Fig. 7(d). In addition to normalized twitch force of each of the 4 muscles, the values of S.I. corresponding to the MG data points are also plotted. a) Most selective activation of MG in one animal using all electrode configurations. The 9 configurations and stimulus currents are given in Table I. b) Most selective activation of MG using only steering modulation with tripole 180°. The labeling of the 6 data points in the same as in (a), and the stimulating currents are given in Table I. (Cat #933).

TABLE I
STIMULATING CONDITIONS CORRESPONDING TO THE NUMBERED POINTS IN FIGURES 7 AND 8

Number	Stimulating Condition		
	Tripole	Longitudinal Current (I_L) mA	Transverse Current (I_T) mA
1	180°	0.25	1.0
2	180°	0.2	1.0
	270°	0.2	0.0
3	180°	0.75	0.25
4	180°	0.75	0.0
5	180°	0.75	0.5
6	90°	0.2	0.0
	180°	0.2	1.0
7	180°	1.0	1.5
8	90°	0.5	0.0
	180°	0.5	1.0
9	180°	0.5	2.0

If the sequence of different electrode geometries necessary to maximize the selectivity of MG were judged to be impractical when considering a functional motor prosthesis, then a simplified protocol may be required. Examination of the conditions required to activate the MG indicated that most of the points on this curve were evoked using tripole 180° with different values of longitudinal and transverse currents. A new plot of force as a function of stimulating condition was constructed as shown in Fig. 8(b) using only points that correspond to data collected using tripole 180° with transverse steering current. The improvement in selective activation achieved when using this last compound recruitment curve (Fig. 8(b)) can be evaluated by comparing it to the best recruitment curve of MG using tripolar stimulation with a single fixed value of transverse current intensity as shown in Fig. 6(c) for the same animal. The specific sequences of current magnitudes that produced the best selectivity for TA, Sol, and MG in another experiment were computed using the same method, and are represented by the bold arrows in Figs. 4(a), (b), and (c). This illustrates that tripolar stimulation with steering current modulation is an effective method for selectively controlling the force in each muscle, and that it is necessary to modulate both the longitudinal stimulus current amplitude and the transverse field steering current amplitude to maximize selectivity.

C. Fascicular Organization of the Sciatic Nerve and Position of the Cuff

Measurements of sciatic nerve diameter *in situ* as described in Sec. II (mean ± standard deviation: 2.7 mm ± 0.3 mm; number of animals, $N = 4$) were similar to diameters calculated from circumference measurements made from histological sections (2.8 mm ± 0.4 mm; $N = 6$). At the end of each experiment the orientation of the cuff around the nerve trunk was determined before removing it, and the position of each tripole was carefully noted. In the first experiment, the chosen cuff was too small and the positions of the steering anodes were not directly opposite the active tripoles. Furthermore, the inner edge of the cuff parallel to the longitudinal axis of the nerve bent into the epineurium, leaving a spacing of about 1 mm between tripole 0° and the nerve trunk surface. This edge-bending effect is believed to have been caused by residual stresses in the silicon rubber sheeting, and was alleviated by trimming the inner edge of all cuffs using a razor blade [11]. In the last four experiments the proper choice of cuff was assured by measuring the nerve diameter, and electrode opposition observed at the end of each experiment was satisfactory. When the cuffs were removed no evidence of edema or neural damage was noted. Histological examination of stained cross sections of the nerve trunk revealed normal-looking nerve fibers with no evidence of neural damage. However, this was an acute preparation and neural damage may not be observable in the period of time of this experiment (12–16 hours).

The fascicular arrangement of the sciatic nerve varied along the three sections taken at the proximal end of the cuff, at the center, and at the distal end. The number of well defined fascicles surrounded by perineurium increased from proximal to distal sections (nonsignificant differences): 6.4 ± 1.7 in the proximal sections ($N = 5$), 7.3 ± 2.4 in the central sections ($N = 6$), and 8.4 ± 3.4 ($N = 5$) in the distal sections. The increase in the number of fascicles was likely a result

TABLE II
SUMMARY OF SELECTIVE ACTIVATION OF EACH MUSCLE IN ALL SIX EXPERIMENTS. THE NUMBERS INDICATE THE MAXIMUM VALUE OF THE SELECTIVITY INDEX FOR EACH MUSCLE AT 100% RECRUITMENT (MG = MEDIAL GASTROCNEMIUS, SOL = SOLEUS, EDL = EXTENSOR DIGITORUM LONGUS, TA = TIBIALIS ANTERIOR, EDL + TA = SELECTIVITY INDEX COMPUTED FOR THE COMBINED PAIR OF EXTENSOR DIGITORUM LONGUS AND TIBIALIS ANTERIOR).

Cat #	MG	Sol	EDL	TA	EDL + TA
875	1.0	0.53	<0.5	<0.5	1.0
893	0.64	0.60	0.63	<0.5	0.63
892	0.91	0.56	<0.5	<0.5	1.0
918	0.60	0.56	0.60	<0.5	1.0
924	0.60	0.57	<0.5	0.60	1.0
933	0.83	0.77	<0.5	<0.5	1.0

of the subdivision of a large fascicle into two or more other fascicles. It was sometimes difficult to assess the identification of a particular fascicle at all three levels because the position of a fascicle and or the number of fibers in a fascicle changed between levels. Nevertheless, it appeared that the position of fibers devoted to the control of a given muscle remained roughly the same inside the nerve, and thus probably along the 20 mm length of the cuff.

As explained in Section II, the branches innervating the four studied muscles were identified. Assessment of the cuff position with respect to the sciatic nerve allowed the identification of the position of the four tripoles with respect to the fascicles (Fig. 9). The tibial and common peroneal components of the sciatic nerve were identified in all cases, as well as the Sol and MG branches in three experiments. In all cases the fibers innervating the TA and EDL muscles did not form well-defined fascicles at the level of the cuff, but they were always contained in an area near the periphery of the common peroneal division. The fibers innervating the Sol and MG were contained within well-defined fascicles at the level of the cuff.

D. *Summary of Selectivity*

A summary of the results of all six experiments is shown in Table II. The entries in the table indicate the maximum value of the selectivity index of each muscle at 100 percent recruitment. In all cases it was possible to activate selectively the Sol and MG, either the TA or the EDL could be selectively activated in three cases, and it was not possible to activate selectively each muscle independently in the same animal. Since TA and EDL are agonists and are innervated by a common region of the nerve trunk, the selectivity index is also presented for the combination of TA and EDL (TA + EDL in Table II), which could be selectively activated in all experiments. The multipolar cuff electrode enabled selective activation of muscles that were innervated by well-defined fascicles over a full range of forces (Sol, MG, and the TA + EDL pair), and allowed selective activation of muscles that were innervated by groups of fibers within larger fascicles (TA and EDL individually) over a smaller range of forces.

IV. DISCUSSION

We have demonstrated that a multipolar cuff electrode, placed without prior reference to nerve fascicle organization, is effective in activating selectively and progressively the forces in four of the muscles innervated by a large nerve trunk. Using simple electrode geometries and stimulus patterns we were able to activate selectively the muscles that dorsi- and plantarflex the ankle. These results suggest that the concern expressed by Caldwell [3], that the high impedance of the perineurium [18] would shunt current into the more conductive epineurium and limit the utility of selective motor control with electrodes placed outside the nerve trunk, was perhaps unwarranted.

We used a tripolar configuration with an opponent steering anode as our primary electrode configuration because previous results have demonstrated that it is more selective than a monopolar configuration [17]. Rather than choosing a single value for the transverse field steering current we modulated the amplitude of the transverse as well as the longitudinal current. Modulating the amplitude of the transverse field steering current provided an additional means to recruit muscle force, and increased selectivity as compared to tripolar stimulation without steering or with a single value of steering current. Maximal selectivity with the tripolar configuration was achieved by modulation of the amplitudes of both the longitudinal and transverse current. Additionally, modulation of the transverse current produced recruitment curves with lower slope than recruitment curves collected by modulating the longitudinal current and recruitment curves collected using cuffs with band electrodes [5].

Whereas Sweeney *et al.* [17] placed a tripole directly above the MG fascicle and a steering anode directly opposite the tripole, the cuffs used in this study were implanted without any prior reference to fascicular locations. Although the relationship between electrode position and fascicle location varied among the experiments (compare Figs. 3(b), 5(c) and 9(d)), in all cases the multipolar cuff enabled selective and progressive control of forces in the muscles that dorsi- and plantar-flex the ankle. We observed that to maximize the effectiveness of transverse field steering currents the cuff should fit snugly around the nerve trunk, and the steering electrode should lie 180° around the nerve from the stimulating tripole.

We employed a twelve-electrode cuff that allowed implementation of a tripolar electrode configuration at four locations every 90° around the circumference of the nerve trunk, and use of transverse field steering current from an anode located 180° around the trunk from the cathode of the tripole. Our results using adjacent tripoles to activate selectively muscles that could not be activated selectively using a single tripole, suggest that additional tripoles within the cuff will improve muscular selectivity and improve the effectiveness of transverse steering current. However, such a cuff will require modified construction techniques to increase electrode density in such a confined space, and will require an increase in the number of leads required for the cuff. Cuff fabrication could be simplified by employing band anodes rather than discrete dot anodes; however, our results demonstrate that such a design will result in some loss of selectivity.

We defined a selectivity index based on the response of one muscle with respect to the group of four muscles. As the purpose of the present study was to determine the performance of a multipolar cuff in activation of discrete populations of nerve fibers, our definition of the selectivity index compared

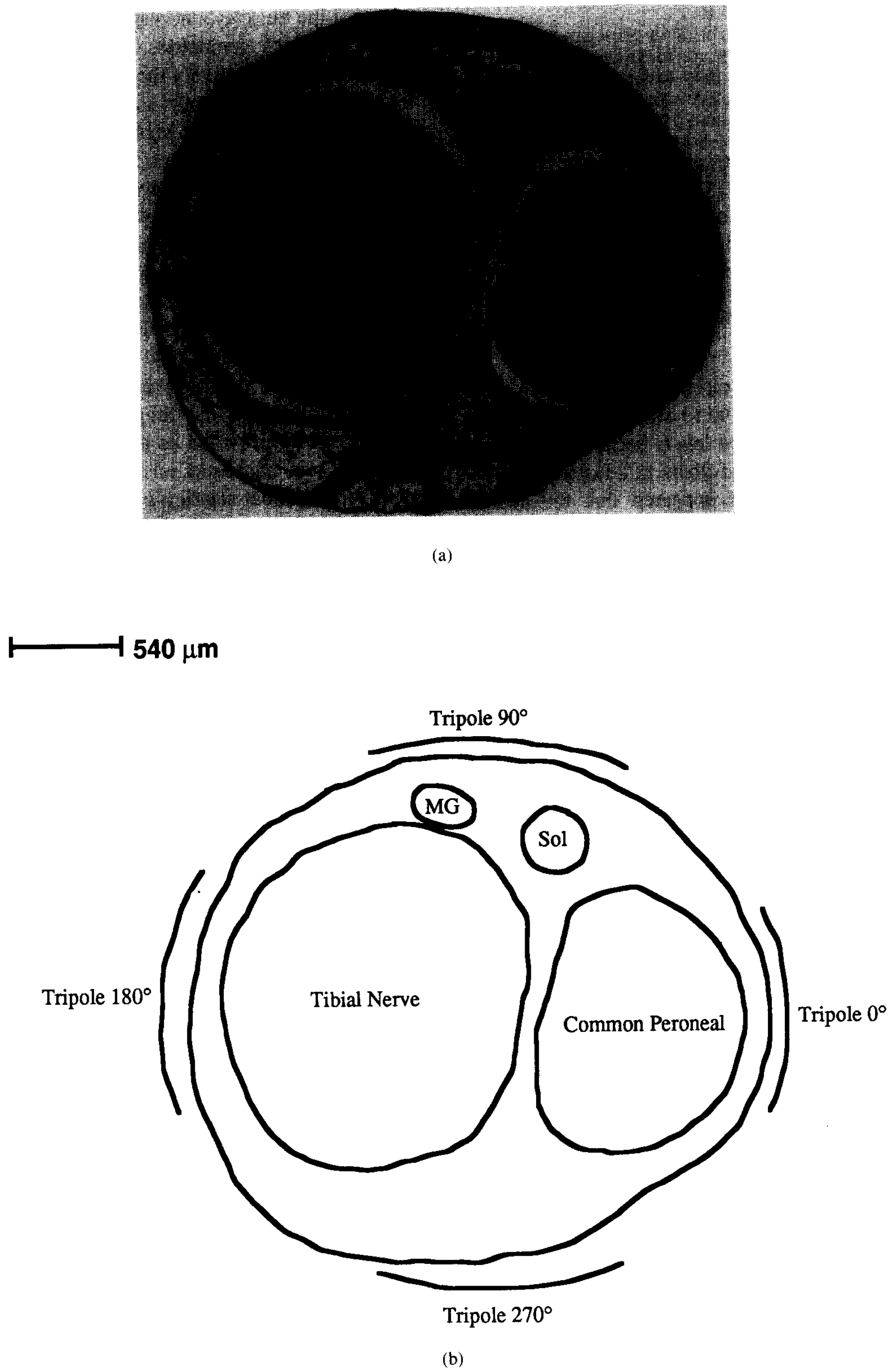


Fig. 9. Example of the fascicular organization of the sciatic nerve at the level of the cuff electrode. The sections are viewed from distal to proximal. a) Cross-section of the sciatic nerve at the level of the middle row of electrodes in the cuff stained with Masson's Trichrome. b) Schematic of cross-section indicating identified fascicles and position of the electrodes (Cat #918).

normalized muscle forces and not absolute forces. The selectivity index provided an objective measure to compare electrode geometries, and was used to determine the stimulating conditions that optimized selective activation of a single muscle over a large range of forces.

We have demonstrated the efficacy of a nerve cuff technique for selective motor control. The results suggest that a multipolar cuff electrode placed on a large nerve trunk will enable control of joint torques and position through selective activation of portions of the nerve trunk. This method provides an opportunity to improve the function of motor prostheses and simplify the implant procedure. Large nerve trunks are easy to access surgically, and therefore the implant surgery will place minimal demands on the patient and surgeon. Additionally, the electrodes need not withstand the mechanical stresses experienced by intramuscular electrodes since they can be positioned in regions of relatively low stress. The current approach to development of motor prostheses requires at least one electrode to activate each muscle, therefore requiring the implantation and maintenance of a large number of electrodes. The function of systems employing muscle electrodes is limited by the requirement that a specific, and often limited, set of muscles be chosen for activation. Rather than being limited by the choice of a limited group of muscles, the function of a system employing the multipolar cuff electrode will be limited by the degree of selectivity available within a large nerve trunk.

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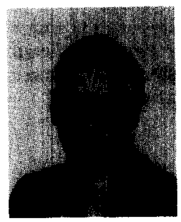

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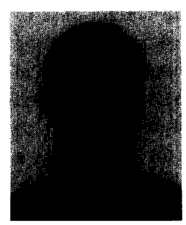

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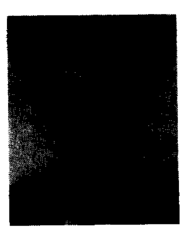

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