Selective and Independent Activation of Four Motor Fascicles Using a Four Contact Nerve-Cuff Electrode

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***Abstract*—Any one of the four motor nerves in the cat sciatic nerve could be activated selectively and independently, from threshold to saturation, using a self-sizing spiral cuff electrode containing four radially placed monopolar contacts. These studies were carried out in nine adult cats with acute implants. Of the 36 possible fascicles, 23 fascicles could be activated selectively with current stimuli applied to a single contact and ten of the remaining fascicles could be activated selectively with current stimuli applied to two contacts, "field steering." In three experiments, time constraints precluded attempting selective activation through "field steering" techniques. In eight of the ten cases where "field steering" was used, a positive and a negative current source (anodic steering) were required to achieve the desired fascicle and in the remaining two cases, two negative current sources (cathodic steering) were required. The relative distance from the electrode contacts to each fascicle was well correlated to the order in which each fascicle was activated. In seven experiments, carried out in two animals, selective activation was verified by collision block techniques. The results of these experiments support the hypothesis that selective and independent activation of any of four motor fascicles in the cat sciatic nerve is possible using a four contact self-sizing spiral cuff electrode. Furthermore, in a more general case, these results support the concept of a "tunable" electrode that is capable of "steering" the excitation from an undesirable location to a preferred location.**

***Index Terms*—Electrical stimulation, nerve cuff, neural prosthesis, selective activation.**

I. Introduction

THE GOAL of this research was to demonstrate that a four contact spiral nerve-cuff electrode placed around the cat sciatic nerve could be used to effect selective and independent activation of any one of the four motor fascicles in the sciatic nerve. Nerve-cuff electrodes that can effect selective and independent activation of fascicles within the cuff are an attractive alternative to separate electrodes that are attached to individual nerve branches or muscles. Present motor prostheses use electrodes either on the surface of the skin or implanted on or within a muscle, and for each muscle desired, a separate electrode and lead wire is required [1]–[3]. The function that has been returned to individuals using these motor prostheses has been remarkable and encouraged both the users and developers to try to achieve even more functional return. To achieve this increased function, additional muscles need to be controlled, which means added electrodes and leads using the present methods. Our hypothesis is that a single nerve-cuff electrode, with multiple contacts and a single lead could serve the function of multiple electrodes with separate leads.

Previous research has shown that nerve-cuff electrodes can be used to activate select regions of a peripheral nerve to produce different torque outputs from a joint. McNeal and Bowman [4] have shown that selective activation of a peripheral nerve using a cuff electrode with multiple electrical contacts can produce selective activation of two antagonistic muscle groups innervated by that nerve trunk. Subsequent work in both acute and chronic animal studies has shown that self-sizing nerve-cuff electrodes, with multiple contacts in a tripolar configuration, could be used to produce controlled and selective recruitment of some motor nerves in a nerve trunk [5]–[11]. More recently, a monopolar electrode with four radially placed contacts was shown to work as well as a tripolar electrode with four radially placed tripoles in both modeling work [12], [13] and on the cat sciatic nerve [14]. In previous work, selective activation was achieved when particular contacts happened to activate a specific fascicle. The goal of this study was to show that any one of the four motor fascicles in the cat sciatic nerve could be activated selectively and independently regardless of the position of the contacts relative to the motor fascicles. This study is of particular importance when nerve cuff technology is moved into the human subject. If a multicontact cuff is to replace many separate electrodes/leads, it will be essential to be capable of "steering" the excitation site from an undesirable location to a preferred position and, thus, "tune" the excitation properties of the neural prosthesis.

II. Methods

A. Implantation

Nine adult cats (on average 3.2 ± 0.6 kg) were used in these acute experiments using methods and procedures that adhere to National Institutes of Health (NIH) guidelines and were approved by the Institutional Animal Care and Use Committee of Case Western Reserve University. The animals were initially anesthetized with ketamine hydrochloride (35 mg/kg intramuscular) and salivation was reduced with atropine sulfate (0.044 mg/kg, intramuscular). An intravenous (IV) line was established in the cephalic vein and anesthesia was continued with sodium pentobarbital (5–10 mg bolus injections) as needed. Through an incision on the backside of the upper hind limb, a 2-cm section of the sciatic nerve was exposed and mobilized. A 1-cm section of the common peroneal, tibial, medial gastrocnemius, and the

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lateral gastrocnemius/soleus nerves were also mobilized. The diameter of the sciatic nerve was measured using a method developed by Atzberger [15]. A four-contact self-sizing spiral cuff was selected with a diameter that was within 0.1 mm of the measured nerve diameter, to insure contact spacing at 90° intervals. This four contact self-sizing spiral-cuff electrode was placed on the sciatic nerve with the lead wires exiting in the proximal direction. No attempt was made during implantation to orient the cuff electrode with respect to any fascicle within the nerve trunk. The lead wires were looped proximally and distally before exiting the surgical site to reduce the likelihood of forces being translated to the nerve from the lead wires. In addition to placing the four-contact cuff electrode on the sciatic nerve, single contact cuff electrodes were placed on each of the four motor nerve branches of the sciatic nerve: the common peroneal (CP), tibial (Tib), medial gastrocnemius (MG), and the lateral gastrocnemius/soleus (LG) nerves. The leads of each of these cuffs were also looped proximally and distally before exiting the surgical site. Once all cuffs were implanted, the incision site was closed and the lead wires were sutured to the skin.

B. Experimental Measurements

Immediately after the cuff implant procedure, the animal was positioned in a stereotactic frame, as described by Grill [16]. The implanted hind limb was kept on the topside and the paw was secured to a metal bracket, termed a "shoe," which was connected to the force transducer. The ankle, knee, and hip joints were fixed at 90° angles. The height of each limb segment was also adjusted to lie in a single plane parallel to ground.

All stimulation and recording was controlled through custom software written in Labview. Each twitch was produced by a single monophasic 10-μs pulse to maximize spatially selective stimulation [17]. Each test set consisted of individual pulses that ranged in amplitude from subthreshold through full activation of at least one fascicle. The resulting force and moments were measured by a six-dimension force transducer (JR3 Inc., Woodland, CA) attached to the "shoe." The output was then translated to the net torque output about the ankle. The three axes about the ankle recorded were plantar/dorsiflexion, external/internal rotation, and eversion/inversion.

The net torque output was graphically presented as a plot of the plantar/dorsiflexion torque versus external/internal rotational torque. A straight line in this graphical presentation represents isometric contraction of a single muscle. Lawrence *et al.* showed that the directionality of the torque vector produced by each muscle or muscle group that is being activated in this study is unique and the magnitude of the torque vector represents the level of muscle activation [18]. Thus, a change of angle in the torque output trace is an indication that nerve fibers that innervate other muscles were activated.

C. Electrode Configuration

The self-sizing cuff electrodes were 8 mm in length and the electrode contacts were evenly spaced at 90° increments when placed on the intended sciatic nerve diameters of 2.6, 2.8, 3.0, 3.2, and 3.5 mm. The contacts were platinum foil laminated between sheets of silicone rubber with a 0.8-mm-diameter opening cut in the silicone rubber to expose the metal contact to the adjacent nerve tissue. Self-sizing cuff electrodes containing a single contact were fabricated with lengths between 3 and 5 mm and internal diameters ranging from 0.6 to 1.0 mm. These cuffs were designed to fit snuggly on one of the four branches of the sciatic nerve, but since there was only one contact in each cuff, exact nerve diameter sizing was not necessary.

D. Stimulation Configuration

Current was applied to one or more contacts inside the nerve cuff to produce either single or multiple contact stimulation. Single contact (monopolar) stimulation was defined as the application of cathodic current to one contact within the nerve-cuff electrode with a distant return contact located in the nape of the neck. Multiple contact stimulation was defined as the simultaneous application of cathodic current to the "primary" contact and a "steering" current, anodic or cathodic, applied to one of the three other contacts with a return pathway, for any net current, through the distant contact located in the nape of the neck. When cathodic "steering" current was used, the same amplitude of cathodic current was applied to each cathodic contact. When anodic "steering" current was used, the amplitude of the anodic current was either 90% of threshold [5]–[7], [10], or was equal to the cathodic current [12], [19], [20].

Four separate cuff electrodes were used to generate the torque output for each of the four motor nerves. Each branch cuff contained a single contact, and current was applied to that contact over a range of amplitudes that would effect the full range of excitation from threshold to full activation of all motor fibers in that branch. The torque output elicited when stimuli were applied to any of the four contacts in the sciatic nerve cuff was compared to the torque output that was elicited by the branch stimulation. Based on this comparison, a representation of the fascicle position relative to a specific contact could be formulated. Further, this comparison was used to classify the contact torque output as either selective activation of a specific fascicle in the sciatic nerve or the activation of a mixture of fascicles in the sciatic nerve. When a particular fascicle was not activated selectively using monopolar cathodic stimuli, steering currents were applied to adjacent contacts. The appropriate contacts were chosen on the basis of their location relative to the presumed location of the target fascicle within the sciatic nerve. Anodic currents were chosen if the excitatory field within the sciatic nerve cuff was to be steered away (pushed) from a contact and a cathodic current was applied if the field was to be steered closer (pulled) to the contact.

In two animals, experiments were performed to test if the results were truly full and selective recruitment of that particular fascicle, and not the summed response of several fascicles that, coincidentally, matched the torque amplitude and direction of the single fascicle. These experiments consisted of three steps. In the first step, the torque output produced by super-maximal stimulation applied to the branch electrode of the target branch nerve was recorded. In the second step, a stimulus level and configuration applied to the nerve-cuff electrode on the sciatic nerve that produces the torque output corresponding to maximal activation of the individual fascicle was determined. The third step was to simultaneously apply stimulation to the branch

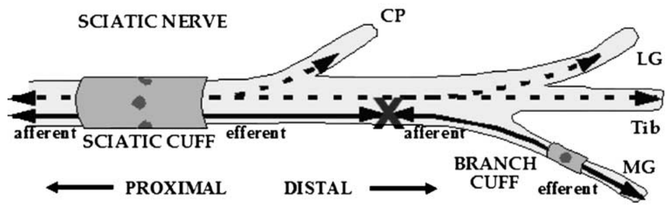

Fig. 1. Full and selective activation of an individual nerve branch was tested by using a branch cuff on the corresponding nerve branch (the MG in this example). The branch cuff was used to activate the branch nerve completely. Activation of nerve fibers serving that nerve branch, by stimulation applied to the sciatic cuff, will not change the resulting output since the branch cuff has already activated those fibers (solid lines). Activation of nerve fibers serving other nerve branches, by stimulation applied to the sciatic cuff, will propagate to different muscles and, therefore, cause a change in the resulting output (dashed lines).

nerve-cuff electrode and the sciatic nerve-cuff electrode, using the exact same parameters as used in the preceding steps. If all of the fibers activated by the contacts in the sciatic nerve cuff were included in the stimulated branch nerve, then the resulting torque output would be the same as supra-maximal stimulation of the branch nerve alone, Fig. 1. If stimulation of the sciatic nerve cuff activated nerve fibers that were in a fascicle different than the one being stimulated by the single contact electrode, the total torque output would be different than the torque elicited by supra-maximal stimulation of the branch nerve alone. Although spatial interaction between the electrical fields generated by the two separate electrodes could cause activation of nerve fibers not activated by either stimulus alone, this problem was not experienced since the two stimulation sites were separated along the length of the nerve by approximately 20 mm. Nonlinear addition of the torque produced by the two stimuli is due, however, to the nonlinear addition, or actually the lack of addition when the same nerve fibers are activated by both of the individual stimuli.

E. Explant

At the conclusion of the experiment, the animal was overdosed with pentobarbitol sodium. The sciatic nerve was exposed and sutures were inserted through the epineurium to mark the circumferential position of each contact. Each one of the branches was identified and also marked with suture for future reference. The sciatic nerve was cut proximal to the multi-contact cuff electrode and each one of the branches was cut distal to the marking sutures. A drawing of the cross-sectional morphology was made based on the suture locations relative to the observed nerve cross-section. The electrodes were removed and the nerve section was immersed in a 10% formalin solution. Following fixation, proximal, central, and distal sections, relative to the location of the cuff on the sciatic, were embedded in plastic and stained with methylene blue for examination under a light microscope.

III. RESULTS

Nine adult cats provided 36 fascicles for testing selective activation. A summary of all nine experiments is shown in Table I. Each row of the table represents a summary of the results for each animal. Each column of the table represents the stimulation pattern that was determined to best achieve the same torque output as a particular nerve branch. A particular configuration was determined to match the output of an individual fascicle if it satisfied two conditions. The first condition was that the direction of torque output, for all stimulus amplitudes up to the putative maximum torque, was in the same sector as produced by the individual fascicle. A sector is defined to be an area in torque space that contains all recorded vectors resulting from activating a specific motor branch. For branches innervating a single muscle, MG, the MG sector represents the variability of the experimental setup. For branches innervating several muscles, e.g. tibial, the sector accounts for setup variability and for activation of motor nerves serving each of the different muscles in all possible orders of recruitment. The second condition to be satisfied was that the 1 standard deviation ring around the putative maximum torque must overlap the 1 standard deviation ring around the supra-maximal stimulation of the individual fascicle. In each cell of Table I, four placeholders were used. An open circle (○) was used as a placeholder when that corresponding contact was not used to effect selective activation of that corresponding fascicle. A minus sign (−) or a plus sign (+) means that the corresponding contact was pulsed in a cathodic or anodic direction, respectively, to effect selective activation of that corresponding fascicle. All four locations marked with filled circles (● ● ● ●) means monopolar stimulation did not produce selective activation of the entire fascicle but multiple contact stimulation was not attempted due to time limitations. In no case was selective activation not achieved when multiple contact stimulation was attempted.

In 23 cases, selective activation was achieved with a single contact. In one of the nine cats (cat #388), each of the four fascicles could be selectively activated by single contacts. The other eight cats required multicontact stimulation "steering" to

TABLE I
SHOWN IN THIS TABLE ARE THE STIMULATION COMBINATIONS USED AT THE LEVEL OF THE SCIATIC NERVE TO ACHIEVE THE SAME TORQUE OUTPUT AS EACH CORRESPONDING FASCICLE FOR EACH EXPERIMENT. FOR EACH CASE IN WHICH THE SAME TORQUE OUTPUT AS THE CORRESPONDING NERVE BRANCH WAS ACHIEVED, FOUR PLACEHOLDERS WERE ENTERED TO REPRESENT HOW THE FOUR CORRESPONDING CONTACTS (0°, 90°, 180°, AND 270°) WERE USED. AN OPEN CIRCLE (○) REPRESENTS A CONTACT THAT WAS NOT USED FOR THAT PARTICULAR CONFIGURATION. A MINUS SIGN (−) INDICATES THAT THE CORRESPONDING CONTACT WAS PULSED IN THE CATHODIC DIRECTION. A PLUS SIGN (+) INDICATES THAT THE CORRESPONDING CONTACT WAS PULSED IN THE ANODIC DIRECTION. FOUR FILLED CIRCLES (● ● ● ●) INDICATE THAT THE PARTICULAR TORQUE WAS NOT ACHIEVED FULLY WITH SINGLE CONTACT STIMULATION BUT NOT TARGETED USING STEERING CURRENTS DUE TO TIME LIMITATIONS. IN NO CASE WAS A PARTICULAR TORQUE NOT ACHIEVED WHEN MULTIPLE CONTACT STIMULATION WAS ATTEMPTED. THE SHADED CELLS ARE THE CASES IN WHICH "COLLISION BLOCK ADDITION" WAS USED TO VERIFY THE CORRESPONDING FASCICLE WAS FULLY AND SELECTIVELY ACTIVATED

Cat #	Medial Gastrocnemius				Soleus/Lateral Gastrocnemius				Common Peroneal				Tibial			
	0	90	180	270	0	90	180	270	0	90	180	270	0	90	180	270
244	-	o	o	o	o	o	-	o	o	-	o	o	-	o	o	+
256	o	-	+	o	-	o	o	o	o	o	o	-	●	●	●	●
262	o	o	o	-	●	●	●	●	o	+	-	o	o	-	o	o
300	-	o	o	-	o	o	o	-	o	o	-	o	●	●	●	●
303	o	-	-	o	o	o	-	o	o	o	-	o	o	-	o	o
302	o	o	-	+	o	-	o	o	-	o	o	o	o	+	-	o
363	o	o	o	-	-	o	o	o	o	-	o	o	o	o	-	o
388	o	-	o	o	o	o	-	o	+	o	o	-	-	o	o	o
383	-	o	o	o	o	-	o	o	o	o	-	+	o	o	+	-

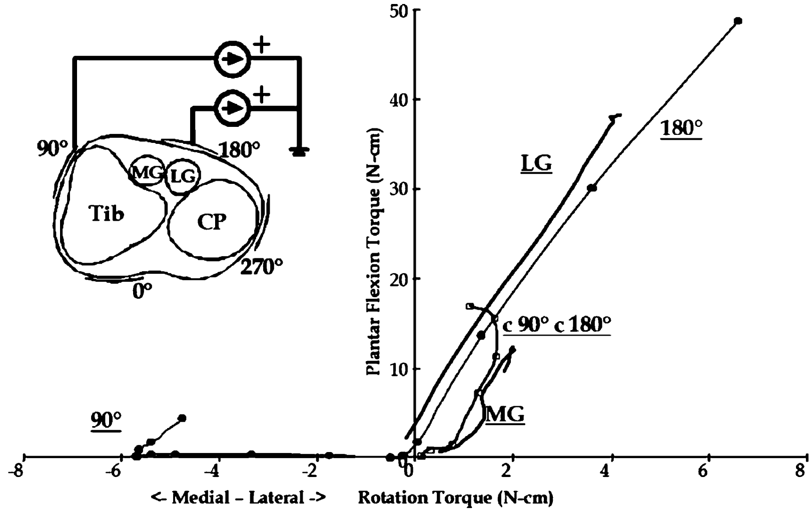

Fig. 2. One case (cat #303) in which multiple contacts were simultaneously stimulated using cathodic current. In this experiment, no single contact activated the MG by itself. The addition of cathodic steering current from the 90° position to the 180° position (labeled c90° c180°) was found to activate the MG. The inset in the top left corner is a reconstruction of the nerve cross-section and the relative locations of each contact. This schematic depicts the current configuration used to apply the steering currents.

achieve selective activation of at least one of the four motor fascicles. Using multiple contacts to achieve selective activation was demonstrated in ten cases. Eight of these ten cases used anodic steering and two cases used cathodic steering. The torque output of the remaining three fascicles, not selectively activated with a single contact, was not attempted with multiple contact stimulation due to time limitations. Of the fascicles targeted for selective activation, there was no case where a fascicular torque output could not be achieved using single or multiple contact stimulation.

Cathodic steering currents were used in both cat #300 and cat #303 to achieve the MG fascicle. In Fig. 2, torque outputs evoked about the ankle joint of cat #303 are shown with plantar flexion in the positive ordinate and lateral rotation on the positive abscissa directions. Stimulation applied to the 90° contact produced medial rotation (suggesting excitation of the tibial nerve) while stimulation of the 180° contact produced torque output representative of the LG. No single contact achieved the same torque output as the MG fascicle. Simultaneous application of independent, but equal, cathodic stimuli to the 90° contact and the 180° contact at multiple amplitudes produced a torque that was consistent with the torque output produced by the MG fascicle. A schematic wiring diagram, illustrating the electrical connections between the stimulator and nerve cuff contacts, and the cross-section of the nerve is shown in upper left panel of Fig. 2. Postmortem examination of the nerve indicated that the MG was located directly between the 90° and 180° contact positions.

An example of multiple contact stimulation using the addition of anodic steering current is illustrated for cat #388 in Fig. 3. In Fig. 3, the total torque output is plotted with plantar flexion in the positive ordinate and medial rotation in the positive abscissa directions. Full and independent production of the same torque output produced by excitation of the Tib, MG, and LG fascicles was achieved using stimuli applied to the 0°, 90°, and 180° contact positions respectively. No single contact, however, achieved selective activation of the torque produced by the CP fascicle. Stimuli applied to the 270° contact position produced a torque output that appeared to be a combination of the torque outputs produced by excitation of the Tibial and CP fascicles, shown in Fig. 3. The simultaneous application of cathodic stimulation to the 270° contact and anodic steering current to the 0° contact produced a torque output that was consistent with torque output produced by the CP fascicle. Shown in the lower right panel of Fig. 3 are the electrical connections between the stimulator and nerve cuff contacts and the cross-section of the nerve in relationship to the electrode contacts. The 270° contact was located directly between the Tib and CP fascicles. The electrical schematic included with the nerve cross-section in Fig. 3 illustrates how the two independent current stimulators were configured to provide the current to the multiple contacts.

In seven cases, experiments were performed to determine if the putative full and selective "fascicle" torque produced by stimulation applied to contacts in the sciatic nerve cuff was due to excitation of the nerve fibers in the respective branch. Fig. 4 shows an example for cat #388 of the results achieved from these experiments. These results verified that the torque produced using the sciatic nerve cuff was the result of full and selective activation of each respective fascicle. Data points labeled MG, LG, Tib, and CP represent the resulting torque output produced by the respective nerve branches when stimulated at an amplitude sufficient to produce full activation of that nerve branch. Data points labeled 0°, 90°, and 180° represent the resulting torque output produced by the respective contact positions in the cuff on the sciatic nerve when stimulated at a level that produced a torque output that corresponded to the maximum torque output of the individual nerve branch. The datum point labeled "c 270° a 0°" represents the two contact stimulation configuration, cathodic stimulation on the 270° position and anodic stimulation on the 0° position, believed to activate the CP fascicle. In each case, the same parameters used individually to produce the results described earlier were delivered simultaneously to both the branch nerve and the sciatic nerve (i.e., 0° + Tib, 90° + MG, 180° + LG, and c270°a0° + CP). A summary of the differences

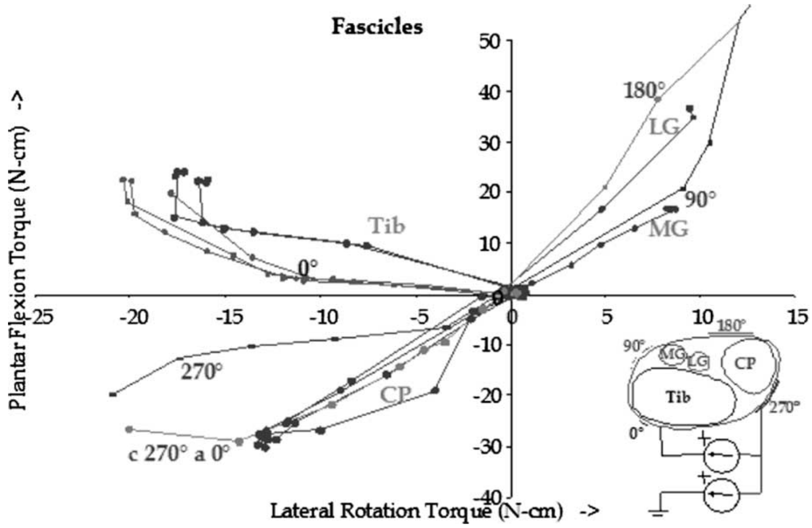

Fig. 3. Comparison of the torque outputs produced by direct stimulation of each branch of the sciatic, labeled Tib, MG, LG, and CP, and stimulation of each contact in the cuff electrode, labeled 0°, 90°, 180°, and 270°, in cat #388. Based on the torque outputs, the Tib, MG, and LG branches of the sciatic were activated by the 0°, 90°, and 180° contacts on the sciatic nerve. No single contact activated the common peroneal by itself. The addition of anodic steering current from the 0° position to the 270° position (labeled c270° a0°) was found to produce the same torque output as is produced by the common peroneal. The inset in the bottom right corner is a reconstruction of the nerve cross-section and the relative locations of each contact. A schematic of the configuration used to apply current for the multiple contact stimulation is also shown.

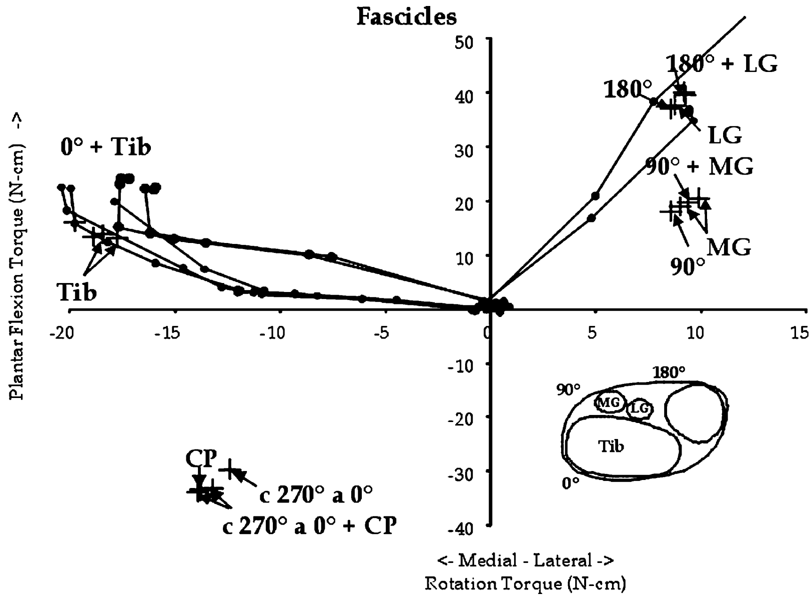

Fig. 4. Using a series of stimulation sets, selective activation of each fascicle in this animal (cat #388) was tested. Each stimulation group included stimulation of an individual branch, a particular configuration on the sciatic nerve, and then both together. Based on these torque outputs, the Tib, MG, and LG branches of the sciatic were fully and selectively activated by the 0°, 90°, and 180° contacts on the sciatic nerve. Anodic current from the 0° position added to cathodic current from the 270° position (labeled c270° a0°) was found to activate the CP fully and selectively. The difference in the direction of torque outputs produced by the 0° and Tib branch stimulation is attributed to the Tib serving multiple muscles. The two different contact locations (one on the sciatic and the other distally on the individual branch) are believed to have activated the individual muscles, served by the tibial, in a different order.

between the super-maximal stimulation of the nerve branch and the combined stimulation are shown in Table II for each dimension. The right half of Table II provides the values for statistical significance, testing the hypothesis that the torque outputs are within the 98% confidence interval of each other. The 98% confidence intervals, 5, 2.5, and 1.7 N-cm for plantar flexion, lateral rotation, and eversion respectively, were based on previous work where the variability was calculated for data achieved after supra-maximal stimulation of the nerve was applied.

IV. Discussion

We interpret these results to support our hypothesis that any one fascicle of a four-fascicle nerve can be fully and selectively activated using a four contact nerve-cuff electrode. In 64% of the cases (23 out of 36), a single contact was found to activate, fully and selectively, a single fascicle in the nerve trunk. This result is similar to the 66.7% frequency of the full and selective activation of a single fascicle from a single contact position found

TABLE II
SUMMARY OF THE RESULTS FROM ALL SEVEN CASES IN WHICH COLLISION BLOCK WAS USED TO TEST IF FULL AND SELECTIVE ACTIVATION OF A PARTICULAR FASCICLE WAS ACHIEVED. THE LEFT HALF SHOWS THE DIFFERENCES, IN EACH DIMENSION, BETWEEN THE SUPRA-MAXIMAL STIMULATION OF THE INDIVIDUAL BRANCH AND THE COMBINED STIMULATION. IN EACH CASE, THE TORQUE OUTPUT FROM THE BRANCH ALONE AND THE COMBINED STIMULATION WERE STATISTICALLY WITHIN 5, 2.5, AND 1.7 N-cm OF EACH OTHER IN THE PLANTAR FLEXION, LATERAL ROTATION AND EVERSION DIMENSIONS, RESPECTIVELY, WITH ALPHA VALUES SHOWN ON THE RIGHT HALF OF THE TABLE

	Δ PF (Plantar Flexion) (N-cm)	Δ LR (Lateral Rotation) (N-cm)	Δ R (Rotation) (N-cm)	Alpha Value for Ho: Branch = Branch + Contact		
				Δ PF by ±5 N-cm	Δ LR by ±2.5 N-cm	Δ R by ±1.5 N-cm
'mg' – 'mg+270°'	0.061	0.084	0.007	0.000	0.002	0.000
'lg' – 'lg+0°'	0.000	0.000	0.000	0.001	0.007	0.001
'tib' – 'tib+180°'	0.000	0.000	0.000	0.001	0.001	0.002
'mg'- 'mg+90°'	-0.842	0.053	0.261	0.000	0.000	0.002
'lg' – 'lg+180°'	0.000	0.000	0.000	0.001	0.001	0.000
'cp' – 'cp+270°a0°'	0.000	0.000	0.000	0.001	0.005	0.001
'tib' – 'tib+0°'	0.000	0.000	0.000	0.000	0.028	0.014
Max	-0.842	0.084	0.261	0.001	0.028	0.014

in the results from previous studies [7], [11]. In ten of the remaining cases whereby steering currents were specifically used to achieve a particular fascicle, the particular fascicle was activated fully and selectively using a steering configuration. The use of anodic currents was found to be effective in 80% of the cases in which multiple contacts were used. Multiple cathodic currents were used in the remaining 20% of the cases.

Anodic steering current was found to be a viable method to shift the excitatory field away from one fascicle to allow activation of an adjacent fascicle. In Fig. 3, the 270° contact was found to produce a torque output between the Tib and CP fascicles. The illustration of the nerve cross-section verified that the location of the 270° contact was between the Tib and CP fascicles. Using the addition of anodic current to the 0° contact, the torque output was the same as that of the CP fascicle. These results are consistent with those of previous investigators [5], [6], [8]–[11], [21].

Cathodic steering current was found to be a viable method to activate a fascicle located between two different contacts. In Fig. 2, the 180° contact was located over the LG. Based on the illustration of the nerve cross-section, the 90° contact was located over the Tib fascicle. Cathodic current applied to both the 90° and 180° contacts excited the MG fascicle before exciting either the Tib or LG fascicles.

Based on the results from nine animals, a four contact cuff electrode could be used to produce the same torque output as any one of the four fascicles in the sciatic nerve. Based on the results of seven cases (in two animals) the production of the same torque was the result of selective activation of the individual fascicle.

V. CONCLUSION

The application of multiple contact stimulation techniques, to electrodes implanted on the cat sciatic nerve, was successfully used to effect selective activation of fascicles previously inaccessible with short duration cathodic stimulation applied to a single contact. The application of anodic steering current was used to hyperpolarize an undesired fascicle while activating the target fascicle. The application of cathodic steering current was used to increase the excitation level of a fascicle located between two contacts while not activating other nearby fascicles. These experiments support the hypothesis that with a multicontact, self-sizing, spiral cuff electrode, it is possible to activate selectively, from threshold to maximum activation, any specific motor fascicle contained within a nerve trunk serving several muscles. Further, these results suggest a new concept for neural prostheses, "tunable" electrodes; electrodes that can create virtual excitation sites when coupled to stimulators that can effect simultaneous positive and negative stimulation at several contact sites.

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