Comparison of Joint Torque Evoked With Monopolar and Tripolar-Cuff Electrodes

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***Abstract*—Using a self-sizing spiral-cuff electrode placed on the sciatic nerve of the cat, the joint torque evoked with stimulation applied to contacts in a monopolar configuration was judged to be the same as the torque evoked by stimulation applied to contacts in a tripolar configuration. Experiments were carried out in six acute cat preparations. In each experiment, a 12-contact electrode was placed on the sciatic nerve and used to effect both the monopolar and tripolar electrode configurations. The ankle torque produced by electrically evoked isometric muscle contraction was measured in three dimensions: plantar flexion, internal rotation, and inversion. Based on the recorded ankle torque, qualitative and quantitative comparisons were performed to determine if any significant difference existed in the pattern or order in which motor nerve fibers were recruited. No significant difference was found at a 98% confidence interval in either the recruitment properties or the repeatability of the monopolar and tripolar configurations. Further, isolated activation of single fascicles within the sciatic nerve was observed. Once nerve fibers in a fascicle were activated, recruitment of that fascicle was modulated over the full range before "spill-over" excitation occurred in neighboring fascicles. These results indicate that a four contact, monopolar nerve-cuff electrode is a viable substitute for a 12 contact, tripolar nerve-cuff electrode. The results of this study are also consistent with the hypothesis that multicontact self-sizing spiral-cuff electrodes can be used in motor prostheses to provide selective control of many muscles. These findings should also apply to other neuroprostheses employing-cuff electrodes on nerve trunks.**

***Index Terms*—Electrical stimulation, monopole, nerve-cuff electrodes, tripole.**

I. Introduction

THE GOAL of this research was to demonstrate the feasibility of using a relatively simple nerve-cuff electrode to activate independently, several different muscles innervated by the same nerve trunk. Present-day motor prostheses using either electrodes on the surface of the skin or implanted in the body require a separate electrode and lead for each muscle that is to be activated [1]–[3]. As the motor prosthesis field advances, it has become apparent that improved performance will require the control of more muscles. Using muscle-based electrode technology, the addition of more muscles will require additional electrodes and lead wires. Nerve-based electrode technology that can activate many muscles offers an attractive alternative to the muscle-based electrode technology. McNeal and Bowman [4] showed that selective activation of a peripheral nerve using a cuff electrode with multiple electrical contacts could produce selective activation of two antagonist muscle groups innervated by that nerve trunk. Modeling work by Chintalacharuvu [5] and Sweeney [6] showed that a snug-fitting cuff electrode employing a tripolar configuration would restrict the activation to a more localized region within a nerve trunk than a cuff employing a monopolar configuration. Using four sets of radially spaced *tripolar* electrodes (12 contacts) within a self-sizing spiral nerve-cuff electrode, Sweeney *et al.*, Veraart *et al.*, and Grill *et al.* performed experiments that demonstrated selective activation of individual muscles in acute experiments [7]–[9] and individual functional outputs in chronic experiments [10], [11]. Based on these experiments, a multicontact-cuff electrode can be used to produce controlled and selective activation of several muscles served by motor nerve fibers contained in a single large nerve trunk [8]–[13]. The cuff electrodes employed in the experiments performed by Sweeney, Veraart, and Grill used 12 contacts set in four tripolar arrays with individual leads serving each contact. At present, an electrode assembly and lead wire connector containing this many contacts and lead wires is technologically difficult to manufacture and probably not feasible for clinical implementation in the near future.

In an effort to reduce the number of contacts and lead wires required for a peripheral nerve-based electrode while retaining the selective activation qualities of the tripolar electrode configuration, a monopolar configuration was investigated. Monopolar configurations use only the centrally placed contact of the three contacts used by the tripolar configuration; the virtual anodes at the cuff edges emulate the other two contacts of the tripolar configuration and, thus, the current pattern is very similar between the monopolar and tripolar configurations, see Fig. 1. Results from modeling work performed by both Parrini [14] and Deurloo [15] support the hypothesis that a monopolar-cuff electrode may be substituted for a tripolar configuration. The objective of the experiments reported here was to test in animal experiments, the hypothesis that the recruitment characteristics of a monopolar-cuff electrode, with four radially placed contacts, are not significantly different from a similar electrode with four radially placed tripoles.

II. Methods

A. Electrode Configuration

Self-sizing spiral-cuff electrodes containing 12 contacts and arranged into four sets of tripoles, were made according to pre-

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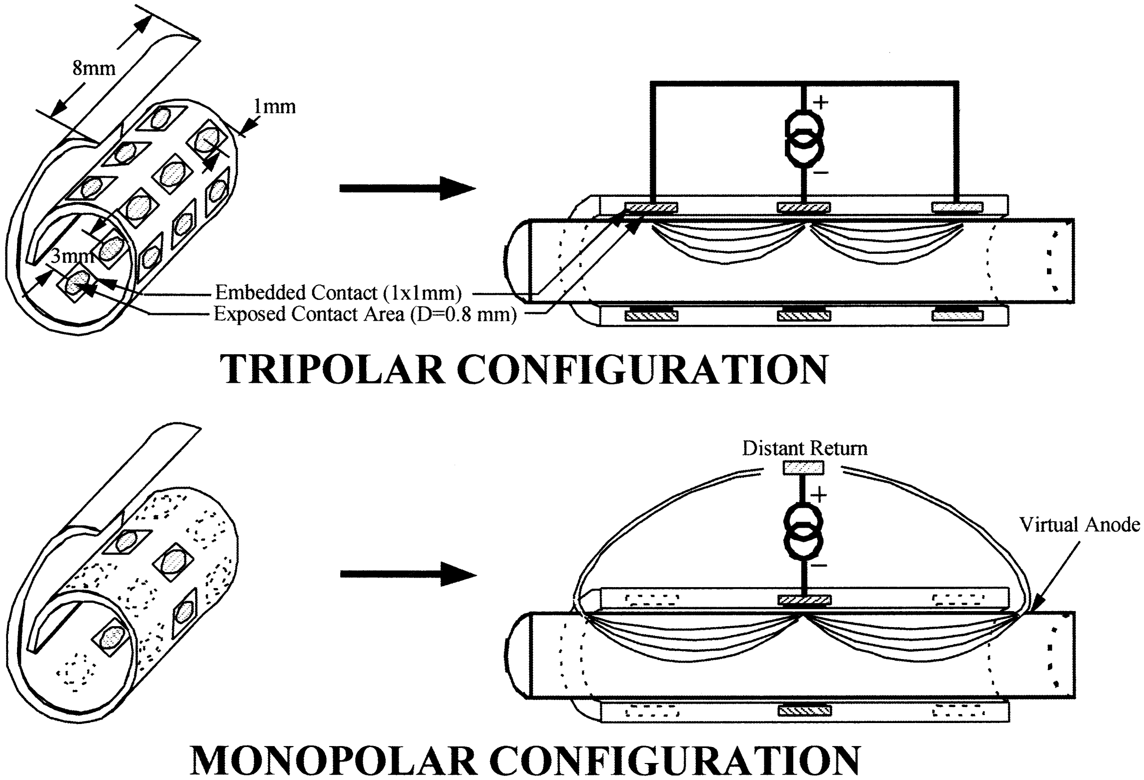

Fig. 1. (left) Monopolar and tripolar-cuff electrode configurations. (right) Schematics of the resulting current flow. With the tripolar configuration (upper half), the current flows between the center contact (cathode) and the two outer contacts (anodes). With the monopolar configuration (lower half), the current flows between the central contact (cathode) and the remote contact (distant anode). The current flow patterns are similar, which suggests the two configurations may yield recruitment results that are not significantly different.

viously developed techniques [8]. These electrodes were made with internal diameters of 2.7, 3.0, and 3.3 mm. Each lead wire was spot welded to a 1-mm square piece of platinum and then embedded within the cuff during the manufacture process. A piece of 0.8-mm diameter stainless steel tubing was used to cut a hole through the inner layer of silicone rubber in the nerve-cuff, over the platinum contact, to expose the contact to the interior side of the cuff. Each cuff was trimmed approximately 1 mm beyond the outer-most anodic contact on each side. Each contact within a single tripole was spaced 3 mm on center resulting in a tripole length of 6 mm and a total cuff length of 8 mm. In each animal preparation, only one 12-contact cuff electrode was used to produce both monopolar and tripolar stimulation, as illustrated in Fig. 1. Using this electrode configuration allowed the investigators to measure the recruitment characteristics (ankle torque as a function of the stimulation) for the monopolar and tripolar electrode configurations without changing the position of the contacts on the nerve.

In Fig. 1, a schematic diagram of the current-flow patterns for a monopolar and a tripolar electrode configuration is shown. Tripolar stimulation was implemented by connecting the cathode of the stimulator to the center contact and the anode of the stimulator to the two outer contacts. Monopolar stimulation was implemented by connecting the cathode of the stimulator to the same center contact and the anode of the stimulator to a distant return electrode, which was a 38-mm-long 1.27-mm-diameter (18-gauge) hypodermic needle placed in the nape of the neck. Each contact (monopole) or set of contacts (tripole) was

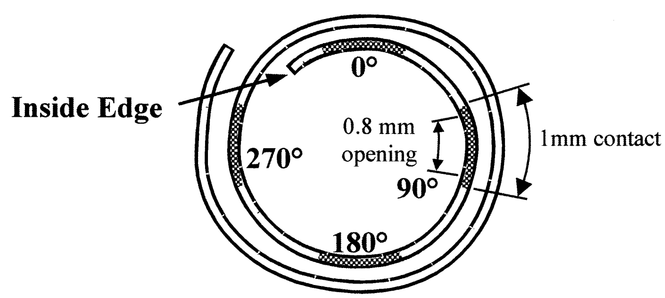

Fig. 2. Cross section of a nerve-cuff illustrating the naming convention of the contacts. The 0°-contact is defined as the contact closest to the inside edge of the nerve-cuff and each contact there after is successively named according to their intended final position around the nerve.

referenced according to its position around the nerve relative to the inside edge of the cuff, as shown in Fig. 2. The monopole or tripole closest to the inside edge of the cuff was defined as the 0° position. The other three monopoles or tripoles were then designated 90°, 180°, and 270° positions, corresponding to their intended orientations around the nerve trunk.

B. Animal Model

The cat sciatic nerve was used as a model of a generic multifascicular nerve trunk. The sciatic nerve of a cat is approximately 3 mm in diameter and contains four motor nerves: medial gastrocnemius (MG), lateral gastrocnemius/soleus (LG/S), tibial (T), and common peroneal (CP). These motor nerves supply all of the muscles controlling the ankle joint.

The medial gastrocnemius and the lateral gastrocnemius/soleus fascicles are the smallest of the four fascicles and usually lie close to each other. The common peroneal and the tibial nerves are the largest of the four fascicles and serve several muscles.

C. Implantation

Acute experiments were performed on six adult cats (2.9, 3.8, 3.45, 2.6, 3.8, 2.5 kg) using methods and procedures that adhered to 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, IM) and salivation was reduced with atropine sulfate (0.044 mg/kg, IM). An 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 dorsal aspect 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 lateral gastrocnemius/soleus nerves were also exposed and mobilized. A self-sizing 12-contact spiral-cuff electrode [16], was placed on the sciatic nerve with the lead wires exiting in the proximal direction. No attempt was made during implantation to position any contact within the cuff electrode with respect to any fascicle within the nerve trunk. To reduce the likelihood of forces being translated to the nerve from the lead wires, the lead wires were looped proximally and distally before exiting the surgical site. Single contact-cuff electrodes were placed on the isolated 1-cm sections of the common peroneal, tibial, medial gastrocnemius, and the lateral gastrocnemius/soleus nerves. These electrodes permitted the application of an isolated electrical stimulus to each of the four motor nerves. The leads from 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.

D. Experimental Setup

Immediately following the cuff implant, the animal was positioned in a stereotactic frame, as described by Grill [11]. The implanted hind limb was kept on the topside and the corresponding 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 in the stereotactic frame as described by Grill [11]. The height of each limb segment was adjusted to lie in a single plane parallel to ground.

All stimulation and recording was controlled through custom software written in Labview. The resulting force and moments produced due to stimulation 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 in terms of plantar/dorsiflexion, external/internal rotation, and eversion/inversion. The stimulation consisted of individual monophasic 10 μs pulses to maximize spatially selective stimulation [17]. The output produced at each stimulation amplitude was defined as the average torque based on five individual twitches at that amplitude. The recruitment properties of each contact or contact set were characterized by the net torque outputs produced over a range of amplitudes. The application of each pulse amplitude was randomized as much as possible and then pulses of the same amplitude were regrouped to be averaged.

E. Explant

At the conclusion of each experiment, the animal was overdosed with pentobarbital sodium. The position of each tripole was marked on the sciatic nerve trunk by inserting sutures into the epineurium. Each of the four motor branches were identified and also marked with suture for future reference. The sciatic nerve was cut proximal to the 12-contact cuff electrode and each branch was cut distal to the marking sutures. The electrodes were removed and the nerve section was immersed in a 10% formalin solution. Following fixation of the nerve section, proximal, central, and distal sections, relative to the level of the cuff on the sciatic, were embedded in plastic and stained with methylene blue for further examination under a light microscope. A drawing of the cross-sectional morphology was made based on the suture locations relative to the observed nerve cross section.

F. Data Analysis

The torque resulting from monopolar and tripolar stimulation was assessed by plotting both the evoked torque in one direction as a function of stimulus amplitude (torque-current plot) and by plotting the evoked torque in one direction as a function of the evoked torque in a second direction. From the torque-current plots, the maximum torque before spill-over, threshold current level and torque gain were measured and recorded, as illustrated in Fig. 3. The maximum torque output before spillover excitation of adjacent fascicles was identified as the torque produced at the first plateau in the torque-current curve. In Fig. 3, the maximum torque outputs for the monopolar and tripolar configurations correspond to the maximum torque output for the common peroneal fascicle. The threshold current, $\mathrm{I}_{\mathrm{thresh}}$, was defined as the current required to achieve 10% of the above defined maximum torque output. The torque gains for the monopolar and tripolar configurations were defined as the slope of the torque recruitment curve between the points that produced 10% and 90% of the maximum torque output. The torque gains for the monopolar and tripolar configurations in the example shown in Fig. 3, were found to be -0.4 and -0.2 N $-$ cm$/\mu$A, respectively.

Plotting the evoked torque in one direction against the evoked torque in a second direction provided a convenient way to assess the similarity of two recruitment curves. This presentation eliminates current magnitude as a variable. The magnitude and direction of the evoked torque on one axis, plantar/dorsiflexion torque, was plotted as a function of the torque resulting on a second axis, external/internal rotational torque. In this graphical presentation, Lawrence *et al.* [18] found that the isometric contraction of a single muscle produces a straight-line trajectory. The torque vector angle is unique to a particular muscle and the magnitude is a function of the level of muscle activation. Any change of angle, occurring in the two-dimensional

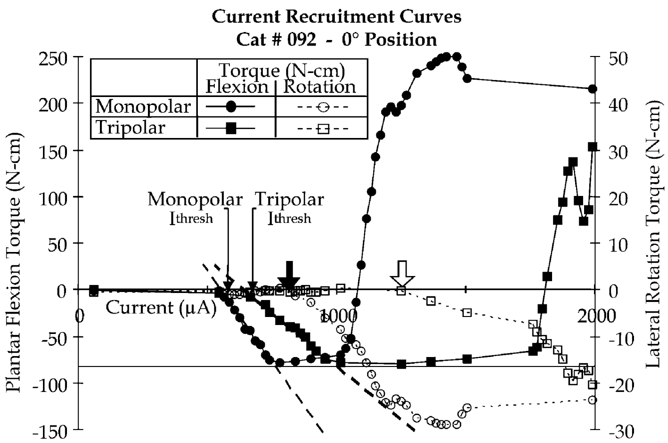

Fig. 3. Monopolar and tripolar current recruitment curves, torque output in plantar flexion, and lateral rotation each plotted against the current injected, using a 10-μs square pulse (0° contact position on Cat #092). The flexion torque is shown with filled symbols relative to the left vertical axis while the rotational torque is shown with open symbols relative to the right vertical axis. The monopolar recruitment, shown with circular data points, was found to have a lower threshold than the tripolar recruitment, shown with square data points. Both monopolar and tripolar recruitment curves were found to achieve dorsiflexion torque equal to the maximum dorsiflexion torque produced by the common peroneal branch alone. The solid arrow (monopolar) and the open arrow (tripolar stimulation) are located where an increase in the rotation torque is first detected, indicating the start of spillover.

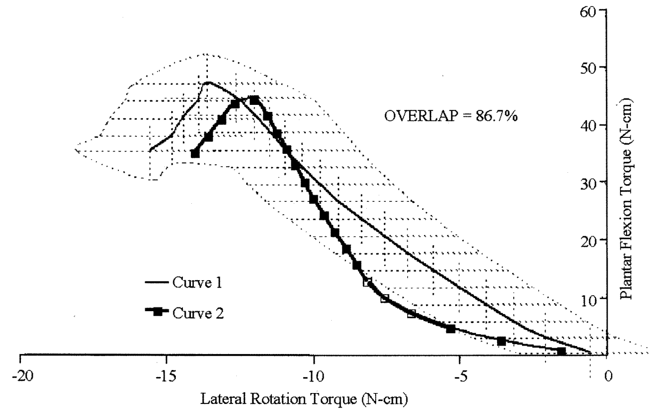

Fig. 4. Example of the similarity measure applied between two curves. Curve 1, the reference curve, is shown with dotted lines around the torque output to indicate the 98% confidence interval. The values for the 98% confidence level define the variability range for data acquired at supra-maximal stimulation. Curve 2, the test curve, is shown with solid square data points where it falls inside and open squares where it falls outside the 98% confidence interval of Curve 1. In this case, 86.7% of the total length of Curve 2 was found to be within the 98% confidence interval of Curve 1. These two example curves are two of the seven curves collected from the 90° contact position on Cat# 201, as illustrated in Fig. 7.

torque trajectory plot, was interpreted as the activation of a previously inactivated muscle. Further, the similarity between the torque output evoked using a contact in the cuff electrode and the torque output evoked from the direct stimulation of a specific nerve branch could also be assessed.

Quantitative comparisons of the torque trajectories recorded for the monopolar and tripolar configurations were made using a method developed by Tyler and Durand [19] to compare two torque curves in space. Recruitment curve similarity was defined as the percent of one curve that was not statistically different from a second curve at a 98% confidence level. The 98% confidence level for these data was found using the Student's t distribution and the standard deviation of points achieved through supramaximal stimulation of the nerve. Points achieved after supramaximal stimulation were selected since, by definition, no additional torque could be achieved and therefore any variability in the measured torque was a characteristic of the muscle/transducer system and not due to changes in the number of fibers activated. Using the 98% confidence level, each point along one curve, the test curve, was tested against each point on the other curve, the reference curve. An example of this procedure is illustrated in Fig. 4. The percentage of the test curve length that was found to be within the 98% confidence interval of the reference curve defined the similarity of the test curve on the reference curve. In the case illustrated in Fig. 4, 86.7% of the length of Curve 2 was within the 98% confidence interval for Curve 1.

The quantitative comparison procedure was used to assess the similarity between five different groups of data. The first two groups, referred to as monopolar versus monopolar and tripolar versus tripolar, were defined as the comparison between the results achieved using the same contact in the same electrode configuration at different times during each experiment. These sets of data would be expected to have the most similarity and, therefore, are used as a benchmark for this analysis procedure. The third group, referred to as monopolar versus tripolar, was defined as the comparison between the results achieved when using a monopolar configuration and the results achieved when using the corresponding tripolar configuration. If this monopolar versus tripolar comparison yields a similarity that is nearly the same as the similarity obtained for the monopolar versus monopolar comparison and the tripolar versus tripolar comparison, we would conclude that for the conditions of these experiments, a monopolar-cuff electrode configuration is a reasonable substitute for the tripolar-cuff electrode. In the fourth and fifth groups, data recorded from two different tripolar contacts (group 4) or two different monopolar contacts (group 5) were compared. These sets of data are expected to be the most dissimilar and are used as a benchmark for little or no similarity. A finding of little or no similarity in this group would also indicate that the different contacts on the same nerve produce significantly different torque output. These results would support the hypothesis that a single nerve-cuff electrode with multiple contacts spaced around the nerve can produce selective activation of that nerve trunk.

III. Results

The ankle torque evoked by stimulating currents applied to monopolar and tripolar electrode configurations was recorded in six acute animals. A typical torque versus stimulus current curve (recruitment curve) is shown in Fig. 3 for plantar flexion and lateral rotation. The peak torque outputs were similar in magnitude for the two electrode configurations but the current for threshold activation was lower for the monopolar electrode configuration. In addition, the slope (gain) of the torque-current curve was higher for the monopolar measurement $(-0.4\ \mathrm{N-cm}/\mu\mathrm{A})$ than for the tripolar measurement $(-0.2\ \mathrm{N-cm}/\mu\mathrm{A})$. Summaries for

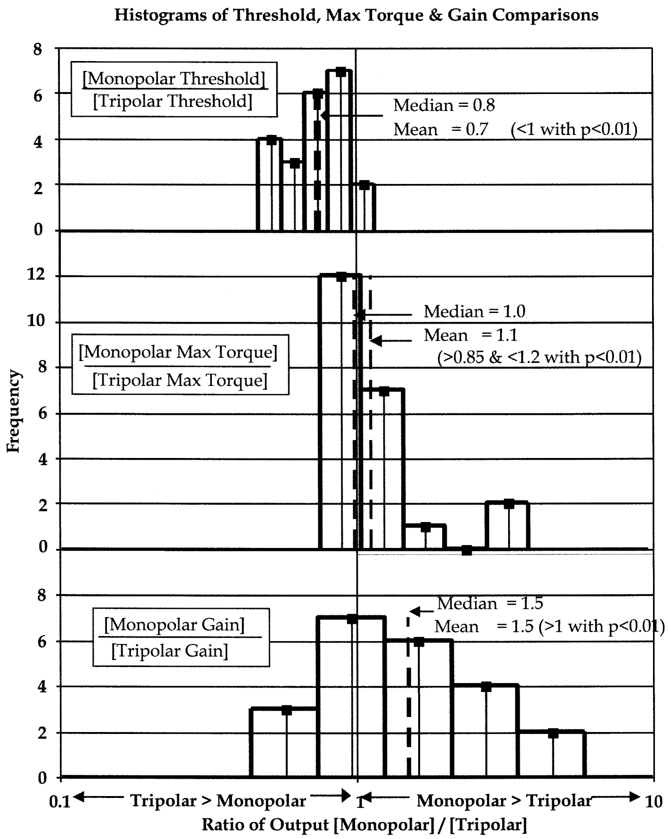

Fig. 5. Histograms of the ratio of monopolar to tripolar threshold current, maximum torque before spillover and torque output gain. Data located on the left side (less than 1) indicate monopolar values that were smaller than tripolar values. Data located on the right side (greater than 1) indicate that monopolar values were larger than tripolar values. Monopolar current required to produce 10% of the maximum torque output (threshold) was found to be less than tripolar threshold. The mean of the ratio of maximum torque outputs before spillover was found to be between 0.85 and 1.2. The torque output gain of monopolar stimulation was found to be greater than tripolar stimulation.

the ratio of monopolar to tripolar threshold current, maximum torque output before spillover and torque output gain, across all six animals, are shown in Fig. 5. Data values less than one, located on the left side of Fig. 5, indicate results where the measured value using a monopolar configuration was less than the value measured using a tripolar configuration. The opposite is true for the data located on the right side of Fig. 5, which had values greater than one. In the case of threshold, the monopolar configuration was found to have a lower threshold value than the tripolar configuration at a 99% significance level. In the case of the maximum torque output before spillover, monopolar and tripolar configurations were found to be the same with a ratio equal to 1.0 $+/-$ 0.2 at a 99% significance level. In the case of the torque output gain, the monopolar configuration was found to have a larger absolute gain than the tripolar configuration at a 99% significance level.

Monopolar and tripolar torque recruitment curves, shown in Fig. 3 by solid circles and solid squares, respectively, were found to both plateau near full dorsiflexion (determined by supra-maximal stimulation of the common peroneal branch to be about 75 N-cm of dorsiflexion). Based on these flexion recruitment curves alone, the first indication of spillover (activation of a different muscle) occurred around 1000 and 1750 μA for monopolar and tripolar stimulation, respectively. However, based on the lateral rotation recruitment curves shown in Fig. 3 (open circles for monopolar and open squares for tripolar stimulation), spillover first occurred at 800 (noted with a solid arrow) and 1200 μA (noted with an open arrow). Using this graphical presentation, two curves for each configuration were required in order to determine and compare the achieved torque output before spillover. By graphing the plantar flexion torque against the lateral rotation torque, a single curve for each configuration can be used to indicate if the two configurations produced the same direction and amplitude of torque output before spillover.

The upper left panel of Fig. 6 displays the same data shown in Fig. 3, except plotted with plantar flexion torque on the $+y$ axis and lateral rotation torque on the $+x$ axis. The other three panels of Fig. 6 display the data recorded using each of the other three contact locations in that nerve-cuff electrode. As previously explained, more than one torque dimension is necessary to determine the muscle recruitment characteristics of a particular stimulation. The spillover excitation shown in Fig. 3 with two different curves is evidenced in torque space, Fig. 6 upper-left panel, by a clearly discernible change in the trajectory of the evoked torque. Initial recruitment of dorsiflexion is represented in Fig. 6 by the recruitment line initially progressing down from zero. The change in line direction from downward to leftward, as noted by both the solid and open arrows, indicates that activation spilled over to adjacent nerve fibers. The maximum torque outputs evoked by stimulation current being applied to the electrodes on each of the four branches of the sciatic nerve (tibial, lateral gastrocnemius/soleus, medial gastrocnemius, and common peroneal) are also shown in Fig. 6 by the solid diamonds (♦). Stimulation at each position around the cuff was found to produce different torque outputs traces (e.g., in Fig. 6, the 0°-position in the upper left panel initially produces dorsiflexion while the 90°-position in the upper right panel initially produces medial rotation). Each output torque trace can be correlated with the illustration of the nerve cross-section to approximate the order of fascicular activation. In each case, the fascicles appeared to be activated according to their respective distance from the contact. The fascicle closest to the contact was activated first and the fascicle furthest from the contact was activated last. In three of the four contact positions in this experiment, full activation of a single fascicle was achieved before a second fascicle was activated. In the fourth case, the 270°-position, both the medial and lateral gastrocnemius fascicles appear to be activated together. Subjectively, the torque output magnitudes and directions produced using monopolar and tripolar electrode configurations were very similar in all cases.

Application of the quantitative comparison procedure from which numerical values for the similarity between the two torque trajectories are shown in Fig. 7 for data collected from another animal. A similarity index of 87.8% was found for the monopolar torque output at the 0°-position of cat #201 when compared with the torque outputs produced by the same monopolar output at different times during the study (M versus M) (Fig. 7 upper left). The comparison between multiple tripolar stimulation trials at the same position (T versus T) was found to be 94.6%. A similarity value of 88.7%

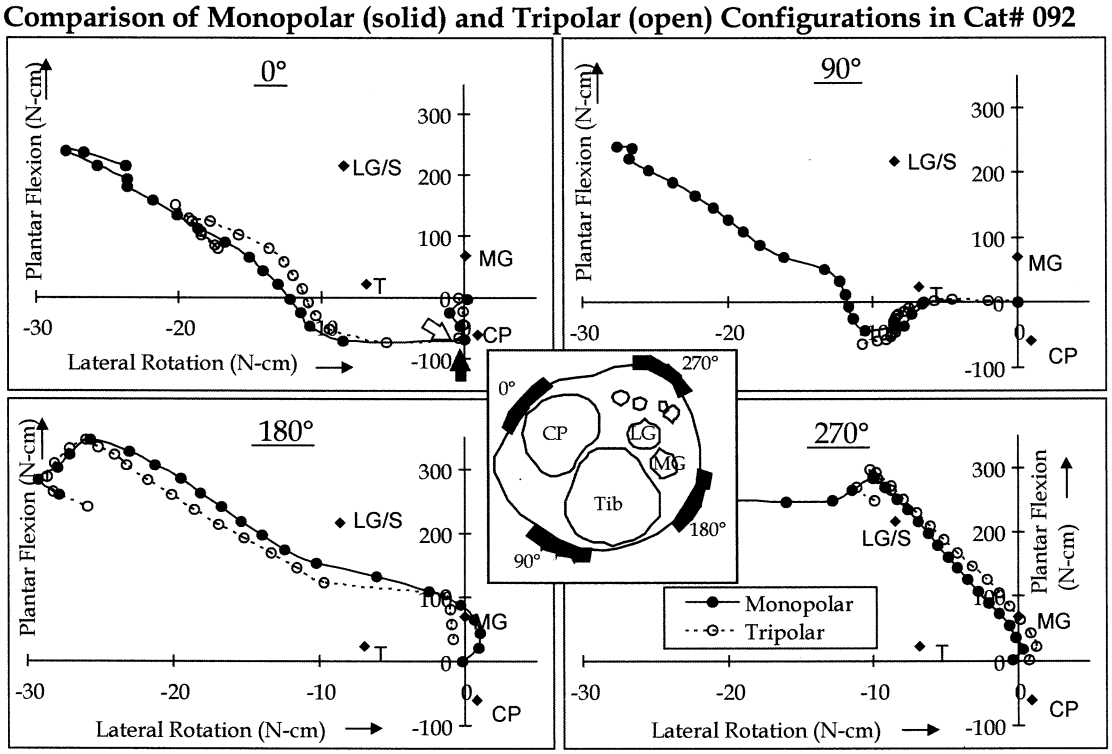

Fig. 6. Monopolar and tripolar torque output achieved at the 0°, 90°, 180°, and 270° contacts in cat #092 shown with plantar flexion plotted against lateral rotation. The monopolar recruitment curves are shown with solid data points while the tripolar recruitment curves are shown with open data points. Full recruitment of each individual fascicle is shown by the corresponding diamond: MG, LG/S, T, and CP. The physical relationship between the electrode and each fascicle within the nerve are illustrated by the inset figure of the nerve cross section. The solid and open arrows in the upper left figure correspond to the arrows in Fig. 3 for monopolar and tripolar configurations respectively.

was found for the comparison between monopolar and tripolar configurations at the same position (M versus T). The lowest similarity value across all six animals was the experiment shown in the lower-right panel for the 270° contact position where a similarity value of 31.0% was calculated.

A summary of the similarity analysis applied to all six animals is shown in Fig. 8. Based on 21 sets of recruitment curves, monopolar configurations were found to have an average similarity of 76% of the resulting torque output trajectory within the 98% confidence interval of the corresponding tripolar trajectory. On average, when the same recruitment curve was repeated at a later time, the two curves were found to be 79% and 78% similar for monopolar and tripolar configurations respectively. Recruitment curves produced using the same monopolar or tripolar configuration applied to contacts at different locations around the nerve were found to be only 19% and 15% similar, respectively. The number of comparisons was based on the number of repeated trials that were performed for each configuration.

The monopolar and tripolar repeatability (similarity value for the same recruitment curve achieved at different times) were found to be statistically within one standard deviation of each other at an alpha level of 0.015. The level of similarity found between stimulation using a monopolar and a tripolar configuration was found to be very close (2%–3%) to the amount of similarity achieved using the same contact or set of contacts at multiple times. These similarity values were also found to be statistically within one standard deviation at an alpha level of 0.015. Conversely, a significant difference (57%–64%) was found between the similarity achieved using torque outputs achieved with different contact locations as compared to the similarity achieved when comparing the outputs produced using the monopolar and tripolar configurations that shared the same center contact. This difference was found to be statistically different at a 98% confidence level.

IV. Discussion

The results of this study indicate that the recruitment curves for monopolar-cuff electrode configurations are very similar to the recruitment curves obtained with tripolar-cuff electrode configurations. These findings imply that the simpler monopolar-cuff/lead assembly could be used in place of the more complex tripole-cuff/lead assembly without loss of performance. This statement is based on acute experiments carried out on the cat sciatic nerve, which is a nerve trunk approximately 3 mm in diameter with four fascicles containing motor axons. These results should apply to other nerve trunks of similar composition.

A. Recruitment Curves

The threshold for monopolar stimulation was measured to be less than the threshold for tripolar stimulation. These results correspond to both previous experimental work [7]–[11] and computer models [5], [6], [14], [15]. The lower current demands of the monopolar configuration may be advantageous in the reduction of current density on the stimulating contacts and to reduce the total power consumption during stimulation.

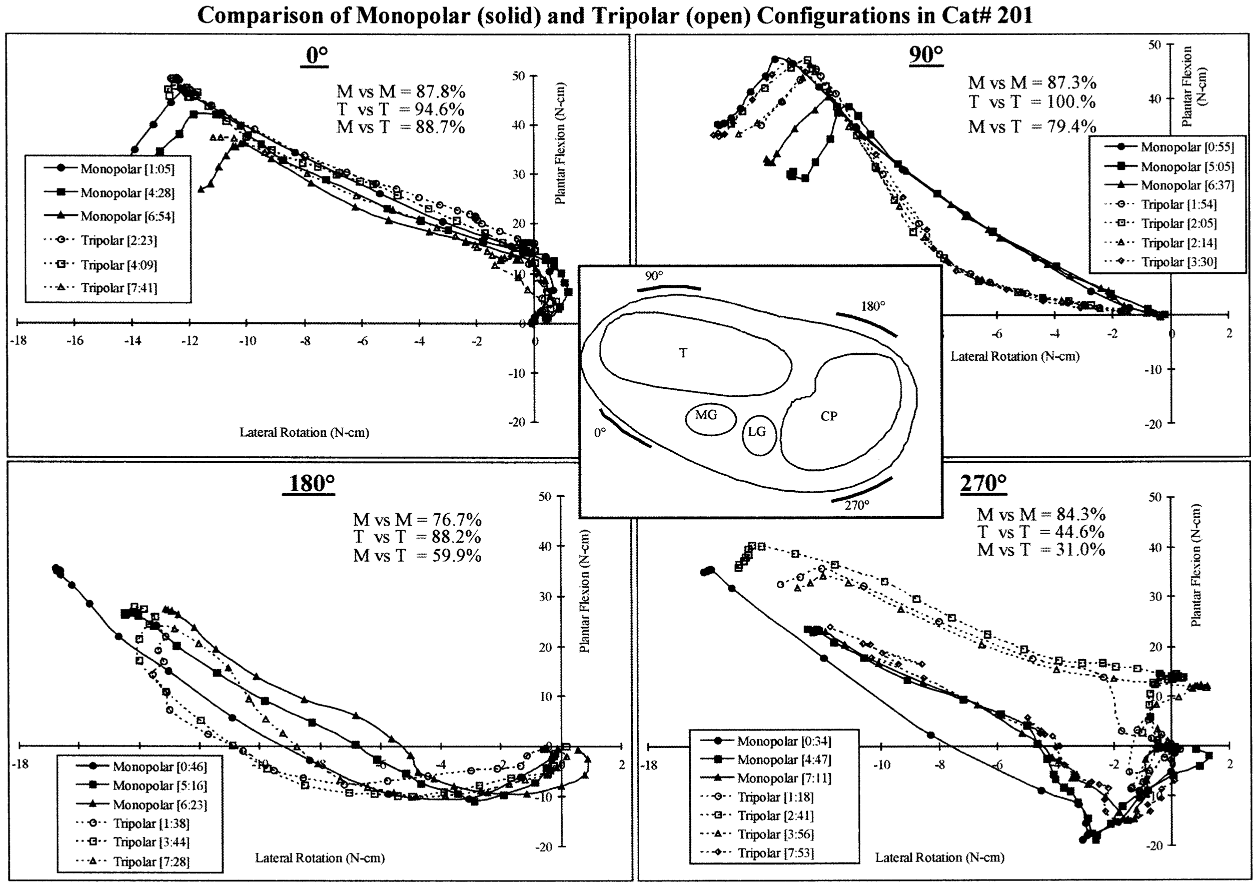

Fig. 7. Monopolar (solid) and tripolar (open) torque output plots achieved at the 0°, 90°, 180°, and 270° contacts in cat #201. The time from the start of the experiment for each trial is presented in the corresponding legend in brackets. Three similarity values are shown for each contact position: monopolar trials compared with other monopolar trials at the same position (M versus M); tripolar trials compared with other tripolar trials at the same position (T versus T), and for monopolar trials compared with tripolar trial at the same position (M versus T). The 270° position was found to exhibit the greatest difference between the monopolar and tripolar positions.

The maximum torque output before spillover for the monopolar configuration was found to be within 20% of the maximum torque recorded before spillover for the tripolar configuration. This indicates that either both configurations tended to achieve full activation of the first muscle before spillover or both configurations tended to spillover to a second muscle at the same percent activation of the first muscle. Based on the torque measured when the isolated branch was stimulated, the output resulting from the monopolar and tripolar stimulation was usually indicative of full activation of a single fascicle before spillover occurred.

The torque output gain was found to be larger for monopolar stimulation than for tripolar stimulation. Although gain is an important factor, especially for control, increasing the resolution of the stimulator can compensate for the increased gain. Since monopolar stimulation was found to have a gain 1.5 times that of tripolar stimulation, a stimulator with 1.5 times the resolution should be used with monopolar stimulation to provide the same level of control as with tripolar stimulation.

When the output torque was compared based on actual muscular output, the vectors produced by both the monopolar and tripolar configurations were very similar in nearly all cases. The greatest differences in the torque vectors were found to occur after activation spilled over to different fascicles (the torque vector trace changed direction). The variation in recruitment after spillover is not expected to be a concern, since most applications target stimulation of individual muscles.

B. Similarity Measure

The similarity measure provided a way to quantify the similarity between two data sets. The actual value of similarity is the percent of data points in one data set that are within the confidence interval of data in the other data set. A value of 100% similarity indicates that both data sets follow the same torque output. When the same contact or contact set was stimulated at two different times, as a measure of repeatability, a value of 100% similarity was often not achieved. These results are attributed to physiological changes (including fatigue) and system variability. Changes in temperature and movement of the electrode may also be factors. The average value of similarity for the monopolar configuration compared to a tripolar configuration was found to be within 1 standard deviation of both the monopolar repeatability and the tripolar repeatability. This result was interpreted to mean that the torque output from both the monopolar and tripolar configurations could not be differentiated. In order to quantify the level of similarity that was achieved

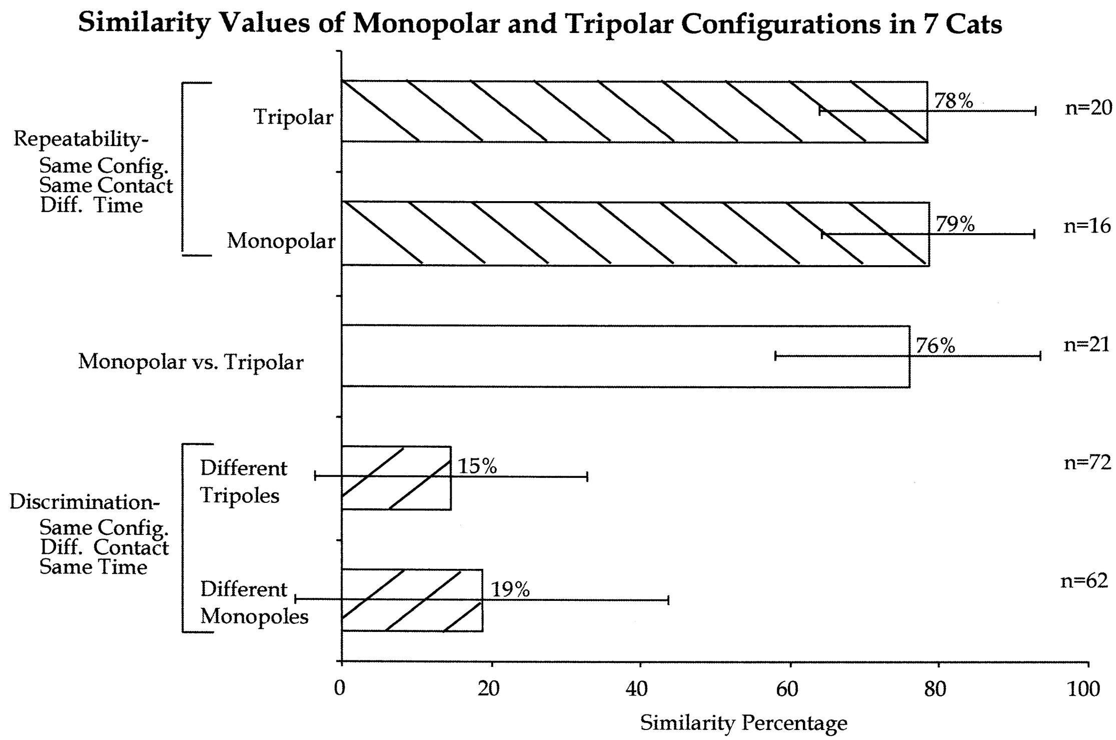

Fig. 8. Summary of similarity values found for monopolar and tripolar configurations. The similarity achieved using the same tripolar configuration at different times (top) and the similarity achieved using the same monopolar configuration at different times (second from top) were found to be 78% and 79%, respectively. The monopolar output torque compared to the tripolar output torque (middle), at a value of 76%, was not found to be statistically different than either the monopolar or tripolar repeatability at a 98% confidence level. The similarity values found for the torque outputs produced by stimulation applied to two different locations around the nerve were found to be 19% and 15%, respectively. The number of comparisons (n) was equal to the sum of every combination of two trials that satisfied the comparison of interest.

due to the finite possibilities of torque output and the finite resolution of the similarity measure, the similarity of the torque output produced by contacts at two different locations around the nerve was calculated. The average similarity between the torque outputs produced at two different locations around the nerve was found to be statistically less than the similarity between the monopolar and tripolar configurations. These results also support the hypothesis that both the monopolar and tripolar configurations exhibit a statistically significant amount of selective stimulation between contacts located at different locations around the nerve trunk.

V. Conclusion

The results of this study indicate that the recruitment characteristics obtained with a self-sizing spiral nerve-cuff electrode containing four radially placed contacts are very similar to the recruitment characteristics obtained with a similar cuff containing four radially placed tripole electrodes. The monopolar configuration tends to require lower stimulation current to achieve threshold activation and to have a higher gain than the tripolar configuration. These experiments also demonstrated, through the use of individual branch output, that it was not unusual to isolate the stimulation to a single fascicle and achieve the full torque output of that fascicle before activating another fascicle. Furthermore, once the fibers in a single fascicle begin to be activated, recruitment can be modulated over a full range before "spill-over" excitation of a neighboring fascicle occurs.

Based on this work, a monopolar contact configuration can be substituted for a tripolar configuration in multicontact self-sizing cuffs used for stimulating motor nerves containing four motor fascicles with little loss of selectivity. This finding is important since a self-sizing cuff electrode system with four contacts, four conductor lead, four channel connector device is technically easier to construct than an electrode system requiring 12 contacts, a 12 (or eight) conductor lead, and a 12 (or eight) channel connector.

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