Selectivity of Multiple-Contact Nerve Cuff Electrodes: A Simulation Analysis

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***Abstract*—Advances in functional neuromuscular stimulation (FNS) have increased the need for nerve cuff designs that can control multiple motor functions through selective stimulation of selected populations of axons. This selectivity has proved to be difficult to achieve. Recent experiments suggest that it is possible to slowly reshape peripheral nerve without affecting its physiological function. Using computer simulations we have tested the hypothesis that changing the cross section of a nerve from a round to a flat configuration can significantly improve the selectivity of a nerve cuff. We introduce a new index to estimate selectivity to evaluate the various designs. This index is based on the ability of a nerve electrode to stimulate a target axon without stimulating any other axons. The calculations involve a three-dimensional finite element model to represent the electrical properties of the nerve and cuff and the determination of the firing properties of individual axons. The selectivity rating was found to be significantly higher for the Flat Cuff than the Round Cuff. The result was valid with uniform or random distribution of axons and with a random distribution of fascicles diameters. Flattening of individual fascicles also improved the selectivity of the Flat Cuff but only when the number of contacts used was increased to maintain uniform contact density. Therefore, cuff designs that can reshape the nerve into flatter configurations should yield better cuff performance than the cylindrical cuffs but will require higher contact density.**

***Index Terms*—Electrical stimulation, nerve cuff electrode, selective.**

I. Introduction

ELECTRICAL stimulation of the nervous system can restore function to individuals with neurologic impairment, such as spinal cord injury, head injury, or stroke [1]. Specific applications include stimulating the phrenic nerve for respiratory control [2], the peroneal nerve for footdrop compensation [4], and upper and lower extremities for functional movement [1]. Future advances in these motor prostheses will require refined control and electrodes capable of stimulating several muscles selectively.

Most recently, electrodes have been developed to stimulate the peripheral nerve that innervates the desired muscles. Peripheral nerve-based electrodes (PNE) offer many advantages over surface or epimysial electrodes. They exhibit greater control over excitation [5], [6], lower stimulus intensities, and reduced susceptibility to mechanical stresses produced during muscle contraction [8]. Many PNE designs involve an electrically insulating cuff that places electrical contacts onto the nerve's surface. These extraneural electrodes are typically cylindrical chambers with an internal diameter equal to or greater than the nerve. The spiral cuff [9], for example, was developed to tightly surround the nerve while allowing flexibility for swelling. A new design proposed by Tyler and Durand [10], the flat interface nerve electrode (FINE), slowly reshapes the nerve into a flat configuration by applying a small, noncylindrical pressure. Flattening the nerve may allow better access of the electrical current to the axons within the nerve, improving the selectivity. A functionally effective nerve cuff should be able to selectively stimulate regions within the nerve, such as fascicles or particular portions of a fascicle down to the axonal level. The goal of this paper is to analyze the effect of the shape of a nerve cuff on its selectivity using computer simulations.

Previous models have been developed to examine the selective activation of various nerve cuff designs. For example, Veltink *et al.* [12] modeled the recruitment of multifascicular nerves using finite difference analysis. Sweeney *et al.* [7] used an analytical method to examine the recruitment properties of monopolar versus tripolar cuff configurations. Koole *et al.* [13] examined the recruitment properties of a multigroove electrode design. Although the goal of these models is to determine and compare the selectivity of various cuff configurations, it has been difficult to generate an accurate method to estimate selectivity. We have developed a selectivity rating index to evaluate the functional. This rating system allows us to compare the selectivity of various cuff designs and, in particular, the to test hypothesis that cuff electrode with a flat configuration have a better selectivity than cylindrical cuffs. This work was published in abstract and thesis format [3], [14], [28].

II. Methods

A. Modeling the Nerve Trunk and Nerve Cuff Electrode

A three-dimensional finite element model (FEM) of the anisotropic, inhomogeneous nerve and cuff was developed and implemented with ANSYS® (SAS IP, Inc., Houston, PA). Two cuff designs were modeled: a "Round Cuff" with a cylindrical geometry and a "Flat Cuff" with a flattened geometry [Fig. 1(a) and (b)]. The FINE was modeled in three different degrees of reshaping: "Flat," "Flat-25," and "Flat-50." "Flat" contained flattened nerve with aligned, round fascicles [Fig. 1(b)]. "Flat-25" and "Flat-50" contained flattened nerves with fascicles flattened by 25% and 50% of their height, respectively. The model includes the endoneurium, the perineurium (30 μm

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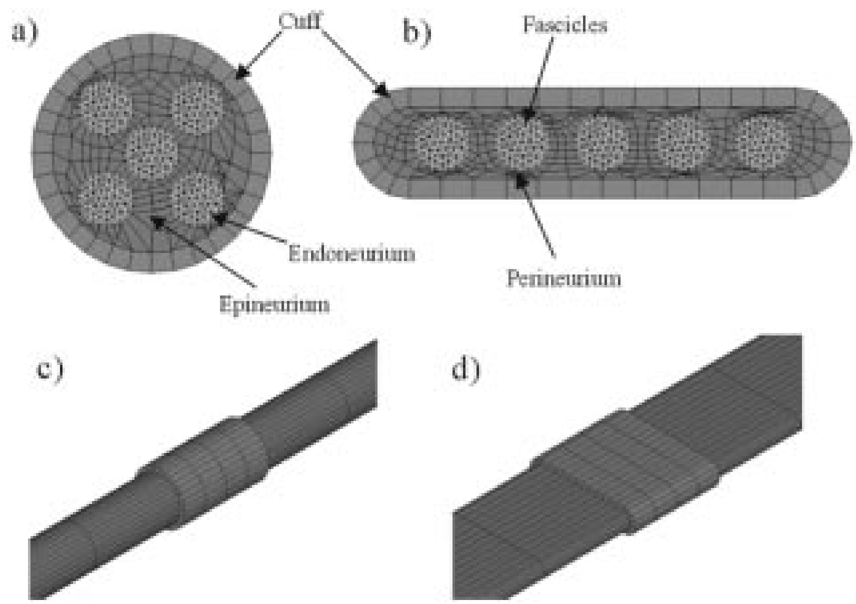

Fig. 1. Volume conducting models for finite element analysis. Tissues are defined by two-dimensional areas and assigned appropriate resistivity values. Areas are meshed using ANSYS internal algorithm [(a) and (b)] and then extruded to three dimensions [(c) and (d)]. The surrounding bath (cylinder 7.8 cm long and 2.2-cm diameter) is not shown but have an appropriate resistivity and mesh. The cross section of all nerves in the simulation was 6.97 mm^2 (a) Mesh of Round Cuff. (b) Mesh of Flat Cuff. (c) Mesh of Round Cuff extruded along the "z" axis. (d) Mesh of Flat Cuff extruded along the "z" axis.

TABLE I
RESISTIVITIES USED FOR MODELING

Perineurium		47.800	kΩ•cm
Epineurium		1.211	kΩ•cm
Saline		0.050	kΩ•cm
Silicon rubber		1.0e9	kΩ•cm
Endoneurium	Longitudinal	0.175	kΩ•cm
	Transverse	1.211	kΩ•cm

thick) surrounding the fascicles, the epineurium connecting the fascicles, the insulating cuff material, and a saline bath. The total volume conductor was a cylinder 7.8 cm long and 2.2 cm in diameter. The diameter of the round nerve was 2.2 mm, the thickness of the silastic layer 0.24 mm and the fascicle diameter was 0.8 mm. The length of the cuff electrode was 0.63 cm. Meshing routines segmented the areas into elements with nodes at each vertex. These areas were then extruded along the length of the nerve to create volumes [Fig. 1(c) and (d)].

The resistivity of each material type was obtained from the literature (Table I). The perineurium resistance was obtained from frog experiments [15] with the assumption that the perineurium thickness in those experiments was 100 μm. The longitudinal and transverse endoneurium resistivities were obtained from cat dorsal column [16]. The epineurium resistivity is not known but was assumed to be equivalent to the transverse resistivity of the endoneurium because of a similarity between the connective tissue. The extraneural environment was assumed to be 1% saline at 38 °C [17]. The silicon rubber resistivity was obtained from engineering references [18], [19].

All nerve models incorporated five fascicles. Initial models had uniform fascicle diameters of 0.8 mm, evenly spaced within the epineurium. All nerve models had a cross-sectional area equal to 6.97 mm^2 that was maintained in both the Round and Flat versions. In later models, the five fascicles were assigned diameters of 0.2, 0.2, 0.4, 0.7, and 0.8 mm. The five fascicles were randomly positioned within the nerve for that series of models. A completed model contained approximately 15 000 nodes. The element size in the fascicles was approximately 60 μm. This generated 60 xy positions with an 0.8-mm fascicle that were used for modeled axons.

All exterior nodes representing the boundary of the model were assigned a node potential of 0 V to represent an infinite reference. The injected current from an electrical contact of the cuff was modeled by a cathodic point source applied to one node lying on the internal boundary of the cuff and set to -1 mA with 0.1-ms pulsewidth with a distant anode. The electric field was solved for each contact separately. The voltages obtained at each node of model were first transferred to MATLAB (The MathWorks Inc., Natick, MA) and interpolated at each node of Ranvier for the axons using cubic spline interpolation. With uniform fiber diameter, the nodes of Ranvier were aligned with the electrical contact. However, when the fiber diameters were randomized, the respective position of the nodes of Ranvier were randomly distributed with respect to the stimulating electrode.

B. Modeling of Nerve Fiber Activation

Axons were modeled as passive electrical networks based on a cable model [20]. Parameters for the axon model are given in Table II [21], [22]. Axon diameters were initially set to 13 μm and but were later assigned a bimodal distribution with even peaks at 7 and 18 μm [23]. The membrane voltage along the axons was determined from [21]

$$V_m(n, PW) = \Psi(0, PW) \cdot \pi\, dl \cdot \left[f(n) + \sum_{j \neq n} \frac{\Psi(|n-j|, PW)}{\Psi(0, PW)} \cdot f(j) \right] \quad (1)$$

TABLE II
AXON CHARACTERISTICS USED FOR MODELING

Axon Diameter	d	Assigned for each model
Axoplasmic Resistivity	R_a	54.70 Ω•cm
Membrane Resistivity	R_m	7.81 Ω•cm^2
Membrane Capacitance	C_m	2.50 μF/cm^2
Nodal Gap Width	l	1.50 μm
Axon:Fiber diameter ratio	d/D	0.6
Internodal Length:Fiber Diameter Ratio	L/D	100.0

where

- $f(n)$ activation function at node n and can be directly obtained from the extracellular voltages obtained from the solution of the FEM;
- $\Psi(x, t)$ passive step response to a node, x nodes away, for a duration of t [21];
- PW pulsewidth;
- d diameter of the axon;
- l nodal length;
- n and j indexes for the nodes of Ranvier along the axon model.

Axonal recruitment was determined by comparing the maximum membrane voltage V_m with the critical voltage (V_c). V_c is the transmembrane voltage generated by a threshold current in a passive axon model [21], −65.68 mV for this study. A given axon was considered "fired" if V_m was equal to or greater than V_c. The recruitment of each contact at various pulse amplitudes was used to calculate the selectivity rating.

C. Calculation of Selectivity

The selectivity of a nerve electrode is defined as the ability to recruit a given fiber or group of fibers while keeping all other fibers below threshold. To quantify this concept, an axon $\mathbf{a}$ is first selected and current is applied to a contact $\mathbf{c}$ until threshold is reached. The number of axons also activated by the same stimulus normalized to the total number of axons is called the recruitment cost for axon $\mathbf{a}$ by contact $\mathbf{c}$ (RC_c^a). The same process is repeated for all contacts and all axons. To determine the ability of a nerve cuff to recruit selectively any axons within the nerve a nerve selectivity (NERVSEL) index is defined as follows: the maximum number of the axons below threshold $(1 - RC_c^a)$ is integrated for all axons within the nerve and all contacts when N_n is the total number of axons in the nerve

$$\text{NERVSEL} = \frac{\sum\limits_{a \in \text{nerve}} \operatorname*{Max}\limits_{c}(1 - RC_c^a)}{N_n}$$

To determine the ability of a cuff electrode to activate selectively the axons within a single fascicle (FASCSEL), the maximum number of axons below threshold is integrated for the axons in the chosen fascicle and normalized to the total number of axons in the fascicle (N_f)

$$\text{FASCSEL} = \frac{\sum\limits_{a \in \text{fasccle}} \operatorname*{Max}\limits_{c}(1 - RC_c^a)}{N_f}.$$

The NERVSEL represents the average maximum (for all contacts) number of axons still below threshold when recruiting any axon within the nerve. It is equal to one if any axon can be recruited without activating any other axons in the nerve and zero if the axon cannot be activated without activating all other axons. Similarly, FASCSEL will be equal to one if all the axons within the fascicles can be activated without activating any other fascicles. Comparisons between the various values of selectivities was performed with one-tailed t-tests in MS Excel (Microsoft Inc., Redmond, WA).

III. RESULTS

A. Induced Voltage and Axonal Recruitment

A plot of the extracellular voltage (produced by the FEM), interpolated to the nodes of Ranvier along a sample axon (13-μm diameter, located in the center of the central fascicle) is shown in Fig. 2(a). The computed transmembrane potential for the same example axon using equation (1) is shown in Fig. 2(b). The result is a triphasic response with a peak of −33 mV, in the center of the cuff, typical of monopolar stimulation [24].

Recruitment maps (Fig. 3) demonstrate axon recruitment for various levels of I_{in} in the Round and Flat Cuff models. The cross-sections show the nerve border with contact positions marked by diamonds. The current pulse amplitudes (I_{in}) for each map are indicated at the top of each plot. The contact marked with an asterisk is the one used for current injection. Each circle represents a 13-μm fiber. Circles marked with an "x" represent axons stimulated by the injected current. Nearly all of the axons within the closest fascicle are recruited before axons in the other fascicles are recruited. The border between stimulated and nonstimulated axons tends to be concave as previously shown by Cavanaugh *et al.* [14] and Deurloo *et al.* [11] for anisotropic nerve models.

B. Recruitment Costs for Round and Flat Cuffs

The RC_c^a for each axon and contact was calculated using the labeling convention shown in Fig. 4(a) and (b). Fig. 4(c) and (d) shows the RC_c^a values for the axon located at the dot in fascicle 3. In both Round and Flat Cuffs, the "optimal contact" is the contact closest to the axon (Round—11, Flat—13). The cost to recruit this axon is clearly lower in the flat configuration. The calculation of the NERVSEL for 300 axons in the model is larger for the flat nerve that the round nerve (Table III). Calculation of the fascicle selectivity (FASCSEL) indicates that fascicle 3 is the primary cause for the NERVSEL difference between the cuff designs, with the Round cuff having a much lower FASCSEL for the central fascicle (Table III).

C. Effect of Contact Number and Position on Selectivity

To examine the effect of the number of contacts and their placement, contacts were removed from the model one at a time. Using the previous model [Fig. 1(a) and (b)], one of the 16 contacts was selected at random and removed from the calculation of selectivity. Subsequent contacts to be removed were selected to maintain the most even spacing possible. The process continued until only one contact remained. The entire process was repeated for 85 trials. Note that while removing contacts does

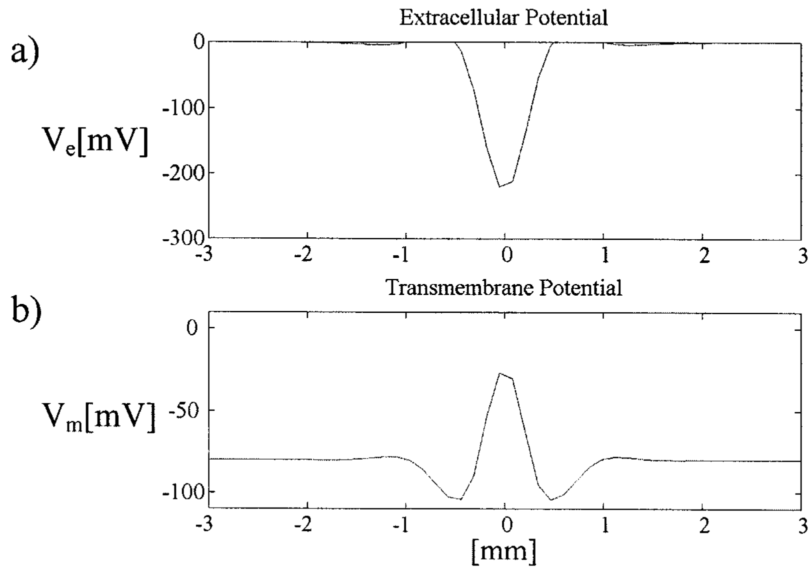

Fig. 2. Typical induced voltages generated in finite element models. An axon was selected as an example. (a) Extracellular potentials along the axon for a stimulation pulse of 1-mA cathodic 100-μs pulse and interpolated at the nodes of Ranvier for the modeled axon by a cubic spline in MATLAB. (b) Transmembrane potentials along the same axon as calculated in MATLAB.

not change the RC_c^a values for each of the remaining contacts, the selectivity estimates will change because there will be fewer choices of contacts.

The results are displayed in Fig. 5. The line represents the mean value of the NERVSEL at each number of remaining contacts. The error bars represent the standard deviations over each of the 85 trials. For both cuff types, a larger number of contacts generally results in a higher selectivity rating. With less than five contacts, each additional contact causes a large improvement in selectivity. There is a small statistical difference between the Round and Flat Cuffs (t-test: $p < 0.05$). With more than five contacts, the NERVSEL in the Round Cuff improves very little with additional contact. However, the selectivity of the Flat Cuff, increases with a larger number of contacts and is significantly higher than the selectivity of the Round Cuff. The variability of the NERVSEL is much larger in the Flat Cuff than in the Round cuff. This is caused by the large variability of the axon-contact distance in the Flat cuff.

D. Effect of Axon Diameter on Selectivity

Using the same geometry as in Fig. 1(a) and (b), the axon models were assigned random fiber diameters from a bimodal distribution. The distribution of axon diameters mimicked a normal physiologic distribution [23] and peaked at 7 and 18 μm. Ten trials of randomly distributed axon diameters were run for both the Round and Flat Cuffs. The mean NERVSEL values obtained were 0.748 ± 0.0078 and 0.902 ± 0.0089 for the round and flat cuff, respectively. Randomizing the axon diameters reduced the NERVSEL compared to the value obtained for the uniform, 13-μm axon diameters by about 5%. Despite the reduction of the NERVSEL values, the Flat Cuff NERVSEL is significantly higher (20%) than the Round cuff NERVSEL (t-test: $p < 0.001$).

E. Effect of Reducing Fascicle Height on Selectivity

Models using the generic nerve geometry of five 0.8-mm-diameter fascicles were generated. Three cuff heights of 1.06 mm (0% reduction in fascicle height), 0.86 mm (25% reduction in fascicle height) and 0.66 mm (50% reduction in fascicle height) were modeled, maintaining a constant cross-sectional area for both the nerve and fascicles. Ten trials of randomly distributed axon diameters were run using the bimodal diameter distribution. Reducing the height of the fascicle by 25% and 50% of their original 0.8-mm height did not improve significantly the selectivity. However, reduction in the height of the cuff while maintaining cross-sectional area, increased the circumference of the cuff and decreases the density of the contacts. By adding four contacts to maintain an electrode separation of 0.9 mm, the value of NERVSEL for ten trials of randomly distributed axon diameters increased significantly when compared to the round fascicle fascicles $0.922 \pm 0.002\,77$ (t-test: $p < 0.001$). Therefore, flattening the fascicles does improve the selectivity if the contact density is maintained.

F. Effect of Fascicle Diameter and Position on Selectivity

Using the nonuniform fascicle diameter models, a total of eight different nerve geometries were simulated. The results for the NERVSEL and FASCSEL are shown in Table IV. There is an overall drop in the NERVSEL compared to the uniform fascicle diameter model (Table III). However, the results obtained by the uniform fascicle diameter model are the same. The FASCSEL for the outer fascicles did not differ from each other (two tailed t-test: $p > 0.25$). The central fascicle (fascicle 3) is much lower in the Round Cuff. The Flat Cuff results in a higher NERVSEL than the Round Cuff (t-test: $p < 0.01$).

To analyze the effect of fascicle diameter on selectivity, the FASCSEL values for all of the fascicles in the eight trials were grouped by cuff type and fascicle diameter. The average value of

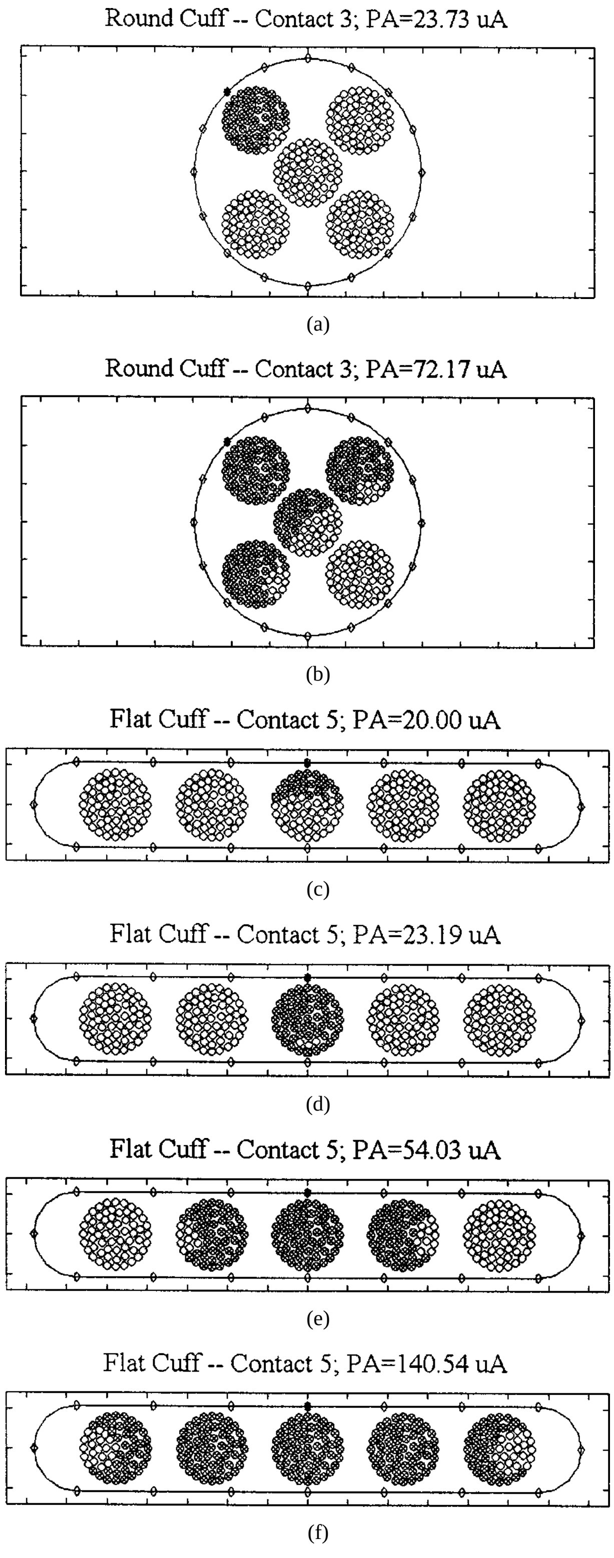

Fig. 3. Typical axonal recruitment in nerve models. Two cuff types are shown, Round and Flat, each with five fascicles, 0.8 mm in diameter. All contacts are shown as diamonds on the cuff's inner surface, with the contact used for stimulation marked with an asterisk. All axons are 13 μm in diameter and indicated with a circle. Axons marked with x are recruited by the marked contact for the given pulse amplitude (100-μs pulsewidth). The axon marked with a square is the target axon whose current threshold exactly equals the given pulse amplitude. Recruitment is spatially located near to the contact in all cases. (a) and (b) Round Cuff, contact 3, 23.73- and 72.17-μA current injected, respectively. (c)–(f) Flat Cuff, contact 5, 20.00, 23.19, 54.03, and 140.54 μA, respectively. The position and numbering of contacts are indicated in Fig. 4.

the FASCSEL is plotted in Fig. 6 as a function of fascicle diameter. Three regression lines were obtained for the Flat Cuff, the outer fascicles of the Round Cuff and the deep fascicle of the Round Cuff and the slopes are -0.157, -0.349, and -0.996, respectively. The deep fascicle (F3) is separated from the other fascicles in the Round Cuff model because of the previously determined difference between deep and outer fascicles (Table III). The data shows that the selectivity of fascicles located deep inside the nerve exhibit a strong dependence on diameter with the small fascicles easier to recruit than the large ones. Similarly, both selectivity regression for the Round and Flat cuff slopes are significantly different from a zero slope (two tailed t-test: $p < 0.01$). The trend indicates that large fascicles are more difficult to stimulate selectively than small fascicles. In addition, the data show that flat cuffs can recruit the large diameter with a higher selectivity than round cuff (t-test: $p < 0.01$).

IV. Discussion

An analysis of the functionality of a nerve cuff has been presented. The process builds upon a previously developed model [14]. The model validation tests show that the nerve-cuff model and the fiber-excitation model can reproduce data obtained experimentally. No difference was observed between the extracellular potentials when the volume conductor was increased in length and diameter [28] suggesting that size of the volume is sufficient to account for the boundary conditions. Moreover, tetanic force recruitment curves were obtained with the model by assigning a weight to each axon and comparing recruitment curves generated by the model with data obtained for tetanic force recruitment [25]. The comparison indicates that the curves generated by the model retain the overall shape of recruitment curves derived from nerve stimulation experiments [28]. A qualitative assessment of the shape of the recruitment curves also indicate that the point source representation of the electrode did not affect the ability of the model to reproduce the data.

The formulation of the selectivity is based on calculations made in experimental work such as percent activation of compound action potentials [26], and percent overlap of torque trajectories [27]. Therefore, it is useful in assessing the potential functionality of a cuff design. Selectivity is defined as the ability to preferentially activate an axon or axons without activation of other, undesired axons. By treating each axon as a potential target, comparisons can be made between any nerve configurations, with or without a fascicular organization and regardless of the number of innervated end organs. In nerve trunks innervating multiple muscles, it will be desirable to selectively activate populations of axons activating synergistic motor units. If the nerve innervates a single synergistic muscle, selective stimulation of sub-populations of axons can be cycled to reduce fatigue and maintain a constant overall output.

The selectivity measure developed above also shows that fascicles positioned deep within the nerve cannot be selectively activated. This finding agrees with previous results [12] showing that preferential activation of deep fibers was not possible with extraneural electrodes. Similar difficulties in selectively activating deep fibers were experienced by others, using the cylindrical nerve cuff electrode [6], [28]. Therefore, one of

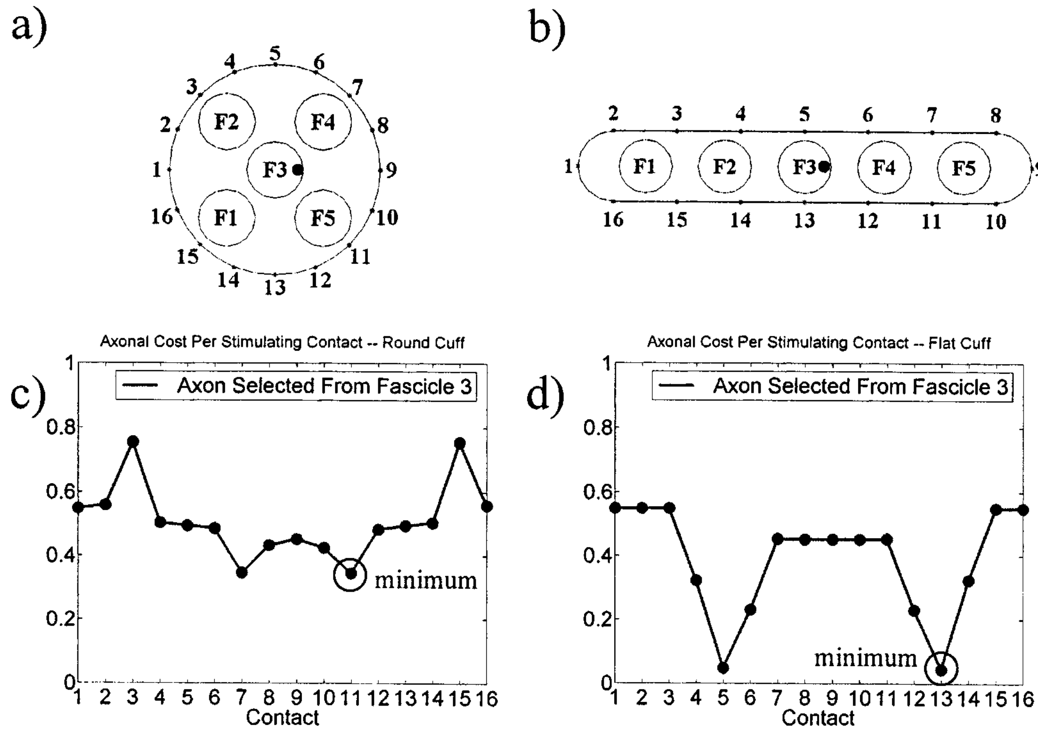

Fig. 4. *Recruitment Costs in Nerve Models.* (a), (b) Schematic of cuff with fascicle numbers (F1–F5) and contact numbers (1–16) indicated. (c), (d) The recruitment costs, calculated with equation (2), are shown for a randomly selected axon from fascicle 3 in the round cuff [indicated by the black dot in (a)]. The same axon was used in the Flat cuff (b). The Optimum Contact (OC) is defined as the one which generates the minimum recruitment cost for an axon, i.e., contact 7 for the Round Cuff and contact 5 for the flat cuff.

TABLE III
AXONAL SELECTIVITY RATINGS FOR GENERIC NERVE

Cuff Type	NERVSEL	FASR				
		1	2	3	4	5
Round	0.798	0.944	0.945	0.212	0.944	0.945
Flat	0.954	0.964	0.944	0.951	0.944	0.964

advantages of the flat cuff is that it does not include any deep fascicles.

Reshaping the nerve [10], however, improved the NERVSEL value over the cylindrical cuff NERVSEL values. By flattening the nerve the FINE can reposition fascicles and effectively eliminates "deep" fascicle. The FASCSEL value of the central fascicle (fascicle 3) is much lower in all of the Round Cuff models than in the Flat Cuff models. All other fascicles (1, 2, 4, and 5) have similar FASCSEL values for both cuff types.

To test the robustness of this result, we constructed a model with a more realistic distribution of axon diameters. Axons were assigned diameters randomly from a bimodal distribution with peaks at 7 and 18 μm [23] and a random position of the nodes of Ranvier with respect to the stimulation electrode. This resulted in a reduction of NERVSEL from the uniform axon diameter models caused by the relative thresholds of large and small fibers. Larger diameter axons have lower injected current thresholds than smaller diameter axons. Therefore, small fibers will have high recruitment costs because larger fibers may be unintentionally stimulated. This effect is evident in both the Flat Cuff and the Round Cuff. The recruitment selectivity of the Flat Cuff, however, is still higher than the Round Cuff.

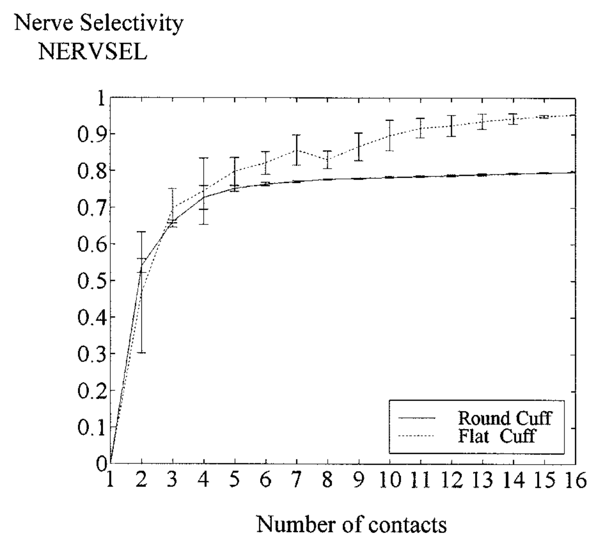

Fig. 5. NERVSEL versus number of contacts. Beginning with the original 16 contact positions, contacts are selected to be as evenly spaced as possible. Typical Round Cuff and Flat Cuff models were used with the idealized five-fascicle model. All axons were assigned 13-μm diameters. In general, larger number of contacts leads to higher NERVSEL Larger variability is seen in the Flat Cuff than the Round Cuff. The Flat Cuff has higher NERVSEL for six or more contacts.

To construct a model with more realistic fascicle diameters and positions, five fascicle diameters were randomly selected from previously collected feline sciatic histology and randomly positioned within the epineurium of the nerve. The position of the nodes of Ranvier with respect to the electrode were

TABLE IV
AXONAL SELECTIVITY RATINGS FOR RANDOMIZED FASCICLE DIAMETERS

(Mean ± STD)	NERVSEL	FASR 1	FASR 2	FASR 3	FASR 4	FASR 5
Round Cuff	0.677 ±0.058	0.899 ±0.058	0.914 ±0.058	0.306 ±0.058	0.784 ±0.058	0.915 ±0.058
Flat Cuff	0.876 ±0.058	0.913 ±0.058	0.916 ±0.038	0.883 ±0.106	0.876 ±0.075	0.927 ±0.047

also randomized. Using multiple fascicle diameters lowered the NERVSEL from the uniform fascicle diameter models. Previous simulations [14], have shown that electric field lines bend around fascicles because of the higher resistivity of the perineurium. This effect causes larger fascicles to require more injected current into the endoneurium before activation can take place. Small fascicles are less affected and thus have lower injected current thresholds for their axons. This explanation can be easily tested by reducing the perineurium resistance to a value equal to the endoneurium resulting in a uniform of fascicles regardless of their diameter [28]. As a result, some axons in smaller fascicles will be recruited when the target axon is within a larger fascicle. Therefore, the FASCSEL for large fascicles is lower than the FASCSEL of small fascicles as previously observed in a previous model [14]. Both the Round and Flat Cuffs are affected by fascicle diameter, but the Flat Cuff still has a better selectivity that the Round Cuff under these conditions.

The results indicate that increasing the circumference of the cuff as in the flat cuff clearly improves the selectivity but only if the contact density is increased. The models in this study used a maximum of 16 contacts, corresponding to a contact spacing of 0.585 mm in the Round Cuff and 0.958 mm in the Flat Cuff. Fabrication, however, puts a limit on the number of contacts on a given electrode.

The conclusions reached with this model are robust since they are still valid in the presence of random distribution of axons diameter and fascicles diameters and position of the nodes of Ranvier. However, many other variables could affect the selectivity results. A more realistic cross-sectional area of the nerve could change the conclusions since the cross-section of the nerve in this model has been idealized to eliminate confounding variables such as fascicle shape. However, histological cross-sectional data show that in a round nerve cuff, fascicles are on average round or ovoid as modeled in this study. Although the relative position of the fascicles to the electrode could be significantly different in a realistic mode, it is unlikely that this factor would affect any of the conclusions since the conclusions were obtained with randomized fascicles diameters and positions. Computer models have shown that longitudinal tripoles can provide improved selectivity and a different arrangement of electrodes could affect the results. However, recent experiments suggest that, in the sciatic nerve, there is no difference in the selectivity when comparing monopolar and tripolar electrodes (Tarler and Mortimer, unpublished data).

In conclusion, this modeling analysis shows that by reshaping the nerve into a flat configuration, it is possible to increase the functional selectivity of a nerve cuff. This result is valid with both uniform and random distributions of axon and fascicles diameters. Moreover, the flat shape allows the selectivity to be significantly improved by increasing the contact density around the nerve cuff. This design could therefore be advantageous to the development of neural prostheses that require selective recruitment of axons.

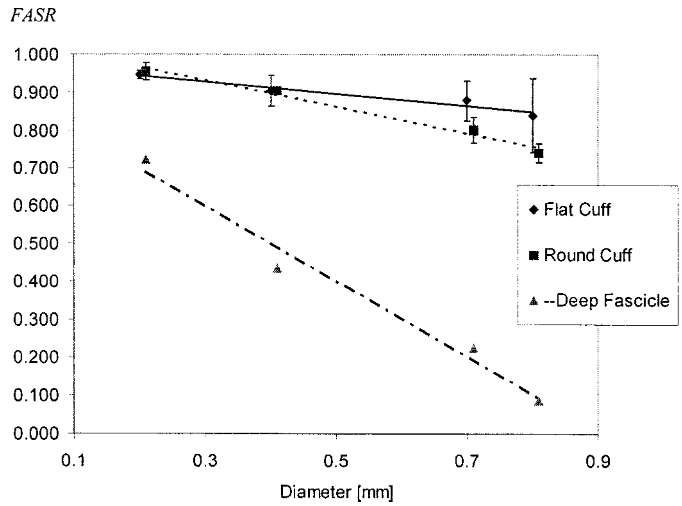

Fig. 6. FASR versus Fascicle diameter. Results of the four trials using the models with random fascicle diameters. Data points represent the mean values of each fascicle diameter modeled and error bars represent one standard deviation ($n = 4$). The lines represent a linear regression through the data. Deep fascicle values were treated separately from the outer fascicle in the round cuff because of the demonstrated effect of position. The slopes of the regressions are -0.157, -0.349, and -0.996, respectively, for the Flat Cuff, Round Cuff outer fascicle, and Round Cuff deep fascicle. These slopes were statistically different (t-test: $p < 0.01$).

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