# A Slowly Penetrating Interfascicular Nerve Electrode for Selective Activation of Peripheral Nerves

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Abstract-To meet the future needs of functional electrical stimulation (FES) applications, peripheral nerve electrodes must be able to safely, selectively, and independently stimulate small subpopulations of the axons within a common nerve trunk. A new electrode has been designed to place contacts outside of the perineurium, but within the epineurium of the nerve. This slowly penetrating interfascicular nerve electrode (SPINE) combines the safety and simplicity of extraneural cuff electrodes with the intimate interface of intrafascicular wire and probe electrodes. We briefly discuss a mathematical method of quantifying performance of nerve electrodes based on the functional output of the intact neuromuscular system. The quantification involves three variables: 1) the functional recruitment trajectory (FRT), 2) functional overlap (O), and 3) overall functional selectivity  $(\Lambda)$ . Second, we present results from six acute SPINE implants on the feline sciatic nerve. Quantification of stimulation results demonstrate interfascicular stimulation is functionally different than extraneural stimulation in 32 of 38 trials. In 19 of 28 trials, interfascicular stimulation is functionally selective based on depth of penetration and 52 of 58 trials demonstrate selectivity based on the side of the penetrating element. Third, tissue sections show that the SPINE electrode penetrates into the nerve within 24 h without evidence of edema or damage to the perineurium.

#### I. INTRODUCTION

**P**ERIPHERAL nerve electrodes show promise to replace intramuscular (IM) electrodes in functional electrical stimulation (FES) applications [1]. Typically, the peripheral nerves are readily accessible with little surgical trauma. Peripheral nerve electrodes can be placed away from the muscles being activated and isolated from the mechanical stresses produced by muscle contraction, thereby, leading to greater longevity of the implanted system. It has also been shown that neural electrodes do not suffer from the length dependent recruitment problems that plague IM electrodes [2]–[5]. The charge requirements for stimulation are typically 1/10th to 1/100th that of IM electrodes. Since a single peripheral nerve contains the motor neurons to several different muscles, a peripheral nerve electrode offers the ability to activate several muscles from a single implanted device.

The two most important issues with peripheral nerve electrodes are the safety and the stimulation selectivity of these devices. First, neural tissue is susceptible to mechanical trauma and sensitive to changes in the vascular supply. Second,

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nerve electrodes must selectively stimulate axon populations to reproduce useful output from the neuromuscular system.

Previous peripheral nerve electrode designs have been either extraneural or intrafascicular. Extraneural electrodes are the least invasive and encircle the nerve without disruption of either the perineurial or epineurial membranes. These electrodes, such as the spiral [6], [7], helix [8], [9], loose cylinders [9], and electrodes sutured to the epineurium [10], place electrical contacts on the circumference of the nerve. While they can selectively activate surface regions of the nerve [11]-[13], questions arise regarding stimulation of central populations of axons without stimulation of surface axons [14]–[17]. Intrafascicular electrodes, such as fine wires [18], [19], [20], [21], [22], silicon probes [23], [24], [25], and regeneration arrays [26], [27], [28], [29], place electrical contacts directly within the fascicles by penetrating both the epineurium and perineurium. These electrodes provide greater access to the central axon population, but the disruption of the perineurium and endoneurial environment can lead to loss of axons, viral infection, and other related problems [30]. The normal encapsulation response to a foreign object will separate the electrode from the axons, partially defeating the original intent. These electrodes can be difficult to implant and often require specialized surgical skills.

In this paper, we present an interfascicular design which combines the simplicity and safety of the extraneural electrodes with the intimate axon contact and stimulation selectivity of intrafascicular electrodes. This electrode places electrical contacts within the nerve, but outside the fascicles.

The interfascicular electrode exploits the differences between the mechanical properties of the epineurium and perineurium. The epineurium is a mechanically loose collagen and fibrin mesh. Its primary purpose is to maintain the peripheral nerve integrity. In contrast, the perineurium is a mechanically tight tissue consisting of several tightly bound cell layers [30]. The perineurium is difficult to penetrate with a blunt object.

Therefore, the interfascicular electrode applies a small force to the nerve with blunt penetrating elements. These elements slowly separate and rearrange the epineurium without compromising the integrity of the perineurium. The elements place stimulation contacts within the nerve for greater access to the central axon population and should provide greater selectivity in neural stimulation. The electrode is referred to as the slowly penetrating interfascicular nerve electrode or SPINE [31].

To test the hypothesis that interfascicular recruitment is different from extraneural recruitment, we have chosen to study SPINE stimulation on the feline sciatic nerve. Grill *et al.* 

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Fig. 1. The slowly penetrating interfascicular nerve electrode (SPINE). (a) Schematic view of the entire SPINE electrode. Each element is slowly urged into the epineurium by a small force applied by the beam. The beams consist of the frayed end of a cylindrical tube. The center of the electrode is closed with either suture or a second tube around the center. (b) A close-up of one beam and element of the SPINE. A surface contact is located in the tube wall, two interfascicular contacts are located on one side of the penetrating element, and the third interfascicular contact is located on the opposite side of the element. All contacts are untreated platinum and circular with approximately 0.75 mm diameter.



Fig. 2. The isometric torque measurement apparatus. This figure shows the cat's hind leg in the stereotactic frame and attached to the JR3 torque measurement device. The cat's knee is rigidly fixed with atraumatic cups over the inner and outer tuberosities of the tibia. The foot is rigidly fixed to an aluminum shoe on the measurement device. The SPINE, implanted on the sciatic, is attached to a computer controlled stimulator. The output of JR3 is sampled and stored by a Mac IIfx. This preparation is described in full detail in [32].

[32], have described a noninvasive, nondestructive experimen-



Fig. 3. Directions of motion about the ankle joint. Dorsiflexion and plantarflexion are the rotation of the toes toward or away, respectively, from the knee. Medial and lateral rotation are the rotation of the toes toward or away, respectively, from the midline of the animal. Inversion and eversion are the rotation of the sole of the foot toward or away, respectively, from the midline.



Fig. 4. Derivation and definitions of the functional recruitment trajectory (FRT). The points in quadrants I and III are the dorsiflexion and medial rotation recruitment curves, respectively, as a function of charge. The combination of these points produces the FRT as shown in quadrant IV. The moment axes are in units of *N*-cm and the charge axes in units of nC.

tal preparation to measure the isometric torque output about the ankle joint of the cat. We present a novel data analysis method that quantifies recruitment differences based on the *functional* results of stimulation rather than individual muscle or fascicle activation. The analysis will demonstrate whether or not interfascicular stimulation produces selective stimulation compared to extraneural stimulation.

#### II. METHODS

#### A. Acute Electrode Design

The SPINE (Fig. 1) consists of a silicon rubber tube of 1.5 mm wall thickness (Body) with blunt "Elements" extending radially into the lumen of the tube. By cutting the end of the tube (labeled Fraying Cut in Fig. 1), the end is divided into four "Beams." When the medial portion of the SPINE is closed, the beams produce a small force on the elements. Following implantation, the elements slowly penetrate within the epineurium without intervention by the surgeon. When the beams have returned to their original position, i.e., the original tube diameter, the applied force will return to zero and the elements will stop penetrating.

Fig. 1(b) shows a typical layout of the electrical contacts on a penetrating element. Each element contains three untreated platinum contacts imbedded in silicone rubber. Two contacts are located on one side of the element and the third on the opposite side. The contacts are circular with a diameter of 0.75 mm. Two of the six tested SPINE electrodes also include surface contacts, as shown in Fig. 1(b), of the same size as the interfascicular contacts.

#### **B.** Experimental Procedure

Six adult cats weighing between 2.8 and 4 kg were used for the experiments. The electrode is implanted via acute surgery on the sciatic nerve in the popliteal fossa. The penetrating elements are placed immediately proximal of the sciatic bifurcation into common peroneal and tibial components. The penetration process does not require any special preparation to the nerve or effort from the surgeon beyond placement of the SPINE on the nerve.

Throughout the implant and experimental procedures, anesthesia is maintained by administration of 0.2cc IV boluses of Nembutal (Pentobarbital Sodium, 50 mg per mL) as indicated by paw pinch, eye, and cough reflexes. Body temperature is maintained by a circulatory water heating pad and radiant heat sources. Approximately 1L of lactated ringer's solution is administered by IV drip over a 24 h period. The animal is intubated and maintains its own respiration.

Following a 12 h penetration period, the cat is placed in the stereotactic frame (Fig. 2) previously described by Grill *et al.* [32]. The knee is clamped with atraumatic cups over the inner and outer tubrosities of the tibia and the foot is clamped into an aluminum shoe attached to a JR3 six degree of



Fig. 5. FRT's of three interfascicular contacts and a surface contact. The three thin lines are the interfascicular contacts and the thick line is the surface contact. (Thr = stimulus charge threshold, 90% = charge at 90% activation,  $\Delta Q$  = change in charge between successive FRT points.) The three interfascicular contacts, *a*, *b*, and *c*, are all functionally unique from each other. The surface contact, *s*, is functionally similar to a portion of contact *b*. However, the surface contact changes direction twice, indicating stimulation spillover to nonsynergistic muscle groups. All of the interfascicular contacts are fairly linear. The region enclosed by dashed lines indicates overlap between contacts *b* and *s*. The amount contact *s* overlaps contact *b*. Contact *b* overlaps 0.49 of contact *s*.

freedom measurement device (JR3, Inc., Woodland, CA). The knee, hip, and ankle angles are fixed at 90°. This experimental preparation measures the isometric torque generated about each axis of the ankle joint in response to electrical stimulation.

We generate an amplitude modulated twitch recruitment curve for each contact on the SPINE. For each stimulus level of a recruitment curve, a current generator delivers five monophasic current pulses with a 2-s delay between each pulse. An A/D board (National Instruments, Austin, TX) samples the JR3 measurements of each twitch for 0.75 s at 200 Hz. A software virtual instrument (VI), created with LabVIEW 2.2 (National Instruments), running on a Mac IIfx, records the value of the maximum deflection from the baseline within each twitch. The largest and smallest twitch deflections are discarded to account for muscle potentiation and the remaining three values are averaged and saved with the standard deviation for later analysis. Durfee et al. [33] and later Grill et al. [32] have shown the peak deflection is a reasonable indicator of the evoked muscle response. A delay of 30 s between each stimulus level of the recruitment curve minimizes muscle fatigue. The pulse width for each recruitment curve is constant and nominally 10  $\mu$ s. The range of pulse amplitude for each recruitment curve is from 50 to 5000  $\mu$ A.

Following the stimulation experiment, the animal is sacrificed with an overdose of pentobarbitol sodium. The fascicles innervating the common peroneal, the lateral gastroc-

TABLE I SUMMARY OF STIMULUS CHARGE LEVELS.

SPINE Number	Threshold (nC)		90% Activation (sC)		
	Mean t Std.	Median	Maran ± Sed	Mediat	
1	184±42	10.0	16.9±5.1	16.8	
2	32.4 ± 18.4	25.0	38.8 ± 1.5	40.9	
3	29.4±25.9	15.0	184.9 ± 35.7	180.5	
4	27.2 a 22.9	21.2	265 8 61 5	46.5	
5	27.8±25.8	38.0	70.9±42.0	42.9	
6	25.4 ± 28.1	16.0	77.5 ± 133.8	44.6	
Overall	24.4±22.6	16.0	\$53±765	41.9	

nemius/soleus, the medial gastrocnemius, and the remaining tibial branches of the sciatic are identified and marked with suture for later reference. The nerve branches are cut distal to the suture markings and the sciatic is cut proximal to the implanted electrode. Without removing the electrode from the nerve, the electrode and nerve are immersed in a buffered 10% formalin solution for several days. Following fixation, the nerve is sectioned at the proximal, medial, and distal levels of the electrode. The sections are embedded in plastic and stained with methylene blue to show myelin.

### C. Data Analysis

Three concepts are introduced to quantify the electrode performance: 1) the functional recruitment trajectory, 2) the overlap of two functional recruitment trajectories (FRT)'s, and 3) an overall selectivity rating.



Fig. 6. The three FRT's of the interfascicular contacts of an element. The *a* (thin line) and *b* (thick line) contacts are located on the same side of the penetrating element. The *b* contact is approximately 0. 5 mm deeper into the nerve. (Thr = stimulus charge threshold, 90% = charge at 90% activation,  $\Delta Q$  = change in charge between successive FRT points.) These two contacts generally recruit plantarflexive-medial rotation moments. Contact *c* is on the opposite side of the penetrating element. It initially generates a planterflexive-lateral rotation moment and then a dorsiflexive-lateral rotation moment. Contact *c* is functionally antagonistic to contacts *a* and *b*.

1) Moment Space and the Functional Recruitment Trajectory: Moment space is defined by the three axis of ankle rotation: dorsiflexion (D), medial rotation (MR), and inversion (I) (Fig. 3). The FRT of the *p*th contact as a function of charge is defined [34] as

$$FRT^{p}(q) = m_{D}^{p}(q)\hat{\mathbf{i}} + m_{MR}^{p}(q)\hat{\mathbf{j}} + m_{I}^{p}(q)\hat{\mathbf{k}}$$

where  $m_D(q)$ ,  $m_{MR}(q)$ , and  $m_I(q)$  are the dorsiflexion, medial rotation, and inversion recruitment curves, respectively.

Fig. 4 illustrates typical experimental data and the FRT. Linear interpolation of the experimental data produces a continuous function for analysis. The FRT is resampled and plotted at constant charge intervals. The interval size is dependent on the threshold and 90% activation levels of the recruitment.

2) Overlap Between Two FRT's: Overlap (O) is defined as the percentage of a given FRT that is functionally equivalent to some portion of a second FRT. An overlap region is defined as the set of points where the FRT's are within the 98% confidence interval of each other. The 98% confidence interval is determined by the measured standard deviations and the student's t distribution.

Fig. 5 demonstrates FRT overlap. The dashed lines outline the region of overlap between the FRT's of contacts s and b. The FRT of contact b overlaps 49% of the FRT of contact s,  $O_{sb} = 0.49$ . However, since the FRT's of different contacts have different lengths, the overlap numbers are not symmetric. In Fig. 5, 69% of the FRT of contact b is overlapped by the FRT of contact s or  $O_{bs} = 0.69$ .

The set of overlap numbers for all possible pairs of contacts generates an overlap matrix,  $\mathbf{O}$ . The diagonal entries are 1.0 since each contact is 100% functionally equivalent to itself. The overlap matrix is used to calculate the overall selectivity, as described below.

3) The Overall Selectivity: Overall selectivity ( $\Lambda$ ) is defined as the percentage of contact pairs that overlap less than 50%. The following example demonstrates the overlap matrix and determination of  $\Lambda$ .

		а	b	С	S
	а	[ 1	0.07	0	0.01
<b>O</b> =	b	0.05	1	0	(0.64)
	с	0	0	1	- 0
	s	0.01	0.46	0	1

**O** is the overlap matrix. a, b, and c are interfascicular contacts and s is the surface contact. Each entry represents the percent of the FRT of the row contact that is overlapped by the FRT of the column contact. The boxes indicate the overlap numbers that compare the surface contact to the interfascicular contacts. The circle indicates that the surface contact overlaps 64% of interfascicular contact b. The circle shows the only



Fig. 7. The two FRT's of contacts on the same side of an element. The *b* (thick line) contact is approximately 0.5 mm deeper into the nerve. (Thr. = stimulus charge threshold, 90% = charge at 90% activation,  $\Delta Q$  = change in charge between successive FRT points.) Both contacts generate a dorsiflexive moment. Contact *a*, however, produces medial rotation while contact *b* produces lateral rotation. Fig. 10 shows the location of this element (labeled "3" in Fig. 10) within the nerve. Notice both contacts are next to the common peroneal fascicle. These contacts have selectively recruited sub-populations within the common peroneal.

overlap greater than 0.50. Therefore, the overall selectivity,  $\Lambda$ , between surface and interfascicular contacts is  $\Lambda = \frac{5}{6} = 0.83$ .

# III. RESULTS

For all six experiments, the threshold stimulus charge value was  $24.4\pm22.6$  nC (mean  $\pm$  std) with a median value of 16 nC. The charge required for 90% activation was  $65.3\pm76.5$  nC with a median value of 41.9 nC. Since the proximity of each contact to the axons is dependent on the penetration, there is a wide variation in the stimulus values. Table I summarizes the stimulus levels required in each of the six experiments. The threshold and 90% activation levels of the surface contacts are  $26 \pm 40$  nC and  $106 \pm 183$  nC as compared to  $24 \pm 20$  nC and  $60 \pm 52$  nC for the interfascicular contacts. A *t*-test of equality of means shows no significant difference between the stimulus requirements of the surface contacts compared to interfascicular contacts.

# A. Functional Selectivity of Interfascicular Stimulation Versus Surface Stimulation

Fig. 5 shows the FRT's of three contacts located on a penetrating element (thin lines) and a contact on the surface (thick line). The surface contact FRT, labeled s, does not overlap the FRT's of interfascicular contacts a or c. At low stimulus levels, the FRT's of interfascicular contact b and the surface contact s are both increasing in the dorsiflexion-lateral rotation direction. As the activation level increases, contact s turns and increases in the dorsiflexion direction only. At higher activation levels, the s contact FRT bends again to increase in

the plantarflexion-medial rotation direction, which is opposite the initial recruitment. The b contact, however, only increases in the dorsiflexion-lateral rotation direction.

Data from the 38 trials comparing interfascicular to surface stimulation produce an average overlap of  $0.21\pm0.28$  (mean  $\pm$  std) with a median value of 0.09. Of the 38 trials, 32 overlapped by less than 50% for an overall selectivity of  $\Lambda = 0.84$ . Fig. 8(a) shows the frequency distribution of the overlap numbers for these 58 trials.

The linearity of the a and b contacts also suggest that the interfascicular contacts are functionally more synergistic than the surface contact. Since the measured system is isometric, increases in activation of a single muscle would only change the magnitude of the FRT vector, but not its direction. The linearity of the interfascicular contacts' recruitment indicates that the stimulated motor units are either all from the same muscle or synergistic muscles.

# B. Functional Selectivity of Interfascicular Contacts on Opposite Sides of a Penetrating Element

Fig. 6 shows the FRT's of the three contacts of a single penetrating element [Fig. 1(b)]. Two contacts (thin lines in the figure), labeled a and b, were exposed on one side of a penetrating element and the third (thick line), label c, was exposed on the opposite side. Contacts a and b generate FRT's in the direction of plantarflexion-medial rotation. Contact c generates a FRT in the opposite direction, dorsiflexion-lateral rotation. Contacts a and b activate functionally antagonistic motor units compared to contact c.



Fig. 8. The distribution of overlap numbers for all trials. (a) Comparing surface to interfascicular contact FRT's. (b) Comparing interfascicular contact FRT's from opposite sides of the penetrated element. (c) Comparing interfascicular contact FRT's of different penetration depths.

Data from the 58 trials comparing interfascicular contacts on opposite sides of the penetrating element produce an average overlap of  $0.15\pm0.27$  (mean  $\pm$  std) with a median value of 0.00. Thirty of the trials generate overlap of 0.00. Of the 58 trials, 52 overlapped by less than 50% for an overall selectivity of  $\Lambda = 0.90$ . Fig. 8(b) shows the frequency distribution of the overlap numbers for these 58 trials.

# C. Functional Selectivity of Contacts at Different Depths of Penetration

Fig. 7 demonstrates the functional selectivity between the recruitment of two contacts on the same side of the penetrating element. Interfascicular contact a (thin line) is located close to the surface and contact b (thick line) is approximately 0.5 mm deeper within the nerve. Both contacts generate a dorsiflexion moment. The a contact, however, produces a medial rotation moment, while the b contact produces lateral rotation.

Data from the 28 trials comparing interfascicular contacts at different depths of penetration produce an average overlap of  $0.28 \pm 0.34$  (mean  $\pm$  std) with a median value of 0.12. Of the 28 trials, 19 overlapped by less than 50% for an overall selectivity of  $\Lambda = 0.68$ . Fig. 8(c) shows the frequency distribution of the overlap numbers for these 28 trials.

Table II summarizes the overlap and overall selectivity ratings for all comparisons presented in this paper. The variation between overlap numbers are consistent between all trials.

TABLE II SUMMARY OF DATA ANALYSIS OF STIMULATION RESULTS

Contact Sets Compared	Number of Trials	Ovedap Moan±5sd	Overlap Medias	Number of Selective Trials (OS0.5)	Overall Selectivity A
Surface v. Interfuscicular	38	0.21±0.28	0.09	22	0.84
Contacts on Opposite Sides of the Element	58	0.1520.27	0.00	52	0.90
Contacts Penetrated to Different Depthe	28	0.2820.34	0.12	19	0.68

#### D. Functional Range of Recruitment

Fig. 9 shows the functional recruitment trajectories of all interfascicular contacts of one SPINE electrode. There is at least one FRT in every quadrant. In three of the six experiments, the SPINE produced FRT's in all four quadrants of the D-LR plane. Of the remaining three experiments all produced FRT's in both the medial and lateral rotation directions of plantarflexion. However, of these three SPINE's, one produced dorsiflexion with medial rotation only and the other two produced dorsiflexion with lateral rotation only.

## E. Neural Penetration and Cross Sectional Alterations

Fig. 10 show cross sections through the medial (a) and distal (b) portions of an electrode and nerve. The fascicles are labeled according to the muscle group they innervate as determined by the suture markings placed on the nerve at explant (see



Fig. 9. All FRT's generated by the contacts of one SPINE containing only interfascicular contacts. The SPINE was able to selectively generate functional output into each of the four quadrants of moment space.

"Methods"). The penetrated elements are superimposed on the distal histology section. The small x's mark the locations of electrical contacts. The element number is marked beside each element.

The medial section [Fig. 10(a)] shows that the nerve is ellipsoidal and all the fascicles within the nerve are nearly circular. The distal section [Fig. 10(b)] shows that the nerve is altered by penetration of the electrode elements.

In the distal section, element 1 has penetrated deep within the nerve and separated the TIB from the MG and LG/SOL fascicles. Element 4 has separated the MG and LG/SOL fascicles from the CP. The CP is isolated between elements 3 and 4.

The two x's on element #3, next to the CP, indicate the a and b contacts. Figs. 5 and 7 show FRT's from element 3 of this SPINE. Contacts a and b show linear dorsiflexion (Fig. 7). Contact a, however, has a medial rotation component while contact b has a lateral rotation component. This indicates that the two contacts have not only selectively activated the CP with respect to other fascicles, but also selectively activated sub-populations within the CP.

Of the six experiments, four show evidence of nerve and fascicle reshaping similar to Fig. 10. The other two could not be analyzed as the electrode was removed prior to fixation.

Preliminary examination of the sections shows no damage to the perineurium of any of the fascicles and the myelin around the axons does not appear to be degenerating. The density of the axon populations is uniform between the section proximal to the cuff through the section distal to the cuff. The histology results, however, are not rigorous enough to provide a sufficient assessment of neural damage. The fixation procedure was not designed to preserve the nerves for a detailed analysis of the tissues or evidence of long term damage to the axons. Moreover, the experiments were only run for 24 h which is insufficient to obtain good histologic evidence of damage. These results, however, indicate that slow penetration within the nerve is feasible.

#### IV. DISCUSSION

#### A. Functional Analysis

The data analysis method presented above is the first to quantify the electrode performance based on functional criteria of the intact preparation. Measurement of isometric joint torque eliminates the effects of muscle length-tension properties and joint dynamics. Although these measurements do not indicate muscle co-activation or joint stiffness, they allow the researcher to quantify the hypothesis that interfascicular stimulation generates functionally different recruitment than extraneural stimulation.

#### B. Surface Contacts Versus Interfascicular Contacts

Extraneural stimulation is limited by its inability to stimulate axon populations deep within the nerve without first stimulating surface axon populations [14], [16]. Grill *et al.* [35] have presented a pulsing paradigm that utilizes the nonlinear dynamics of the membrane to stimulate deep populations prior to surface populations. These schemes, however, are complicated and require further experimental verification.

Our results also show that different interfascicular locations generate different recruitment. Contacts separated by only 0.5



Fig. 10. Neural reshaping caused by a SPINE electrode. (a) The medial section of the nerve and electrode. The nerve is ellipsoidal and all the fascicles are nearly circular. (b) The distal section of the same nerve. The small *x*'s represent the location of contacts upon the elements and the numbers represent the element number. Elements 1 and 4 have penetrated deep within the nerve. Element 1 has separated the tibial (TIB) fascicle from the lateral gastrocnemius/soleus (LG/SOL) and medial gastrocnemius (MG) fascicles. Element 4 has separated the common peroneal (CP) from the LG/SOL and MG fascicles. The electrode has separated the nerve into three compartments. All of the fascicle are slightly distorted and not circular. (c) The location of the medial and distal section relative to the electrode.

mm depth of penetration were selective in 68% of the trials. Similarly, interfascicular contacts on opposite sides of the penetrating element were selective in 90% of the trials. It is beneficial, therefore, to place contacts throughout the nerve to obtain maximum functional benefit from neural stimulation.

Interfascicular stimulation shows a further qualitative advantage over the surface contacts. Typically, the FRT's of the interfascicular contacts are more linear than those of the surface contacts. The linearity of the FRT indicates the synergy of the recruited axon population and is beneficial for control in FES applications using peripheral nerve stimulation.

# C. Nerve Alteration and Penetration

The histology results from these experiments do not imply the chronic safety of the SPINE. Sections were taken only 24 hours post-implant, which is not sufficient to thoroughly examine encapsulation, giant cell activity, or other immunologic responses to the electrode. It is possible, however, to show 1) that the penetration of the element is nearly complete within 24 h and 2) the absence of any gross damage due to the electrode or the implant procedure. If the pressure created by the electrode had been excessive or had occluded the blood flow to the neural tissue, these sections would have shown edema and some evidence of myelin deterioration [36]. Also, the sections would have shown damage to the perineurium caused by the elements. None of these were present in any of the 18 histology sections from the six cats.

The histology demonstrates two penetration results. First, the pressure applied slowly and passively by the SPINE to the surface of the nerve causes reorganization and alteration of the nerve cross section. Fig. 10 shows very different organization between the medial and distal sections of the nerve. The electrode elements penetrate deep within the epineurium of the nerve to divide it into separate compartments.

Second, the SPINE also altered the shape of the fascicles, suggesting that sufficient time and appropriate pressures could cause invagination of the perineurium to further segregate a fascicle. It could be possible to divide the common peroneal, for example, into two or three sub-fascicles to achieve greater functional selectivity. If this can be shown with further experimentation, the SPINE concept could also be used for mono-fasciculated nerves.

Finally stimulation results suggest that the SPINE did not damage the motor units. If the SPINE had caused acute damage, one would have expected several of the axons to stop propagating action potentials. The number of motor units stimulated would then have been reduced and the output force would have been diminished. Observed maximal moments correspond to the published results of similar experiments [37], [32], [13]. We, therefore, conclude that most or all the motor units were functioning normally.

## V. CONCLUSION

Stimulation results from the SPINE experiments show interfascicular stimulation provides additional recruitment to enhance surface stimulation. In all comparisons—surface and interfascicular, different sides of penetrated elements, and different depths of penetration—greater than 68% of the trials showed that interfascicular stimulation produces additional functional output.

Histologic cross sections show that the slowly penetrating interfascicular nerve electrode rearranges the neural epineurium and penetrates deep within the nerve. This new design is able to place electrical contacts in locations previously inaccessible with extraneural stimulation. Histology also shows that the penetrating elements did not damage or disrupt the perineurium and there is no gross evidence of axon damage or loss throughout the nerve.

In summary, we have verified that interfascicular stimulation generates functionally different recruitment than extraneural stimulation. Interfascicular stimulation is a viable and attractive alternative providing an effective compromise between extraneural and intrafascicular stimulation methods.

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