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2.2.2: Electrical Stimulation II

FINITE ELEMENT ANALYSIS OF ELECTRICAL NERVE STIMULATION

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Abstract **- A nerve stimulation model and tool have been developed to analyze and optimize the design of nerve cuff electrodes. A finite element method was used to determine the electric potentials in the volume conductor. Nerve fiber excitation was determined using the net driving function algorithm.**

Extraneural and interfascicular cuff electrode configurations were modeled. Selectivity indexes were calculated on various cuff configurations to analyze the effectiveness of selectively activating a given fascicle. Our results show that interfascicular cuffs have higher selectivity than extraneural cuffs due to isolation created by the cuff itself.

I. INTRODUCTION

Selective activation of nerve fascicles is required to improve muscle recruitment during Function Electrical Stimulation. Several electrode cuffs have been developed to improve fascicle selectivity allowing electrodes to be placed on the surface of the nerve, between fascicles within the nerve, and within fascicles, respectively labeled extraneural, interfascicular, and intrafascicular electrodes. However, the effectiveness of these cuffs is difficult to analyze because of variations in experimental designs and the inability to modify parameters, such as conductivity and fascicle sizes. Our motivation is to develop a method to optimize the design of such cuffs prior to fabrication and implants.

Interfascicular stimulation has shown to be highly selective causing minimal damage, so we have concentrated our modeling on the SPINE cuff electrode recently developed by Tyler and Durand [1]. The SPINE electrode uses a penetrating element to place the electrodes closer to the fascicles while isolating them from neighboring fascicles. The complexity of such a model prevents an analytical solution from being developed, so an approximate solution using a finite element method was implemented. Previous models have used this method analyzing extraneural and interfascicular stimulation [2][3]. In this study, we developed such a model in order to analyze the ability of various designs to selectively activate a given fascicle.

II. METHODS

Two models were used in our analysis. The first model shown in figure 1, shows the interfascicular cuff with the penetrating element. The second model for the extraneural cuff is similar to figure 1, except the penetrating element was not included. The locations for the point source electrodes used in each model are shown. A 1 mA cathodic stimulation pulse with a 20μs width was used. Both models contain four fascicles with diameters of 0.6 mm, 0.4 mm, 0.3 mm, and 0.5 mm, (fascicles 1,2,3 and 4 respectively) surrounded by a highly resistive perineurium 30 μm thick. The cuff encircles the nerve with a 50μm layer of saline, a 50μm tight encapsulation layer and an epineurium. The cuff and nerve are contained in a saline solution. Tissue and material conductivities were taken from a previous model [3]. Axon diameters were randomly chosen from two modified normal distributions with peaks of 10 μm and 20 μm. Longitudinal node placements were chosen randomly from a uniform distribution.

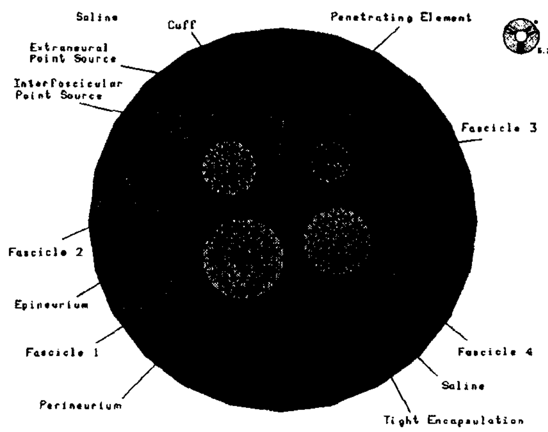

Figure 1 - Interfascicular Cuff showing mesh of elements.

A commercial package, ANSYS 5.1, was chosen to generate the element mesh shown in figure 1 and to calculate, using a wavefront solver, the voltages generated from the point source for each model. The same mesh was used for both models.

Once the extracellular voltages were obtained for an axon, fiber excitation was determined using a passive model approximation method developed by Warman et al. [4]. The finite element nodal solutions were fed into a program (PAxsys) developed in MATLAB 4.2, implementing the net driving function algorithm. Each node within a fascicle represented an axon location. Interpolation was used to determine the voltages at each axon node for varying nerve fiber diameters. The transmembrane potentials were calculated and compared to the critical voltage, -56.07 mV for a pulse width of 20μs to determined fiber excitation.

The selectivity index (SI) was calculated from the percentage of stimulated fibers within a fascicle given by:

$$SI_n = \frac{\text{\% of Fibers Stimulated in Fascicle}_n}{\sum_j \text{\% of Fibers Stimulated in Fascicle}_j}$$

III. Results

The generated mesh, shown in figure 1 consisted of 26,200 elements with 22,113 nodes, taking about 30 minutes to solve on a DEC Alphastation 250. PAxsys, took about 1 minute to load the data, calculate the results, and plot the results for 236 axons. Figure 2a shows the excited axon population for the extraneural model. Not the wide spatial distribution in each fascicle corresponding to the distribution of large and small fibers and easier excitation of larger fibers. The percentage of fibers stimulated in each fascicle as a function of current amplitude (recruitment curve) is shown in figure 2b. Note the large slope at the onset of excitation for each fascicle. Note also the plateaus seen in each plot, representing the dependency of fiber recruitment on axon diameter. This recruitment curve is similar to those obtained experimentally for muscle fibers shown by Tyler [1]. The selectivity indexes for the extraneural model are shown in figure 3a. Notice the correspondence between the percentage of fibers stimulated and the selectivity index. An SI of 1 represents the electrode being solely selective of that fascicle, so for low amplitudes the extraneural cuff is highly selective for fascicle 3 and the selectivity decreases with fascicle size and distance.

The SI for the interfascicular cuff model are shown in figure 3b. Note the high selectivity for fascicle 2 compared to fascicle 3 for the extraneural cuff. The penetrating element provides isolation for fascicle 2 increasing the effective distance to fascicle 3.

V. Conclusion

The models show that interfascicular stimulation with a highly resistive penetrating element is more selective for a given fascicle than extraneural stimulation, because of isolation that it provides from the neighboring fascicles. The selectivity is however highly dependent upon the geometry and placement of the electrode. The model and tool have proven to be effective in analyzing cuffs and can now be used to optimize the designs of such cuffs before fabrication and experimental testing.

Acknowledgments
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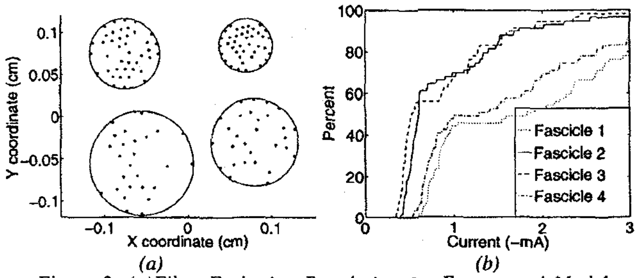

Figure 2: (a)Fiber Excitation Population for Extraneural Model showing the excited axons within each fascicle and, (b) the percentage of active fibers in each fascicle for the applied stimulus (recruitment curve).

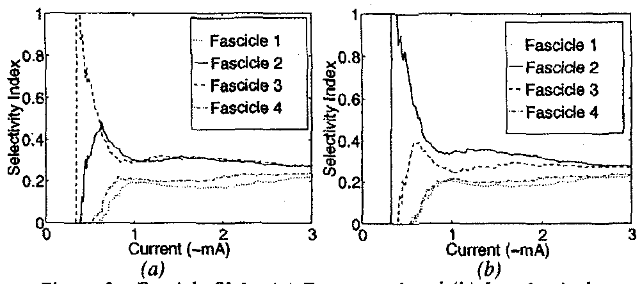

Figure 3: Fascicle SI for (a) Extraneural and (b) Interfascicular Models.

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