Standing Neuroprosthetics: Modeling Selective Stimulation with a FINE

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Abstract

The long-term goal of this research is to restore standing function through selective activation of target fascicles in the femoral nerve by a flat interface nerve electrode (FINE). The optimal number and location of contacts in a FINE had not been determined previously. A realistic three-dimensional finite element model based on a cross section of human femoral nerve and FINE is presented. Simulated voltages are applied as an extracellular field to the MRG double-cable axon model. Initial simulations indicate that optimal contacts may exist for each fascicular group. Further, nerve reshaping improves selectivity by 26%. Models indicate the FINE can be used for selective muscle activation in standing neuroprosthetics.

1. INTRODUCTION

Spinal cord injuries significantly reduce the independence and quality of life of the individual. Options to increase mobility include wheelchairs, standing frames, and personal assistants. Still, pressure ulcers are common within this population and, left untreated, can progress to tissue necrosis and systemic infections. Additionally, decreased bone strength and density has been correlated with muscle disuse [1]. Restoration of standing function to paralyzed individuals could significantly increase mobility and decrease the frequency of maladies associated with immobility.

Surface and percutaneous electrode systems have successfully allowed small and average sized patients to stand. To improve the performance of neuroprosthetics and increase the patient population that can benefit from them, a larger, extended and controllable moment at the knee needs to be generated. By recruiting the entire muscle, a selective flat interface nerve electrode (FINE) attached to the femoral nerve, which innervates muscles of the upper leg, could generate larger moments and extend the patient population that can benefit from this technology.

The objective of this study is to develop a FINE with a minimal number of contacts located at optimal locations to selectively activate the fascicles within the femoral nerve that control target muscles of the upper leg. The hypothesis of this study is that FINE applied to the femoral nerve with optimally-positioned contacts can activate 90% of the axons innervating each target muscle without activating more than 10% of the axons innervating nonagonist muscles using a monopolar, square, cathodic waveform. Knee extensors were considered nonagonists of hip flexors and vice-versa.

2. METHODS

A digitized image of the cross section of a human femoral nerve containing 47 demarcated fascicles was imported into AutoCad 2000 (Autodesk; San Rafael, CA) [2]. Borders of the epineurium and endoneurium were traced. Perineurial thickness was set at 3% of the diameter of the fascicle based on unpublished findings from a study at our facility. The AutoCad image was imported into Maxwell 3D v.10 (Ansoft; Pittsburg, PA), where the cross section was extruded 60 mm to create a three dimensional finite element model (FEM).

A FINE was modelled in Maxwell as a silicone cuff around the femoral nerve (Fig. 1a). The FINE was 10 mm in length, 11.8 mm in width, and had a 3.8 mm opening height (Fig. 1b). In a second model, the epineurium was reshaped by reducing the opening height of the FINE to 2.3 mm (Fig 1c). The wall thickness was 0.6 mm. Contacts had a stimulating surface 0.5 mm x 0.5 mm with 0.5 mm between them, resulting in 22 contacts total [3, 4]. Contact impedance was 1E-8 KΩ-cm. The resistivity of the perineurium and epineurium was 47.80 KΩ-cm and 1.211

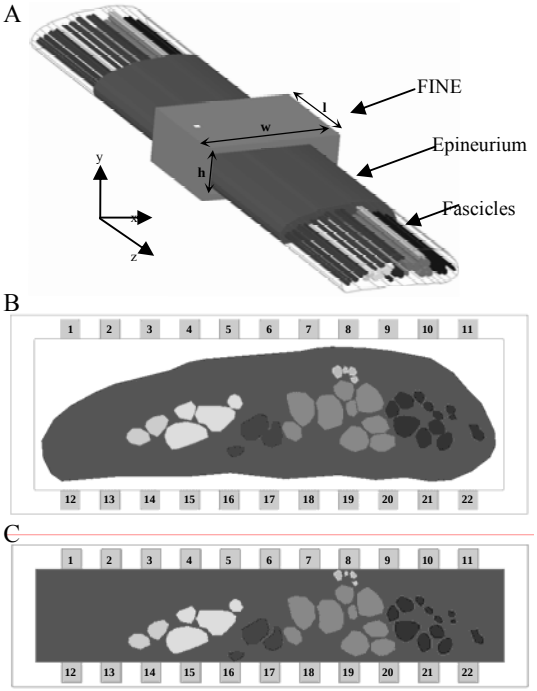

Fig. 1: A) Three-dimensional view of the nerve surrounded by a 22-contact flat interface nerve electrode (FINE). The epineurium has been made transparent on both ends to reveal the fascicles inside. Highlighted square on FINE indicates location of Contact 1. The opening height (h), width (w) and length (l) of the FINE are shown. B) Cross section of the excised human femoral nerve (Model 1). C) Reshaped cross section (Model 2). The seven fascicular groups (# of fascicles/group) (L to R): Sartorius (13), Rectus Femoris (2), Vastus Lateralis (4), Vastus. Intermedius (3), Vastus. Medialis (9), Pectineus (4), and Medial Cutaneous/Saphenous (12).

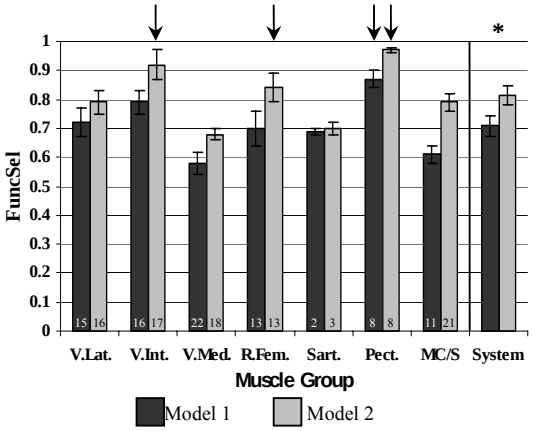

Fig. 2: Maximum functional selectivity achieved for each muscle group in the two models as well as the overall system selectivity. Number at the bottom of each bar indicates which contact achieved the maximum functional selectivity. Arrows indicate models that met the criteria set forth in the hypothesis (RB≥0.90, RC≤0.10). *: $p<0.05$

KΩ-cm, respectively. The endoneurium had a transverse resistivity of 1.211 KΩ-cm and a longitudinal resistivity of 0.172 KΩ-cm based on published values [5]. Fascicles were not compressed or rearranged. The nerve and surrounding FINE was encased in a saline volume that was large enough to prevent skewing of results due to boundary conditions at the edges of the saline (0 mV), but not so large as to introduce too many nodes for the finite element solver.

Simulations in Maxwell created voltage distributions at FEM nodes that were imported into MATLAB R14 (The Mathworks, Inc.; Natick, MA) and interpolated along axons with a three-dimensional cubic spline procedure. 100 axons were randomly and uniformly distributed throughout each fascicle. The diameter of each axon was randomly chosen from a known distribution [6]. The offset of the Node of Ranvier closest to the center of the stimulating electrode was randomly varied between 0 (the node was directly beneath the electrode) and half of the internode length

In NEURON (Hines, Moore, and Carnevale; http://www.neuron.yale.edu), interpolated voltages were applied to the MRG double cable axon model [7, 8]: a non-linear model that accurately represents the mammalian response of stimulated axons, including after-hyperpolarization and depolarizing after-potentials. NEURON models ran at discrete values over a range of pulse widths (0.05 to 10 ms) and amplitudes (0.5 to 2 mA) for each axon in the nerve. Results from these simulations were analyzed in MATLAB.

In order to quantify the models, *functional selectivity*, which was adapted from [5], was defined as the percentage of axons activated within a target fascicular group (RB) minus the percentage of axons activated in fascicles that did not innervate synergistic muscles (RC).

Selectivity values were weighted by fascicular cross-sectional area. A selectivity value of 1 indicated that 100% of axons in the target fascicular group were activated while 0% of axons outside of the fascicular group were activated. A selectivity value of -1 indicated that 0% of the axons within the target fascicular group were activated by a given contact while 100% of the axons of nonsynergistic fascicular groups were activated. For each pulse width and pulse amplitude combination, the greatest selectivity produced by any contact for a specific fascicular group was found. *System selectivity* was the average of the seven values.

3. RESULTS

Simulations demonstrated optimal contacts existed for each fascicular group. Figure 2

details which contacts produced the greatest selectivity for both models respectively (arrows at RB>0.90 and RC<0.10). The overall system selectivity for Model 1 was 0.71, while that for Model 2 was 0.81, which was significantly greater ($p<0.011$). The most selective contact per muscle differed between the two models for 5 of the 7 muscle/sensory groups.

4. DISCUSSION AND CONCLUSIONS

Selective stimulation on the fascicular and sub-fascicular level with a FINE has been demonstrated through computer simulations and in acute and chronic *in vivo* animal studies [3, 5, 9-12]. These studies found that fascicular selectivity could be achieved with a small number of small contacts positioned around the electrode. Also, as the number of contacts increased, the overall selectivity in the system increased toward an upper limit. However, the nerves used in those experiments contained a small number (usually five or less) of large fascicles whereas the current geometry contains a large number (47) of small fascicles.

The primary hypothesis of this study was that a FINE applied to the human femoral nerve with optimally-positioned contacts can activate 90% of the axons innervating a target muscle without activating more than 10% of the axons innervating nonagonist muscles, and without the use of field steering. Model 1 did not meet these criteria for any fascicular group except Pectineus. Model 2 satisfied these criteria for three fascicular groups. The effect of reshaping the nerve by decreasing the opening height of the FINE and bringing the contacts closer to the axons was an increase in the maximum selectivity obtained for each fascicular group and an increase in system selectivity by 26%.

These results support minimizing the distance between contacts and fascicular groups, but reducing the opening height may physically redistribute fascicles within the nerve. This may also occur when the nerve is manipulated during FINE implantation. The fascicles innervating a specific muscle are grouped together just proximal to primary nerve branching, but it is unknown if reshaping the nerve will redistribute fascicles [2]. If fascicular grouping is not maintained, a minimal-contact FINE may no longer be optimal. If a reduction in FINE opening height spreads the fascicles out, more contacts may be needed to achieve high selectivity. Thus, the effects of reshaping on fascicle distribution need to be investigated.

Other femoral nerve cross-sections will be used to form robust conclusions, which will shape the first generation of FINEs used for selective standing neuroprosthetics. Clinically functional FINEs may not require the ability to selectively stimulate each muscle. It may be acceptable to selectively stimulate all muscles responsible for knee extension or hip flexion.

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