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# Models of Selective Stimulation with a Flat Interface Nerve Electrode for Standing Neuroprosthetic Systems

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***Abstract*—The long-term goal of our research is to restore standing function via selective activation of target fascicles in the femoral nerve by a flat interface nerve electrode (FINE). The optimal number and location of contacts within 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 but an acceptable selectivity may require nerve reshaping.**

## I. Introduction

SPINAL cord injuries (SCIs) significantly reduce an individual's independence and quality of life. Wheelchairs and vehicular modifications allow these individuals to drive and increase mobility. However, such therapies do not address the common problem of pressure ulcers, which, left untreated, can progress to deep tissue and bone necrosis and systemic infections. Additionally, decreased bone strength and density has been correlated with muscle disuse [1-7]. Restoration of standing function to paralyzed individuals could significantly increase mobility and independence and significantly decrease bone loss and the occurrence of pressure ulcers.

Surface and epimysial electrode systems have been successful for some patients, but a reliable standing system is still needed. A primary challenge to developing a reliable system is the generation of a sufficient and repeatable moment greater than the estimated 40 Nm of knee extension required for the sit-to-stand transition when using upper-body strength for additional support [8]. A selective flat interface nerve electrode (FINE) attached to the femoral nerve, which innervates muscles of the upper leg, could generate moments sufficient in magnitude while interleaving the contraction of different muscles or muscle segments to allow people with challenging body types to stand for functionally relevant periods of time.

The objective of this study is to develop a FINE with the minimal number of contacts located at optimal locations to selectively interleave activation of fascicles within the femoral nerve that innervate target muscles of the upper leg: the Vastus Lateralis, Vastus Medialis, and Vastus Intermedius for knee extension, the Rectus Femoris for knee extension and hip flexion, and the Sartorius and Pectineus for hip flexion. The hypothesis of this study is that FINE applied to the femoral nerve with optimally-positioned contacts can selectively activate each muscle innervated by the femoral nerve, producing functionally relevant moments, using a monopolar, square, cathodic waveform.

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## II. Methods

A digitized image of the cross section from the same location of three human femoral nerves distal to the inguinal ligament and proximal to branching, each containing 22 to 47 fascicles, were imported to AutoCad 2000 (Autodesk; San Rafael, CA). Borders of the epineurium and endoneurium were traced. AutoCad images were imported to Maxwell 3D v.10 (Ansoft; Pittsburg, PA), and a perineurium equal to 3% of the diameter of the fascicle was added [9]. All tissue was extruded 60 mm, a length found to produce results that differed by less than 1% from a model with a length of 500 mm (considered semi-infinite) with a simulation time that was reduced by 89.5%.

A FINE was modeled in Maxwell as a silicone cuff around the femoral nerve (Fig. 1). The FINE was 10 mm in length, 11.8 mm in width, and had a variable opening height of 3.8, 2.3, or 1.4 mm, representing no epineurial reshaping, minimal epineurial reshaping without fascicular redistribution, and moderate epineurial reshaping with fascicular redistribution, respectively. No fascicles were compressed. The wall thickness of the FINE was 0.6 mm. Platinum contacts had a stimulating surface 0.5 x 0.5 mm with 0.5 mm between them, allowing for a total of 22 contacts [10, 11]. The length of the FINE was limited by the smallest reported distance between the inguinal ligament and the first branching point of the femoral nerve [12]. A 1 mA cathodic current was injected through each contact independently. The resistivity of the perineurium and epineurium was 47.80 KΩ-cm and 1.211 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 [13].

The nerve and FINE were encased in a 150 x 150 x 200 mm saline volume. This volume prevented skewing of results due to boundary conditions at the edges of the saline (0 mV), without becoming computationally unwieldy.

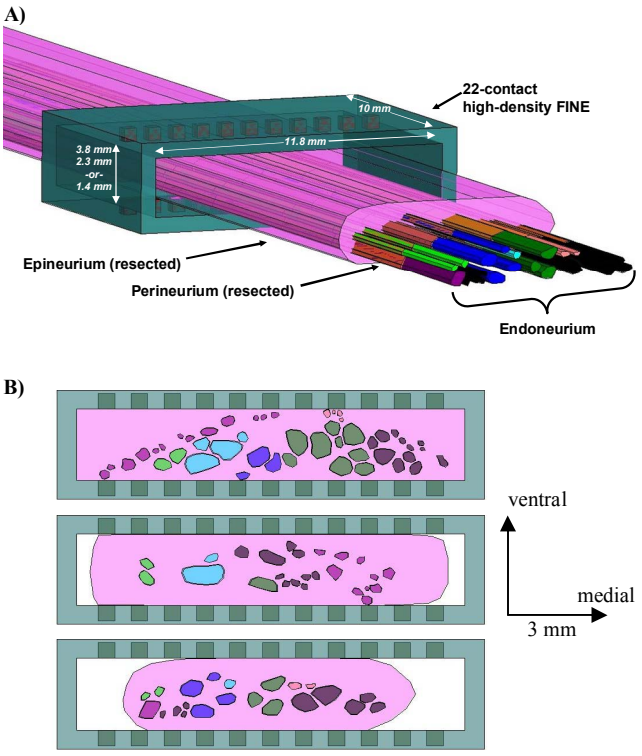


Fig. 1. A) 3D FEM of the nerve surrounded by a 22-contact flat interface nerve electrode (FINE). The epineurium and perineurium have been resected to reveal the endoneurium inside. The opening height, width and length of the FINE are shown. B) 2D FEM cross sections based on three excised human femoral nerves. FINE opening height was 2.3 mm.

Simulations in Maxwell determined node voltages 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 [14-16]. 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 (freeware by Hines, Moore, and Carnevale; http://www.neuron.yale.edu), interpolated voltages were applied to the MRG double cable axon model: a non-linear model that accurately represents the mammalian response of stimulated axons [17, 18]. The model included persistent and fast sodium, slow potassium, and leakage currents. Models ran over a range of pulse widths (0.05 to 10 ms) and amplitudes (0.5 to 2 mA).

Two selectivity measurements were defined to quantify the models in MATLAB. Adapted from [13], muscular selectivity (MuscSel) was defined as the percentage of axons activated within a target fascicular group (the "recruitment benefit" or "RB") minus the percentage of axons activated outside the target fascicular group (the "recruitment cost" or "RC"). The RB in functional selectivity (FuncSel) accounted for stimulation of synergistic muscles while the RC accounted only for activation of fascicles that did not produce synergistic functions. For example, the number of axons activated in the Vastus Intermedius and Vastus Medialis did not contribute to the recruitment cost when calculating functional selectivity of the Vastus Lateralis.

Selectivity values were weighted by fascicular cross-sectional area. A selectivity of 1 indicated that 100% of target axons were activated while 0% of non-target axons were activated. A selectivity of -1 indicated that 0% of target axons were activated while 100% of non-target axons were activated. For each combination of pulse width and pulse amplitude, the contact location producing the greatest selectivity for a specific fascicular group was found. One contact was selected per fascicular group (up to six contacts per cross section: one for each innervated muscle) because currently available implantable stimulators have a limited number of stimulation channels and minimization of time to clinical deployment is a priority. Paired T-tests ($\alpha$=0.05) were performed to determine if a decrease in opening height significantly affected a fascicular group's RB or selectivity.

For each muscle innervated by the femoral nerve, simulations were performed in SIMM (Musculographics, Inc.; Santa Rosa, CA) to determine the expected moments at the knees and hips during maximal isometric muscle contraction. RBs and RCs were applied to these individual moments and the cumulative system moments were investigated. It was assumed that the percentage of axons activated within a fascicular group equaled the percentage of maximum muscle moment generated for that muscle.

## III. Results

On average, Maxwell calculated voltage distributions in under 70 minutes per contact. MATLAB interpolated the voltages along 100 randomly positioned axons (per fascicle) induced by each contact in 2 hours. NEURON simulated all axons in approximately 10 days/cross section/opening height on a workstation using an AMD FX-53 processor with 4 GB of RAM. Simulation time was reduced via parallel processing at the Ohio Supercomputing Center.

Optimal contacts existed for each fascicular group but did not remain the same for all cross sections. Regarding the quadriceps muscle, fascicles innervating the Vasti were located centrally and fascicles innervating the Rectus Femoris were located laterally. Fascicles innervating the Pectineus were located in the ventral medial quadrant of the nerve. No clear generalization of Sartorius fascicle location was possible except that they were not located centrally.

Based on all cross sections, using the contact, pulse width, and pulse amplitude combination that maximized the MuscSel, an RB of 0.72±0.15, 0.87±0.12, and 0.79±0.12 and resulting MuscSel of 0.57±0.13, 0.68±0.12, and 0.67±0.11 was obtained for all fascicular groups with the 3.8, 2.3, and 1.4 mm FINE, respectively (Fig. 2A). RB for the Sartorius and the Vasti was significantly greater for the 2.3 mm cuff than for the 3.8 mm cuff ($p<0.01$) as well as for the Rectus Femoris and Pectineus ($p<0.05$). The decrease in RB for the Sartorius and Vasti when the opening height decreased from

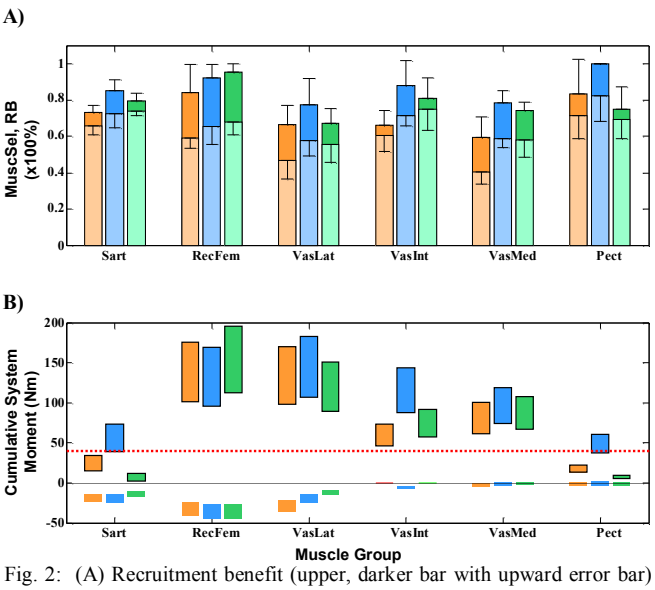


Fig. 2: (A) Recruitment benefit (upper, darker bar with upward error bar) and muscular selectivity (lower, lighter bar with downward error bar) obtained for target muscles with a FINE opening height of (L to R) 3.8, 2.3, and 1.4 mm. (B) The cumulative moment at the knee (with outline) and hip (without outline) produced by the muscle activations in the system resulting from the single best contact, pulse width, and pulse amplitude combination that maximized the muscular selectivity for the target muscle. Moments: >0: extension; <0: flexion. 40 Nm (dashed line): required for the sit-to-stand transition when using arms strength for additional support.

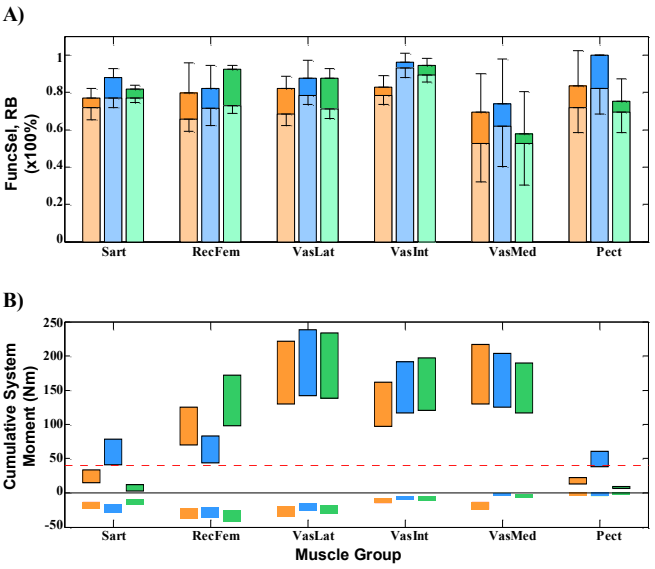


Fig. 2: (A) Recruitment benefit (upper, darker bar with upward error bar) and functional selectivity (lower, lighter bar with downward error bar) obtained for target muscles with a FINE opening height of (L to R) 3.8, 2.3, and 1.4 mm. (B) The cumulative moment at the knee (with outline) and hip (without outline) produced by the muscle activations in the system resulting from the single best contact, pulse width, and pulse amplitude combination that maximized the functional selectivity for the target muscle. Moments: >0: extension; <0: flexion. 40 Nm (dashed line): required for the sit-to-stand transition when using arms strength for additional support.

2.3 mm to 1.4 mm was not significant ($p>0.10$) while the decrease in RB for the Pectineus was ($p<0.01$). The MuscSel for the Sartorius and the Vasti was significantly greater for the 2.3 mm cuff than for the 3.8 mm cuff ($p<0.01$) as well as for the Rectus Femoris ($p<0.05$). The increase in MuscSel for the Pectineus from the 3.8 mm to the 2.3 mm FINE was not significant ($p>0.10$). The decrease in MuscSel for the Sartorius and Pectineus from the 2.3 mm to the 1.4 mm FINE was significant ($p<0.01$), but all other differences in MuscSel between these two systems were not ($p>0.10$).

Muscle recruitment percentages were applied to the minimum and maximum hip and knee joint moments predicted by the SIMM model (Fig. 2B, 2C). Cumulative muscle moments produced by contacts selective for each Vastus muscle exceeded 40 Nm for all opening heights.

Functional selectivity results were similar to Muscular Selectivity (Fig 3). When functional selectivity was maximized, an average RB of 0.79±0.14, 0.87±0.15, and 0.81±0.17 and a resulting FuncSel of 0.67±0.14, 0.76±0.15, and 0.71±0.15 was obtained for all fascicular groups with the 3.8 mm, 2.3 mm, and 1.4 mm FINE, respectively.

## IV. Discussion

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 [10, 13, 19-22]. These studies found that fascicular selectivity could be achieved with a small number of small contacts positioned around the nerve. 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 (>22) of small fascicles.

The hypothesis of this study was that FINE applied to the femoral nerve with optimally-positioned contacts can selectively activate each muscle innervated by the femoral nerve, producing functionally relevant moments, using a monopolar, square, cathodic waveform. Simulations support this hypothesis.

In general, as the opening height of the FINE decreased, the recruitment costs in the system decreased. Examining the cumulative joint moments confirmed this. For muscles that cross only one joint (all but the Rectus Femoris), the cumulative moment at the joint not affected by contraction of the muscle decreased as the opening height of the FINE decreased. In all cases, as the opening height of the FINE decreased from 3.8 mm to 2.3 mm, the recruitment benefit and the selectivity (MuscSel or FuncSel) increased. A further decrease in opening height to 1.4 mm produced varied results. Unique to the 1.4 mm FINE models was the redistribution of fascicles, such that fascicles from different groups intermingled. In some cases this intermingling forced the fascicular group to split into two or more subgroups, which would be more difficult to selectively stimulate with a single contact.

This generation of models did not allow multiple contacts to operate simultaneously. Preliminary simulations have shown that simultaneous use of two contacts increase selectivity by increasing recruitment benefit and decreasing recruitment cost. The effect of simultaneous stimulation

from multiple contacts on selectivity will be thoroughly explored in future models.

Limited conclusions can be drawn from results based on a three nerve cross-section at three opening heights. Ideally, many more femoral nerve cross-sections would be used to form robust conclusions. However, femoral nerve cross sections in which the fascicular constituents have been delimited are not available except for these three nerves and the process of obtaining these data is time intensive.

The final conclusions drawn from these models will shape the first generation of implantable FINEs used for selective neuroprosthetics on the femoral nerve. Finding that many very small contacts are required to selectively activate muscles innervated by the femoral nerve for functionally relevant periods will drive forward implantable stimulator technology, which is currently limited to very few contacts.

## V. Conclusion

Initial models indicate that selectivity can be achieved for each of the fascicular groups by using optimally positioned contacts but that optimal contact choices do not remain the same for all cross sections. Reducing the opening height significantly increased selectivity by decreasing costs for some muscles. Models indicate that the resulting moment at the knee should exceed 40 Nm, has been reported to be required for the sit-to-stand transition [8]. A clinically functional FINE may not require the ability to selectively stimulate each fascicular group. Instead, it may be acceptable to selectively stimulate the fascicular groups responsible for knee extension – the Vastus Medialis, Vastus Intermedius, and Vastus Lateralis – or to selectively stimulate the fascicular groups responsible for hip flexion – the Sartorius, Rectus Femoris, and, to a lesser extent, Pectineus. (The Medial Cutaneous and Saphenous fascicles are not desirable targets.) In this case, an optimal FINE may contain significantly fewer contacts.

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