Selective Control of Leg Muscle Activation Patterns and Ankle Forces Using a Multi-Chambered Stimulation Cuff Implanted on the Sciatic Nerve

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OVERVIEW

A 20-mm Neurocuff ™ with 8 sets of tripolar electrodes placed inside longitudinal chambers separated by insulating ridges [1] was implanted on the left sciatic nerve of 3 cats. Epimysial bipolar EMG electrodes were sutured onto 8 calf muscles. During the next 3-12 mo, force and EMG recruitment properties produced by Neurocuff stimulation were tested under anaesthesia using a 3D force/torque sensor. We found that:

1) Every major muscle supplied by the sciatic nerve can be activated through at least 1 of 8 stimulation channels.

2) Individual Neurocuff channels typically recruit functionally synergistic muscle groups.

3) Single channels produce substantial forces and force recruitment can be well controlled.

4) Forces produced by simultaneous activation of 2 channels sum linearly and predictably, with only modest overlap of axon pools activated by nearby channels.

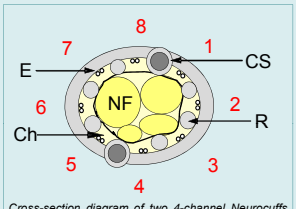
INTRODUCTION

A multi-channel nerve cuff placed around a main nerve trunk such as the sciatic nerve is a simple and efficient means for generating ankle torques in several directions [2]. In this study we investigated the extent to which individual muscles are recruited, patterns of recruitment of synergistic muscles, and summation properties of the forces generated when two or more electrodes were simultaneously stimulated.

METHODS

Experiments involved 3 specific-pathogen-free adult male cats (4-6 kg). Simon Fraser Univ. Animal Care Committee approved all protocols. ***Two 20 mm long 4-channel Neurocuffs***(™) *with interlocking piano-hinge closing system [3] were assembled to form* ***one 8-channel cuff*** *(11 mm inside perimeter) that was surgically installed around the left sciatic nerve, 10-20 mm proximal to the tibial/peroneal bifurcation.* ***Epimysial bipolar EMG electrodes*** *were sutured near nerve entry points of following* ***8 hind limb muscles supplied by the sciatic nerve:***

Dorsiflexor muscles		Plantarflexor muscles	
Anterior tibialis	(AT)	Flexor digitorum longus	(FDL)
Ext. digitorum longus	(EDL)	Soleus	(SOL)
Peroneus brevis	(PB)	Plantaris	(PLA)
Peroneus longus	(PL)	Medial gastrocnemius	(MG)



Cross-section diagram of two 4-channel Neurocuffs assembled on the sciatic nerve. ***CS****: closing system.* ***E****: electrode.* ***Ch****: chamber.* ***NF****: nerve fascicle.* ***R****: longitudinal ridge.* ***Red numbers*** *indicate 8 separate stimulation channels.*

For the selectivity experiments, a biphasic pulse generator and an isolated biphasic current stimulator (BAK) generated stimulation pulses 100 µs long with regulated current amplitude. All other experiments were conducted with a Neurostep(™) implantable stimulator with 3 constant-current programmable channels, each producing stimuli at 25 Hz [3, 4].

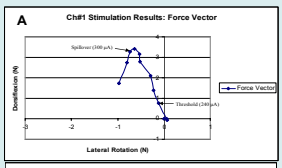
For the force/torque measurements the left hind paw was placed in an adjustable brass boot coupled to a Gamma 3D force/torque transducer (ATI Industrial Automation). Dorsiflexion, plantarflexion, pronation, supination, inversion and eversion forces and torques were collected at 66.7 Hz. The stimulus-evoked EMG compound action potentials were amplified and sampled at 2000 Hz. All signals were digitally stored and analyzed off-line using MATLAB (version 5).

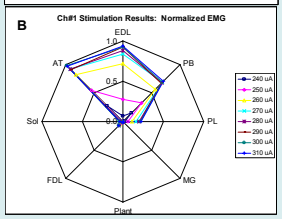
RESULTS

Example of **"Dorsiflexor Channel"** *(Subject M,* ***Channel #1****, day 64).*

A: *When Neurocuff Channel #1 was stimulated in incremental 10 µA steps between* ***threshold*** *and* ***spillover*** *(arrows), the* ***ankle force*** *increased quite linearly in the* ***dorsiflexion*** *and* ***medial rotation*** *directions.*

B: *Polar display shows* ***normalized peak EMG activity*** *generated in each of the 8 monitored muscles during stimulation. In Subject M, day 64, the* ***dorsiflexor muscles*** *were mainly recruited. Their EMG levels increased toward near-plateau values as the stimulation current approached spillover (300 µA). Each point is the mean of 8 trials at same stimulus intensity, delivered at 1 Hz.*

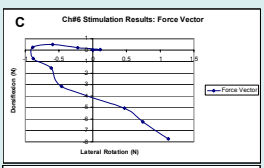


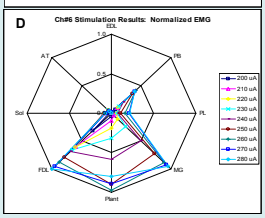


Example of **"Plantarflexor Channel"** *(Subject M,* ***Channel #6****, day 64).*

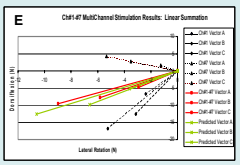
C: *Force first increased modestly in a dorsiflexion/ medial rotation direction,* ***reversed*** *for 220 µA (****plantarflexion threshold****), then grew fairly linearly in the plantarflexion direction with a smaller lateral rotation component.*

D: *Polar display of EMG amplitudes confirms that the* ***plantarflexor*** *muscles were predominantly recruited, but so was PB, especially at the lower currents (which may have accounted for the initial dorsiflexion force direction; see* ***A****). Force and EMG levels were substantial and did not saturate at the highest current tested (280 µA).*





Multi-channel force summation properties *(Subject M, day 148).*



E: *Forces produced by stimulation of two channels matched the directions of, but had somewhat lower magnitudes than, the predicted sums of "single channel" forces.* ***Black****: force vectors produced by separate activation of* ***Ch #1*** *&* ***#7*** *(3 current levels).* ***Green****:* ***predicted*** *combined forces, based on the algebraic summation of pairs of individual force vectors.* ***Red****:* ***actual forces*** *that resulted from the combined stimulation of* ***Ch #1 + #7****.*

DISCUSSION AND CONCLUSIONS

These results demonstrate that a multi-channel, multi-chambered Neurocuff™ placed around a main nerve trunk, such as the sciatic nerve, is a simple and efficient means to selectively recruit several functionally distinct muscle groups. In the cat hind limb, very low stimulation currents (under 0.3 mA x 100 µs) generated substantial forces. Force recruitment could be graded by varying the stimulation intensity over a considerable dynamic range. The anatomical segregation of nerve axons within fascicles in major nerves facilitates the simultaneous recruitment of synergist muscles. These features, together with the simplicity and safety of surgically implanting a nerve cuff on a large nerve, make the multi-channel nerve cuff approach preferable to other methods (such as implanting epimysial single-muscle stimulation electrodes) for a variety of clinical applications.

How many independent channels are required? This will depend on the anatomical properties of the stimulated nerve and the objectives of each application. In an initial human clinical trial, a single 4-channel Neurocuff™ placed on the common peroneal nerve was sufficiently selective to control the direction and magnitude of ankle dorsiflexion [3]. Future applications such as for the control of standing and transfers in paraplegia [5] may require Neurocuffs™ with 4, 8 or 12 channels placed on sciatic, femoral and obturator nerves, so as to independently control every major group of paralyzed leg muscles.

REFERENCES

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