

# 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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## Abstract

*A 20-mm Neurocuff<sup>TM</sup> with 8 sets of tripolar electrodes placed inside longitudinal chambers separated by insulating ridges (Hoffer et al., 1998) 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 months, force and EMG recruitment properties produced by Neurocuff stimulation were periodically tested under anaesthesia using a 3D force/torque sensor (Gamma ATI).*

*We found that: 1) every major muscle supplied by the sciatic nerve can be activated through at least one of eight 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*

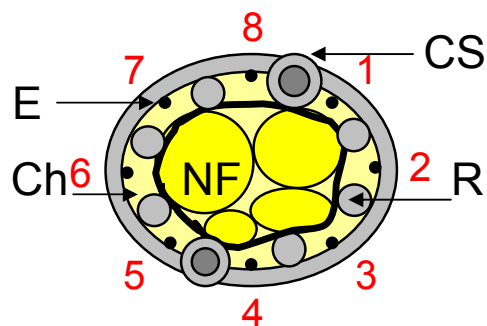
*4) Forces produced by simultaneous activation of two channels sum linearly and predictably, indicating that the axonal pools activated by nearby channels can overlap only modestly.*

## 1 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 [1]. 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.

## 2 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<sup>TM</sup> with interlocking piano-hinge closing system [2] were assembled to form one 8-channel cuff (11 mm inside perimeter; Fig. 1) that was surgically installed around the left sciatic nerve, 10-20 mm proximal to the tibial/peroneal bifurcation.



**Figure 1.** Cross-sectional diagram of two 4-channel Neurocuffs assembled around the sciatic nerve. **CS:** closing system. **E:** electrode. **Ch:** chamber. **NF:** nerve fascicle. **R:** longitudinal ridge. **Red numbers** indicate 8 separate stimulation channels.

Epimysial bipolar electromyographic (EMG) electrodes were sutured near nerve entry points of 8 hind limb muscles supplied by the sciatic nerve, listed in Table 1.

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)

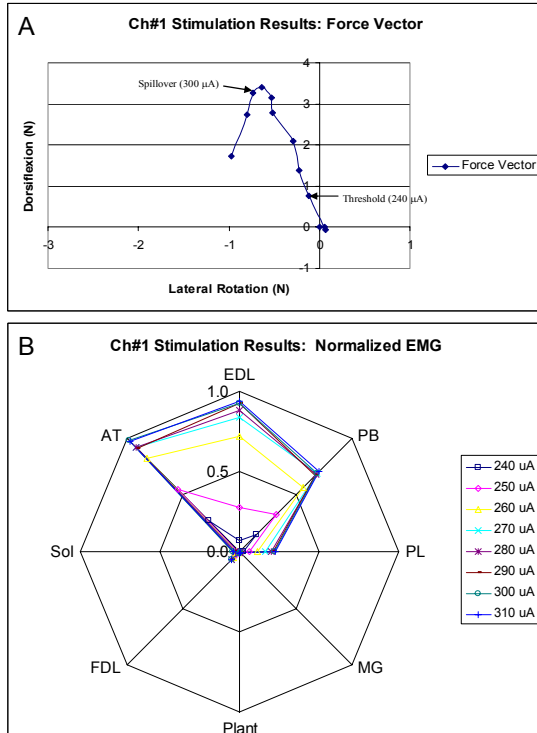
**Table 1.** Muscles implanted with EMG electrodes.

For the selectivity experiments, a biphasic pulse generator and an isolated biphasic current stimulator (BAK) generated stimulation pulses 100  $\mu$ s long with regulated current amplitude. All other experiments were conducted with a Neurostep<sup>TM</sup> implantable stimulator with three constant-current programmable channels [2, 3].

For the force/torque measurements, the left 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).

### 3 Results

Figure 2A shows an example of the changes in magnitude and direction of ankle force when the stimulation applied to a single nerve cuff channel was increased in 10  $\mu\text{A}$  steps. Figure 2B displays the normalized peak EMG activity generated in each of the 8 monitored muscles at the same stimulus levels. Each plotted point is the mean of 8 trials at same stimulus intensity, delivered at 1 Hz. Similar data was collected for the 8 Neurocuff channels.

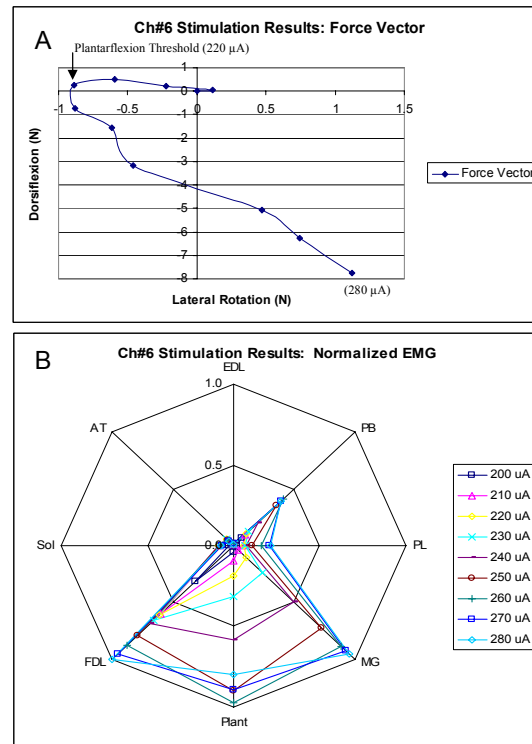


**Figure 2.** Results from stimulating Channel #1 in Subject M on day 64 (a “Dorsiflexor Channel”). **A:** Force increased quite linearly in the dorsiflexion and medial rotation directions for stimulation levels between threshold and spillover (arrows). **B:** Polar display shows that the dorsiflexor muscles were predominantly recruited. Their EMG levels continued to increase, and tended to plateau as the stimulation current approached spillover (300  $\mu\text{A}$ ).

Figure 2B shows that at threshold current for Channel #1 (240  $\mu\text{A}$  x 100  $\mu\text{s}$ ) the AT, PB and EDL muscles were activated, while no evoked EMG activity was detected in other monitored muscles. With larger stimuli, evoked EMG levels increased in AT and EDL. PB EMG increased for the first 4 stimulus levels, then stopped increasing for the next 4 increments. PL was also steadily recruited, up to 23% of its maximum evoked EMG, throughout the Ch #1 stimulation range up to spillover (defined as the stimulation current for which the direction of ankle force reversed; i.e., 300  $\mu\text{A}$  in Fig. 2A).

Some recruitment of FDL EMG could be seen (Fig. 2B) as the stimulation level spilled over to the ‘plantarflexor region’ of the sciatic nerve.

The AT, PB and EDL muscles contributed to the dorsiflexion action before spillover occurred in Fig. 2A. The AT has a medial rotation component, also seen in Fig 2A. At spillover, the dorsiflexion force decreased and the medial rotation component increased. This suggests that another muscle or muscles that were not monitored, possibly tibialis posterior or flexor hallucis longus, began to influence the total force output in both the plantarflexor and medial rotation directions.



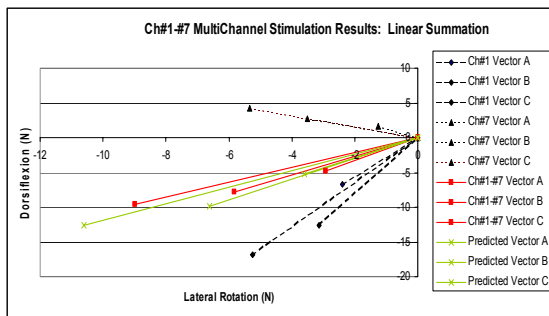
**Figure 3.** Results from stimulating Channel #6 in Subject M on day 64 (a “Plantarflexor Channel”). **A:** Force first increased modestly in a dorsiflexion/medial rotation direction, reversed for 220  $\mu\text{A}$  (plantarflexion threshold), then grew fairly linearly in the plantarflexion direction with a smaller lateral rotation component (note the different axis scales). **B:** Polar display confirms that the plantarflexor muscles were predominantly recruited but so was PB, especially at the lower currents and may have accounted for the initial dorsiflexion direction (see A). Force and EMG levels were substantial and had not saturated at the highest current tested (280  $\mu\text{A}$ ).

In each cat, similar synergistic activation of AT, EDL and often PB and PL muscles was obtained by stimulating one, two or three Neurocuff channels that acted as “dorsiflexor channels”. This finding could be anticipated, as the nerves from the ankle dorsiflexor muscles

run together in the common peroneal fascicle within the sciatic nerve. Similarly, each of the 8 sets of tripolar electrodes disposed inside the Neurocuff recruited unique groups of muscles that typically were functionally related and together provided a somatotopic representation around the sciatic nerve. An example of a “plantarflexor channel” is shown in Figure 3.

EMG activation patterns showed that every major muscle supplied by the sciatic nerve could be activated through at least one of the eight channels, and its recruitment was progressively graded as stimulation increased.

Given that individual stimulation of each set of tripolar electrodes gave distinct force patterns that involved different combinations of muscles, we tested the summation properties of resultant forces when 2 or more electrodes were jointly activated. Figure 4 shows an example.



**Figure 4.** Forces produced by separate vs. combined channels (Subject M, day 148). **Black:** force vectors generated by separate activation of Ch #1 and Ch #7 at 3 current levels. **Green:** combined forces predicted from algebraic summation of pairs of black vectors. **Red:** measured forces with combined activation.

In the example of Fig. 4, each of two channels was first stimulated alone at 25 Hz at 3 current intensities (vectors A,B,C). Next, both channels were simultaneously stimulated, each at 25 Hz, 13.3 ms out of phase. The green traces show the predicted resultant forces based on vector summation of the individual forces produced by each channel. The red traces show the actual forces that were produced by the combined stimulation. We found very good agreement in the direction of predicted and actual resultant forces, but the magnitudes of actual combined forces were 10-20% lower than predicted. This disparity indicates a partial overlap of the pools of motor axons stimulated by the two electrode sets and suggests that ~10-20% of the activated motor units were recruited by both electrodes.

#### 4 Discussion and Conclusions

These results demonstrate that a multi-channel, multi-chambered Neurocuff<sup>TM</sup> 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  $\mu$ s) 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<sup>TM</sup> placed on the common peroneal nerve was sufficiently selective to control the direction and magnitude of ankle dorsiflexion [2]. Future applications such as for control of standing and transfers in paraplegia [4] may require Neurocuffs<sup>TM</sup> 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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