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Neural Interfacing with the Peripheral Nervous System

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Abstract— **Although electrical stimulation has proven to be capable of restoring neuronal function in the damaged or injured nervous system, there are several limitations to this technique. The availability of electrodes capable of selective fascicle recruitment and physiological fiber diameter recruitment (from small to large) is crucial for the development of successful prostheses. Nerve cuff electrodes have several advantages over other methods since they can provide activation of multiple muscles groups from a single site. Current cuff electrodes are reshaping the nerve into round shapes and making it difficult to recruit selectively fibers in the center of the nerve. Yet two major problems have not yet found satisfactory solutions: 1) Fascicle selectivity and fiber diameter selectivity.**

We present here a new design that reshapes the nerve into a flat configuration, the flat interface nerve electrode (FINE). This design can improve the ability of the electrode to selectively activate the various fascicles of the nerve. Experiments to measure this selectivity were carried out on the hypoglossal nerve and its three main branches. The ability to recruit various fascicles was estimated using a selectivity index (SI). The overall performance of the FINE, as defined by the selectivity index (SI), showed a high degree of selectivity at both the fascicular and muscular levels: 0.91 ± 0.05 (n = 5) and 0.85 ± 0.03 (n = 4), respectively.

This flat interface design minimizes the maximum distance between each contact and the fibers. Computer simulation have shown that it is possible to reverse the recruitment order by using electrode arrays placed along the nerve. This model prediction was tested in the Lateral Gastrocnemius/Soleus branch of the sciatic nerve in cats since these muscles are innervated by fibers with different diameters. A stimulus electrode was placed around LG nerve. Tendons of LG and soleus muscles were separated and attached to two independent force transducers. The recruitment curves generated by tripolar and array electrodes were compared. Tripolar stimulation recruited LG before soleus muscles as expected, whereas the electrode array fully activated soleus while activating only 50% of LG muscles.

These results show that the electrode array is capable of reversing the recruitment order by manipulating the extracellular voltage along the nerve.

Keywords—**Neural prostheses, recruitment order, selective nerve stimulation.**

I. INTRODUCTION

Electrical extracellular stimulation of peripheral nerve has been developed for restoring lost motor functions in paralyzed patients. Several types of electrodes have been designed and are currently in use. Surface electrode, epimysial electrodes and cuff electrodes are the most common designs. A cuff electrode is placed around the nerve and is mechanically stable. It is not sensitive to elongation or shortening of the target muscle. However, current designs are round and tend to reshape the nerve, normally oblong into a disk shape. The round shape provides the minimum circonference/cross sectional area. Therefore, it provides the least amount of space for placing electrodes. Moreover, it is not possible to activate axons located in the middle without first activating the axons located in the periphery. In particular, the reshaping of the nerve into a round shape would push some fascicles in the middle of the nerve and make fascicular selectivity difficult to achieve. What is needed is an electrode capable of placing individual contacts closer to the axons for improved fascicle selectivity. What is also needed is a method to reverse the recruitment order.

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One of the major problems in peripheral nerve stimulation is that electrical stimulation activates large diameter fibers before small ones as the current amplitude is increased [1]. This reversed recruitment makes muscle control difficult since the large diameter fibers activate large motor units and promotes rapid onset of muscle fatigue [2]. Anodic block [3], single cathode [4], subthreshold-depolarization prepulse [5] have been proposed to solve this problem. However, these methods require a long stimulus pulsewidth (>500μs), which could lead to electrode corrosion [6].

We report here a novel stimulation techniques to allow selective stimulation of fascicles and for reversing the recruitment order of peripheral nerve stimulation. The design of the electrode requires that electrical contacts be placed in close proximity of all fibers within the nerve and requires reshaping the nerve into a flat configuration [7].

II. FASCICLE SELECTIVITY

Fascicle selectivity was tested with acute experiments in beagles dogs. The electroneurogram (ENG) and electromyogram (EMG) signals from the target fascicles and muscles, respectively, were used to compute a selectivity index (SI) in order to quantify the ability of an electrode to selectively stimulate a fascicle.

IIa. METHODOLOGY

Five adult beagles (9-12 kg) were anesthetized with an initial I.V. injection of Pentothal (1ml/kg) and subsequent ventilation of 1-3% halothane mixed with 100% Oxygen. The XIIth nerve and extrinsic tongue muscles are exposed and a FINE electrode with 12 tripole stimulation sites is placed on the nerve proximal to the branching point. Recording electrodes are placed in the three main nerve branches and four muscles (Genioglossus (GG), Styloglossus (SG), Hyoglossus (HG) and Geniohyoid (GH) (see Fig 1). Each tripole of the FINE was stimulated, and the resulting ENG (i.e., compound action potential (CAP)) and EMG signals were recorded. The voltages were normalized to peak values and the selectivity was computed from (1), where FASCi or FUNCi, are calculated from ENG and EMG signals respectively.

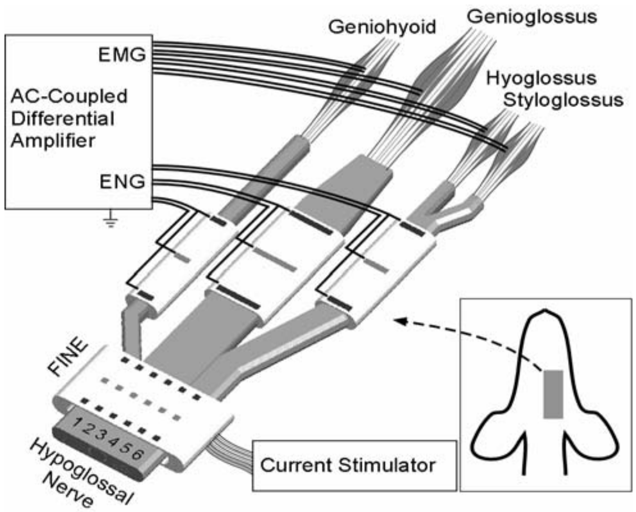


Fig. 1. The site of implantation in the submandibular region of the supine beagle is given in the inset. [Geniohyoid (GH); Genioglossus (GG); Hyoglossus (HG); Styloglossus (SG)]

Stimulation was considered selective under the following conditions: a) target $V_b \geq 0.8$ and b) the maximum V_b of each non-target is 0.2. Hence, a FASCi or FUNCi ≥ 0.67 would specify selectivity.

$$\underset{\text{(ENG or EMG)}}{\text{FASCi or FUNCi}} = \max\left[\frac{Vb\ \text{(target)}}{Vb\ \text{(target + non-target)}}\right] \qquad (1)$$

The overall selectivity index SI ($0 \leq \text{SI} \leq 1$) of the FINE was defined as the average selectivity (FASCi or FUNCi) for all respective targets.

IIb. RESULTS

Stimulation of branches 1 and 2, activates single muscles: GH and GG, respectively but branch 3 stimulation actives both HG and SG (Fig 2). The average V_b of these two functionally similar (i.e., tongue retractor) muscles was used to compute the FUNCi. Typical recruitment curves for the tripole stimulation are plotted as a function of current (fig 3). In this case, the data show that tripole 6 is selective for branch 3 (HG/SG), from threshold to 0.2 mA. The selectivity results are shown in table 1 and indicate a high degree of fascicular and functional selectivity. The overall index SI confirms a high degree of selectivity at both the fascicular and muscular levels: 0.91 ± 0.05 and 0.85 ± 0.03, respectively.

TABLE 1.
Mean selectivity for each target nerve/muscle: mean ± SEM.

	Branch1 (GH)	Branch2 (GG)	Branch3 (HG/SG)
FASCi (n=5)	0.95±0.05	0.85±0.13	0.93±0.07
FUNCi (n=4)	0.85±0.02	0.76±0.11	0.93±0.04

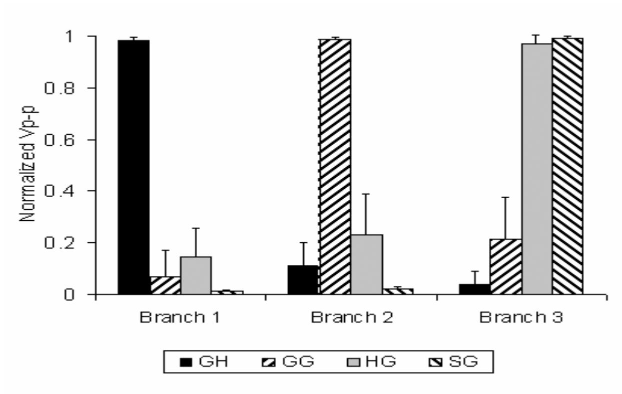


Fig. 2. Fascicle mapping of the XII nerve (n = 4)

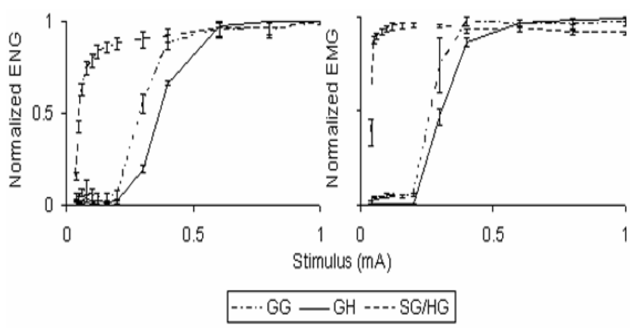


Fig.3. Recruitment curves via stimulation of tripole 6 (refer to Fig.1)

III. DIAMETER SELECTIVITY

Previous computer simulations [8] have shown that it is possible to selectively recruit small fibers without activating large fibers by using an array of electrodes placed along the axons. The array can change the voltage profile along an axon and increase the activating function of small fibers relative the large diameter fibers. The array works only if the electrodes can be placed close to the axons and therefore the FINE design is required for the implementation of the diameter selectivity. This model predictions were tested in in-vivo acute experiments.

IIIa METHODS

The effect of array stimulation on neural excitation was tested on the lateral gastrocnemius (LG) branch of the sciatic nerve of cats. This branch innervates both the LG (fast twitch fibers) and soleus slow twitch) muscles. Axonal distribution in the sciatic nerve is bimodal with peaks at 7 and 11μm [9]. The electrode array was fabricated using medical-grade silicone (Nusil:MED-4210) with rectangular opening [7] of 0.4x4mm, allowing the maximum axon-electrode distance to be maintained within 0.2mm, Fig 4. The electrode array had 9 contacts made of stainless steel wire (Dia = 100um) on both top and bottom sides with 0.55mm (±0.05mm) electrode separation.

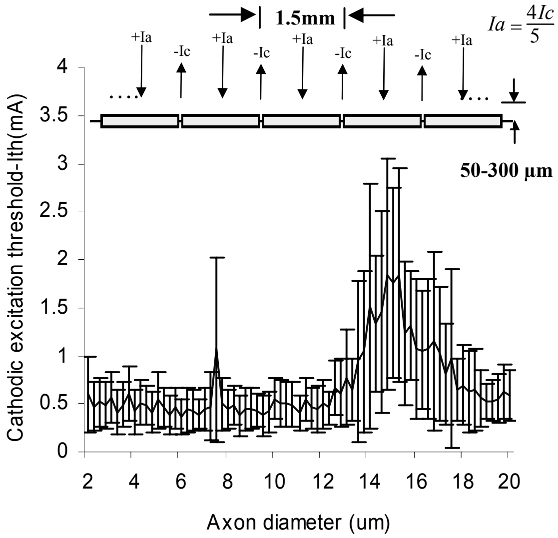


Figure 4: Excitation threshold (I_{th}) for an electrode array stimulation. I_{th} of the array was calculated with 1.5mm intercathodic distance and randomly-selected axon-electrode distance between 50-300µm (N=100). I_{th} of axons within 13-17µ diameter is higher than others.

The animals were anesthetized with IM of ketamine and maintained on IV of α-chrolarose as needed (5ml). Tendons for LG and soleus muscles were separated and attached to two individual force transducers. The femur was fixed in a rigid frame. An electrode was placed around the LG branch.

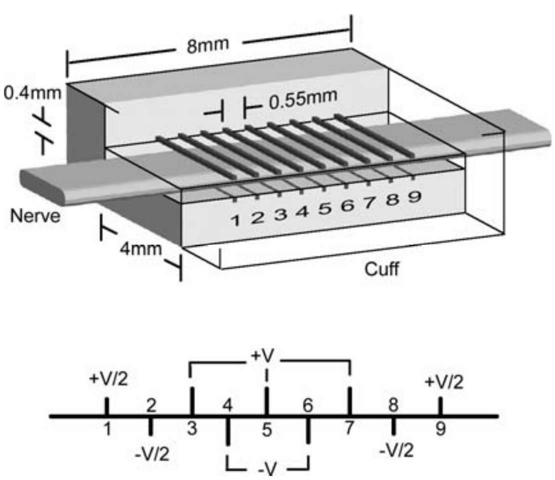


Figure 5: An electrode array stimulation. a) Electrode array consisting of 9-pair contacts with the opening of 0.4x4mm and 8mm long. b) Stimulus configuration with the electrode array to produce the pre-determined voltage profile; an alternation of anodes and cathodes with 1.1mm intercathodic distance.

IIIb. RESULTS

The profiles of twitch force of LG and soleus from one of the animals were normalized and plotted in Fig. 6. The twitch response from the LG muscle is clearly narrower than that of soleus as expected since the LG and soleus are fast and slow twitch muscles respectively.

Stimulation was first tested with a standard tripolar electrode. The recruitment curves from one experiment were normalized and plotted in Fig.7a. Stimulus amplitudes activating 30% and 60% of soleus recruit 80% and 95% of LG respectively. The recruitment curves of LG and soleus generated by the tripolar stimulation show that the LG is activated at lower stimulus amplitude than the soleus.

The recruitment curves of LG and soleus with the electrode array stimulation from the same experiment were normalized and plotted in Fig 7b. The recruitment order of these two muscles is reversed. The amplitudes activating 30% and 60% of soleus recruit only 20% and 30% of LG respectively. Moreover, at stimulus level activating 90% of soleus, only 50% of LG was recruited.

IV. DISCUSSION

Fascicle selectivity is a measure of the average non-target activity, for a given level of target activation ($V_b \geq 0.8$). For example, a fascicle selectivity for branch 1 of .95 (FASCi = 0.95, see Table1) indicates that the average non-target activity (i.e fascicle 2 and 3) will be 4.2% of its total activity when stimulating at least 80% of fascicle 1. These results indicate a high degree of selectivity. Overall, this study demonstrates the feasibility of selectively stimulating the UAW muscles with the FINE. Similar results have been obtained on the sciatic nerve both in acute and chronic experiments [10].

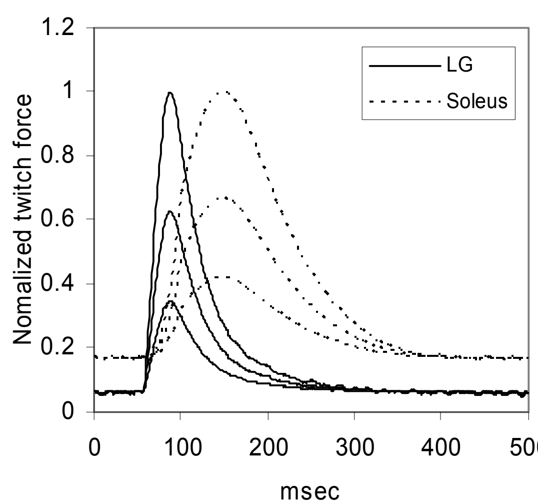
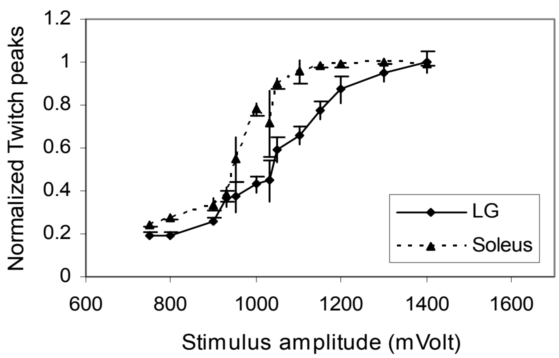


Figure 6: Profiles of twitch force for LG and Soleus. LG has fast twitch muscles (narrow profile), whereas Soleus has slow twitch muscle (wide profile).

The reshaping allows the electrodes to place close to the fibers. This is a crucial factor in reversing the recruitment curves of the LG and Soleus muscles with the array. The effect of the array is attributed to the ability of the array to recruit small fibers before large ones since the mean fiber diameter distribution for the soleus is smaller that the LG muscle. The result is consistent with the preliminary results of computer simulations [9] in that selective activation of small axons can be produced by an electrode array with intercathodic space equal or close to the internodal space of large axons and this effect is independent of stimulus pulsewidth. The effect is independent of the pulse-width used but requires additional charge. However, it is dependant on the relative close proximity of the electrode from the nerve fibers.



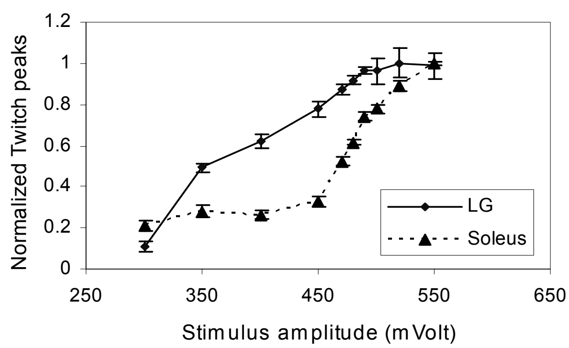


Figure 7: Recruitment curves of LG and soleus. a) Tripolar stimulation: LG was recruited prior to soleus as the stimulus amplitude increased. b) Electrode array stimulation. At stimulus amplitude about 1,100mV, soleus was fully activated while activating only 50% LG in both animals, showing the recruitment order was reversed. (Stimulus pulsewidth 50µs)

V. CONCLUSION

The results of the study show that by reshaping the nerve into a flat shape it is possible to align the fascicles to allow fascicle selectivity. Moreover, by reshaping the nerve, it is also possible to place electrode arrays close to the fibers. When the distance between the electrode is equal to the internodal distance of the large fibers, by alternating anodes and cathodes, it is also possible to reverse the recruitment order of nerve fibers.

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