Communications

Selective Stimulation of Peripheral Nerve Fibers using Dual Intrafascicular Electrodes

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Abstract—**We have studied activation of nerve fibers by pairs of Pt–Ir wire electrodes implanted within single fascicles of the nerve innervating the gastrocnemius muscle in cats. The purpose of this study was to determine if these intrafascicular electrodes can activate nerve fibers in different fascicles independently of each other and if they can also be used to activate separate subsets of axonal populations within a single fascicle. The average overlap of activated nerve fiber populations was 5.5% between fascicles and 27% within a fascicle, indicating that such selective activation is possible with these electrodes.**

I. Introduction

Functional electrical stimulation is a developing technology intended for use in applications such as providing movement to paralyzed limbs, restoring functional bladder control in paraplegics, or supplying sensory feedback from prosthetic limbs. A key component of any functional electrical stimulation system is the ability to selectively activate populations of axonal fibers, on the basis of size or location (topography).

Some degree of size selectivity has been achieved using novel stimulus waveforms with nerve cuff electrodes [1], [2], and topographical selectivity has been demonstrated in whole nerves using extraneural stimulation [3]–[7].

Single electrodes implanted within a nerve fascicle can produce axonal recruitment with almost neutral size specificity [8]–[10]. Since the electrodes are inside the perineurium, the current and charge requirements for stimulation are much lower than with externally placed electrodes [11]–[13].

Intrafascicular stimulation using a silicon electrode array has shown that the number of motor nerve fibers activated increases as stimulus current increases, and that different electrode sites could be used to activate different fibers [13]. A recent modeling study predicts that topographic selectivity with this type of electrode array can be further enhanced with the use of tripolar stimulation [14].

In the present study we evaluate whether nerve fibers in fascicles in close proximity to one another can be independently activated using Pt–Ir wire intrafascicular electrodes. We further evaluated whether graded recruitment of independent sets of nerve fibers can be achieved by pairs of electrodes implanted within a single fascicle.

II. Methods

Experiments were conducted on eleven adult cats maintained under sodium pentobarbital anesthesia. The tibia was mechanically fixed, and pairs of intrafascicular stimulating electrodes were implanted into each of two fascicles innervating the gastrocnemius muscle using techniques described elsewhere [12], [15]. A load cell was connected to the calcaneus along the line of action of the gastrocnemius muscle, and the muscle was preloaded to a level where small changes in preload did not cause significant changes in the active force produced during twitch contraction.

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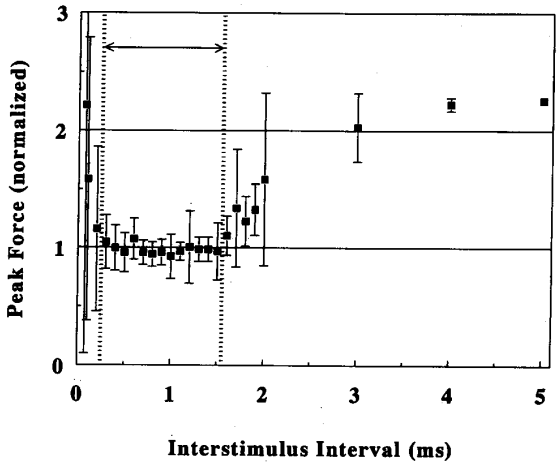

Fig. 1. Effect of stimulus separation (interstimulus interval) on twitch forces evoked in the gastrocnemius muscle by pairs of stimuli applied to a single electrode implanted within a fascicle of the tibial nerve. Stimulus pulse width and current amplitude were fixed: only the interval between stimuli was changed. The contraction force was minimal when the second pulse occurred during the period when axons activated by the first pulse were refractory (region indicated by the arrow between the dotted lines). Outside the refractory region, the force was greater due to current summation (for short intervals) or production of pairs of action potentials in single motor nerve fibers (long intervals). Shown are the mean ±s.d. of normalized twitch contraction forces.

The stimulus waveform consisted of a rectangular depolarizing pulse followed 500μs later by a rectangular charge balancing pulse [16], [17]. Stimuli were delivered independently to each of the two intrafascicular electrodes with respect to an extrafascicular indifferent electrode.

A pulse width and current amplitude that elicited a half maximal twitch contraction was determined for each electrode at the beginning of the experiment. The fatigue/potentiation state of the preparation was then determined periodically throughout the experiment by using the same stimulus and measuring the resulting twitch contraction force. A 25 s interval between tests was found to be adequate to minimize the effects of potentiation and fatigue so that the response to this stimulus varied by no more than 10% during the course of the experiment.

III. Results

For pairs of stimuli delivered to electrodes in different fascicles, the twitch force was independent of the stimulus order or interstimulus interval. This indicates that the stimulus currents were confined within the fascicle they were injected into. For pairs of stimuli delivered through a single electrode, the twitch force depended on the relative timing of the two stimuli, indicating an interaction between the stimuli (Fig. 1). To evaluate electrode selectivity, we used interstimulus intervals which fell within the refractory region (indicated by the

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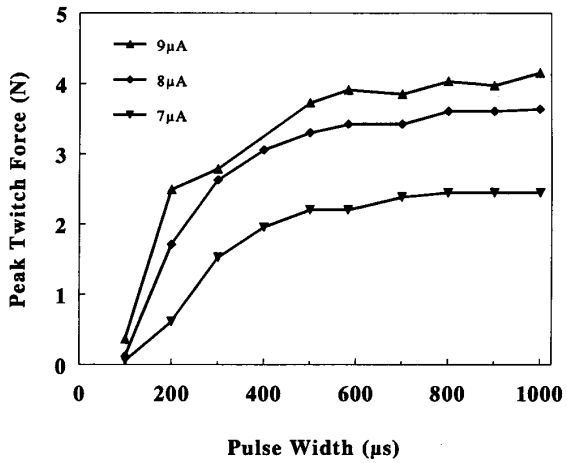

Fig. 2. Twitch contraction force versus stimulus pulse width for different stimulus current amplitudes in a single preparation. Each curve was generated using pulse width modulation of constant current stimuli. Unlike current amplitude modulated recruitment curves, which would all plateau at the same, maximal contraction level, the plateaus of the pulse width modulated recruitment curves increase with increasing current, indicating an increasing area of axonal activation within the fascicle as stimulus strength increases. The maximum contraction force with current amplitude modulated stimuli in this preparation was 5.27 N.

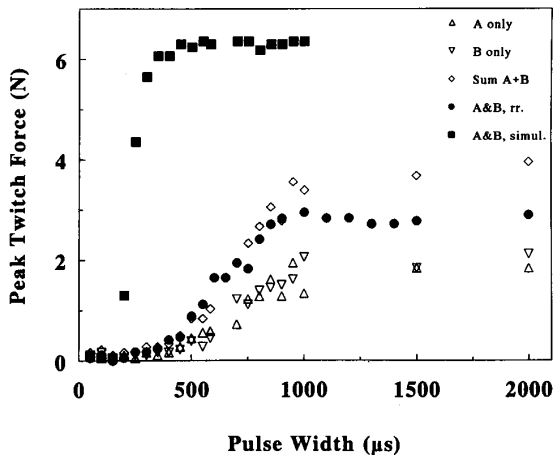

Fig. 3. Recruitment curves for pulse width modulated, constant current stimuli delivered to two electrodes implanted in a single fascicle. The current amplitudes for each electrode were selected to provide a twitch force plateau somewhat less than half the force elicited by supramaximal stimulation. Open triangle symbols show recruitment curves produced with single electrode stimulation. The open diamond symbols show their arithmetic sum, the expected force for independent electrodes. Solid symbols show recruitment with paired stimulation in which the two stimuli were delivered either simultaneously (simul.) or with an interstimulus interval in the refractory region (rr.).

dotted lines and arrows in Fig. 1), where axons excited by the first stimulus were still refractory at the time the second stimulus was delivered.

Maximal axonal recruitment was determined by using stimuli with a fixed 100 μs pulse width and increasing the current amplitude until the contraction force no longer increased. The average maximum twitch force for single fascicle stimulation was 6.8 ± 1.2 N, and the average maximum twitch force when stimulating separate fascicles with paired stimuli was 12.9 ± 2.9 N. The average current amplitude to elicit a maximal twitch force was 22.5 μA, corresponding to an average charge of 2.3 nC and charge density of 2.9 μC/cm^{-2} per phase. These levels are considered to be well within safe limits [18].

Using stimulus currents below this level restricted the activation of axons to subsets of axons within the fascicle as evidenced by the lowering of pulse width modulated recruitment curve plateaus (Fig. 2). This behavior was repeatable and did not depend on stimulus order, ruling out the possibility that it was an artifact due to fatigue. The average current level which limited the plateau force to half the maximum twitch force was $7.6 \pm 4.8\mu$A.

Overlap of stimulated populations of axons was determined for electrodes implanted in separate fascicles and for pairs of electrodes implanted in a single fascicle. For electrodes implanted in separate fascicles, current levels were selected that gave a maximal twitch force at long stimulus durations. For pairs of electrodes implanted in a single fascicle, currents that gave no more than half maximal twitch forces were used.

Typical recruitment curves for stimulation with two electrodes in a single fascicle are given in Fig. 3. In this example, dual channel stimulation with an interstimulus interval in the refractory region approximated the sum of the two single-channel recruitment curves for pulse widths below 750 μs. For longer pulse widths, the paired stimuli produced less force than the sum of the two channels individually. This deficit indicates that overlapping populations of axons were recruited by the two electrodes [16].

Data such as those in Fig. 3 were evaluated to calculate the percent overlap in single fascicle stimulation using the following equation:

$$\%_{\text{overlap}} = \left(\frac{F_a + F_b - F_{ab}}{F_{ab}} \right) \times 100$$

where

F_a = Force from stimulating with electrode a,

F_b = Force from stimulating with electrode b,

F_{ab} = Force from stimulating with both electrodes using an interstimulus interval in the refractory period of the axons.

The calculated overlap for electrodes in separate fascicles ranged from 0.8 to 15.6% with a mean $\pm$ standard error of $5.5 \pm 2.2\%$. The one large value in this series was an artifact due to movement of the tibia during testing. Overlaps for electrodes in the same fascicle ranged from -11.2 to 66.5%, and averaged $26.6 \pm 8.4\%$. The one negative value in this series is within the error limit expected if there were no overlap but some potentiation during the test run.

When the stimuli were delivered simultaneously to two electrodes in a single fascicle, the recruitment curve was steeper and the level of force production was higher than both that predicted by summing the individual electrode curves and that produced by stimulation with an interval in the refractory zone (Fig. 3). On average, simultaneous stimulation gave a 63% larger twitch contraction force than refractory region stimulation. Note that this is not a measure of overlap in the activated populations: rather, it reflects the presence of axons not activated by either electrode alone but activated by summation of current from two different electrodes. This effect was not seen with stimuli delivered to separate fascicles.

IV. Discussion

Our results are consistent with theoretical expectations based upon the biophysical properties of peripheral nerve axons. Twitch contrac-

tions produced by paired stimuli delivered to electrodes implanted in separate fascicles were independent of the interstimulus interval over the range tested, as expected if independent populations of axons were being activated by the electrodes.

Paired stimuli delivered to a single fascicle with interstimulus intervals outside of the refractory region showed greater forces than stimulus pairs within the refractory region. Since the refractory region is comprised of both absolute and relative refractory periods, its duration is a function of stimulus strength. The length of the refractory zone measured in this experiment, 1.5 to 2.0 ms, is consistent with relative refractory periods reported by others for small stimulus amplitudes [13], [19], [20].

Topographical selectivity of axonal recruitment is a function of both electrode spacing and current strength [13]. The decrease in pulse width modulated recruitment curve plateau force with decreasing stimulus current indicates that axonal activation is restricted to a subset of the fibers within the fascicle. This is expected for point source stimuli delivered within the fascicle: high field curvatures activate axonal fibers in the vicinity of the electrode but fail to activate more distant fibers where the curvature is less and the current density is below the rheobase limit for peripheral nerve fibers [9], [14], [21]–[23]. Thus, force recruitment by current amplitude modulation is not truly equivalent to that seen with pulse width modulation when low current levels are used [12].

The observed average single fascicular stimulation overlap of 27% obtained in these experiments should not be taken as a fixed value. Rather the overlap depends on the current amplitudes used for the stimuli. Lower currents give less overlap, but at the expense of recruiting a smaller fraction of the axons in the fascicle. Given the current levels used here, our results are consistent with those found in rats using a silicon intraneural electrode array [13].

These results demonstrate not only that separate fascicles can be independently activated by intrafascicular electrodes but also that the activation of subpopulations within a single fascicle is also possible using intrafascicular electrodes. Although the selective axonal recruitment was assessed by evaluating the twitch force produced by activation of motor neurons, the results can be applied to stimulation of sensory fibers as well. For example, intrafascicular electrodes implanted into nerve stumps of amputees could be used to provide localized sensory feedback from a prosthetic limb by stimulating nerve fibers that had formerly innervated tactile and proprioceptive receptors.

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