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2.2.2: Electrical Stimulation II

Electrical Stimulation of the Ventral Lumbo-Sacral Spinal Cord Results in Mixed Recruitment Order of Quadriceps and Tibialis Anterior Motor Units

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***Abstract*-Pulse width modulated, twitch recruitment curves for quadriceps and tibialis anterior were obtained by stimulating their respective motor activation pools in the ventral lumbo-sacral portion of the spinal cord. The duration of the twitch responses were analyzed as a function of stimulus strength to determine the order of motor unit recruitment. It was found that activating the quadriceps or tibialis anterior by stimulating the spinal cord resulted in a predominantly *mixed* recruitment order of its motor units. These results suggest that spinal cord stimulation could have application in future neuromuscular stimulation systems where normal recruitment order of muscle fibers is desired for producing fine control of muscle activity and enhancing fatigue resistance.**

I. INTRODUCTION

In the absence of regeneration following spinal cord injury, electrical stimulation of motor units has been used to artificially restore function to paralyzed limbs. One challenge associated with current stimulation methods is the reversal of the natural order of recruitment such that larger, fatigue prone motor units are more readily activated than smaller, fatigue resistant motor units. Due to the relatively large forces produced by the rapidly fatiguing large muscle fibers, reversed recruitment provides only coarse control of muscle force [1].

The ventral lumbo-sacral spinal cord has been shown to be a favorable location for functional neuromuscular stimulation: the spinal cord is distant from contracting muscles, thus the implanted electrodes are not subjected to continuous movement and high stresses; selective activation of muscles can be obtained because motor neurons to a given muscle are functionally segregated in the ventral portion of the cord; and stimulating the motor pool with multiple electrodes may allow for finer and more stable muscle contractions [2]. In this report, we demonstrate that more normal recruitment orders are achieved with spinal cord stimulation.

II. METHODS

Pulse width modulated twitch recruitment curves were obtained for the quadriceps and tibialis anterior muscles by stimulating their respective motor pools in the ventral lumbo-sacral spinal cord in cats, and the temporal characteristics of the generated twitches were analyzed.

Acute experiments were performed on 8 adult animals anesthetized with sodium pentobarbital. Clamps and pins were used to stabilize the spinal cord and the cats' left leg. Either the Achilles or the tibialis anterior tendon was detached at its point of insertion and attached to force transducers for isometric force measurements. A combination of EMG electrodes and force transducers were used to monitor activity in the remaining muscles of the leg. A laminectomy was performed to expose the lumbo-sacral spinal cord and a tungsten needle penetrating electrode was used to stimulate motor neurons in the motor pool of the muscle under investigation. The stimulus consisted of a single biphasic pulse with a 500 μs interphase interval. Stimuli were delivered 60 seconds apart to minimize muscle fatigue. The pulse amplitude was chosen to be 10% less than the maximum current level above which spread of activity to a different muscle was detected.

Each twitch was normalized to its peak amplitude and all the normalized twitches in a recruitment curve were overlayed to visualize their temporal characteristics. Twitch width, measured at the 40% level, was used as an indicator of recruitment order [3, 4], and was plotted as a function of stimulus strength.

III. RESULTS

Three relationships between twitch width and stimulus strength were observed: 1) twitch width *decreased* significantly as stimulus strength increased ($p < 0.05$), 2) twitch width *increased* significantly as stimulus strength increased ($p < 0.05$) and 3) no statistically significant relationship between twitch width and stimulus strength was observed. A typical record of decreasing twitch width with increasing stimulus strength is given in Figure 1. Fig. 1A shows all the normalized twitches collected for the recruitment curve and Fig. 1B demonstrates the twitch width - stimulus strength relationship for the same twitches. Table I provides a summary of the frequency of occurrence of the three twitch width - stimulus strength relationships in quadriceps and tibialis anterior.

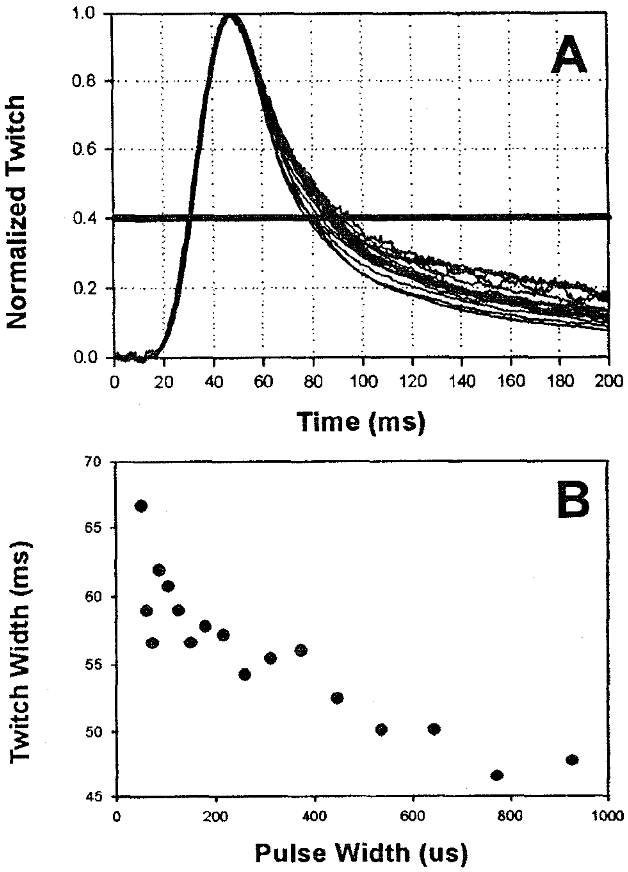

Fig. 1. Twitch responses from a single quadriceps recruitment curve. (A) Twitch waveforms normalized to their peak amplitudes and overlayed. (B) Twitch width at the 40% level, as indicated by the darkened line in (A), plotted as a function of stimulus pulse width.

TABLE 1. Change In Twitch Width With Increasing Stimulus Strength. Shown are the relative frequencies with which twitch width showed a statistically significant decrease or increase with increasing stimulus strength, or there was no significant effect of stimulus strength on twitch width.

TWITCH WIDTH	QUADRICEPS	TIBIALIS ANTERIOR
Decreased	35%	47%
Increased	26%	18%
No effect	39%	35%

IV. Discussion

With conventional electrical stimulation methods, twitch durations increase as stimulus strength is increased, indicating a fast to slow motor unit recruitment. Twitch force profiles obtained by activating quadriceps or tibialis anterior through stimulation of their spinal cord motor pools had a mixed relationship between twitch width and stimulus strength. This indicates that a mixture of small and large neurons were activated with every stimulus.

The key difference between spinal cord stimulation and conventional peripheral nerve electrical stimulation methods is that focal stimuli are utilized in spinal cord stimulation. This means that the current field curvature is very steep close to the electrode tip, thus allowing for activation of *both large and small fibers* near the electrode before more distant large fibers are recruited. In addition, the difference in motor neuron cell sizes in the spinal cord tends to be less dramatic than the difference in the size of their axons [5], providing for less disparity in their recruitment order under electrical stimulation conditions.

V. Conclusion

We have shown that spinal cord stimulation for activation of hindlimb muscles in cats leads to a more natural recruitment pattern of motor neurons compared to conventional peripheral nerve stimulation methods. This finding could be of great benefit for investigators in the field of functional neuromuscular stimulation.

VI. References

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