Muscle Recruitment Through Electrical Stimulation of the Lumbo-Sacral Spinal Cord

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***Abstract*—The goal of this study was to determine the feasibility of producing graded muscle contraction in individual muscles or muscle groups by electrically stimulating motor neurons in the lumbo-sacral spinal cord. Recruitment curves were obtained for quadriceps, tibialis anterior and triceps surae/plantaris by stimulating their activation pools in the ventral horn of the feline spinal cord. Mean twitch times-to-peak for quadriceps, tibialis anterior and triceps surae/plantaris were 33.0, 41.0, and 36.0 ms, respectively. Twitch duration as a function of stimulus strength demonstrated a mixed motor unit recruitment order, distinctively different from the inverse recruitment order exhibited by conventional methods of electrical stimulation of peripheral nerve. The recruitment curve slopes (expressed as a percentage of maximum force per nanocurrent of delivered charge) were shallow: 7.9 for quadriceps, 2.6 for tibialis anterior and 8.5 for triceps surae/plantaris. These results show that graded control of force in individual muscles or muscle groups can be obtained through spinal cord stimulation, and suggest that spinal cord stimulation could be used for functional neuromuscular stimulation applications.**

***Index Terms*—Functional neuromuscular stimulation (FNS), motor pools, muscle recruitment, spinal cord stimulation.**

I. Introduction

PARALYSIS due to an acute spinal cord injury interrupts the communication link between the brain and peripheral nerves, but in general leaves the motor neurons in the spinal cord below the level of the lesion largely intact [1]–[3]. Functional neuromuscular stimulation (FNS) utilizes artificial stimulation of motor nerves in individuals with paraplegia and quadriplegia as a means of restoring function to their paralyzed muscles and organs [4]–[7]. Current FNS systems employ cuff or motor point electrodes to electrically activate paralyzed muscles. Though some of these systems have been successful (e.g., diaphragm pacing), several limitations have adversely affected their overall long-term performance. Technical limitations include frequent lead breakage due to the need for implanting the stimulating electrodes close to the contracting target tissue, thereby subjecting the wires and electrodes to high stresses and strains [8]. Physiological limitations include lack of selectivity in muscle activation [9], [10], dependence of recruitment on placement of the electrode relative to the motor point [10], and reversed recruitment order of motor neurons which in turn results in reduced fatigue resistance under conditions of maintained and submaximal muscle contraction [11]–[13].

Some of the approaches utilized for combating the physiological limitations include electrode designs and implantation sites that promote selective activation of muscles [14]–[16] and novel stimulus waveforms that allow for recruiting motor nerve fibers in a more normal physiological order [17], [18]. In addition, varying degrees of fatigue resistance have been achieved by delivering asynchronous stimulation through multiple electrodes, each at frequencies less than that required for contractile fusion [19]–[22].

We have previously suggested direct stimulation of motor neurons in the ventral lumbo-sacral spinal cord as an alternative FNS technique [23]–[25]. The spinal cord is distant from contracting muscles, thereby minimizing complications due to movement of target tissue. This has been confirmed in a chronic study in which electrodes were implanted in intact, freely moving animals for 6 months [26]. The spinal cord lumbar region is condensed in the spinal column [27], allowing implantation of all the electrodes needed to control the leg muscles in a single localized region. In the companion paper we demonstrate, using microstimulation mapping techniques, that the lumbo-sacral portion of the cat spinal cord contains "activation pools," or regions that when electrically stimulated, specific muscles or muscle groups are activated in isolation [28]. In a related study, we demonstrated that stimulating the spinal cord through multiple electrodes in an interleaved manner significantly reduces muscle fatigue [25]. In this paper, we report on the recruitment of force in individual hindlimb muscles or muscle groups evoked by electrically stimulating activation pools in the ventral horn of the lumbo-sacral spinal cord in cats.

II. Methods

Details of the experimental setup are provided elsewhere [28]. A brief description of the details pertinent to the data presented here is given below.

A. Animal Preparation

Acute experiments were performed on 12 adult cats anesthetized with sodium pentobarbital administered intraperitoneally (40 mg/kg) and maintained with a 1:10 solution of pentobarbital in saline administered as needed through a catheter inserted in the cephalic vein. The animals used in this study were a subset of the ones used for the fine spinal cord mapping study described in the companion paper [28]. Each cat was placed on a heated plate to maintain its body temperature near 37.5 °C and the left hind leg and back were shaved. The

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cat was then positioned in a Kopf spinal unit consisting of two hip pins and a vertebral clamp that firmly held the spinous process of the third lumbar vertebra. Bone pins were placed in the lateral epicondyle of the femur, proximal medial surface of the tibia and medial malleolus of the tibia. Depending on the muscle to be studied, the patellar ligament, tibialis anterior tendon, or Achilles/Plantaris tendon was dissected from its point of insertion and attached to a force transducer (model SM-25 for patellar ligament and Achilles/Plantaris tendon and model MB-5 for tibialis anterior tendon, Interface, Scottsdale, AZ) allowing measurement of isometric muscle forces. A combination of force transducers and EMG electrodes was used to monitor activity in the remaining muscle groups of the cat's hindlimb [28]. A dorsal laminectomy was performed to expose spinal cord segments L5–S1, the dura mater was opened with iridectomy scissors and the dorsal surface of the spinal cord was covered with saline to prevent its dehydration.

B. Stimulation Protocol and Data Acquisition

Both stimulation of the spinal cord and recording of muscle force and EMG activity were performed under the control of an IBM compatible 80486 computer. Twitch contractions were used to minimize the effects of muscle fatigue. All stimuli were charge balanced, biphasic pulses with a constant interphase interval of 500 μs. The pulses were delivered, cathodic phase first, from a voltage controlled constant current source through a punctate penetrating tungsten needle electrode, 100 μm in diameter and 4 cm long (AM Systems, Everett, WA), sharpened and insulated except for a 50-μm exposure at the tip (impedance 25 to 50 kΩ). An 18-gauge hypodermic needle, placed in the right longissimus dorsi muscle toward the rostral end of the exposed spinal cord, served as the return electrode. Force and EMG responses were digitized at 4 kHz for 200 ms.

The stimulating electrode was mounted in a Narishige micromanipulator which controlled its three-dimensional positioning in the lumbo-sacral spinal cord. The electrode was positioned at locations within the ventral horn where electrical stimulation elicited contraction in a single muscle (e.g., tibialis anterior) or muscle group (e.g., triceps surae/plantaris) of the hindlimb. Since these sites were within the motor pools for the corresponding muscles and were far enough away from motor pools of neighboring muscles such that activation of the individual muscles in isolation was obtained, we refer to the electrode as being within a muscle's "activation" pool [28]. At each site, recruitment curves were generated by delivering balanced biphasic pulses of varying duration in pseudorandom (i.e., random without repetition) order. The pulse durations were incremental steps of 20% between 50 and 940 μs. The peak force of the elicited muscle twitch was determined for each stimulus. A 60-s interstimulus interval was used to reduce muscle fatigue and eliminate possible potentiation effects.

The pulse amplitude used for generating the recruitment curves was 10% less than either the maximum current that could be used before activity was detected in another muscle, or 100 μA, whichever was lower [28]. Prior to initiating the recruitment curve protocol, a submaximal standard stimulus was delivered through the stimulating electrode and the force (standard response) was recorded. Muscle fatigue was periodically monitored during the recruitment curve protocol by delivering the standard stimulus and comparing the force to the standard response. If the generated force was not within 10% of the standard response, the muscle was considered to be fatigued and was given enough time to recover before resuming the recruitment curve protocol. In addition to monitoring the muscle fatigue level, the periodic delivery of the standard stimulus served as an indicator of response repeatability.

At the end of the experiments, electrolytic lesions were placed in the spinal cord to serve as location markers [28]. Depending on the muscle under investigation, the femoral nerve, or the sciatic nerve in the popliteal fossa, was exposed and increasing levels of suprathreshold stimuli were delivered to the nerve through hook electrodes until the maximum twitch force generated by the quadriceps, tibialis anterior or triceps surae/plantaris muscle was reached. Since the target muscle's tendon was already detached from its point of insertion and attached to a force transducer, no efforts were made to denervate the various muscle groups innervated by the sciatic nerve prior to obtaining maximum twitch forces of the tibialis anterior or triceps surae/plantaris muscles. The cat was then perfused through the heart with a buffered, 3.7% formaldehyde fixative using our standard laboratory procedures [29]–[31], and the spinal cord was removed. The cord was subsequently sectioned and the locations of the stimulated sites were verified to be within the boundaries of each of the investigated muscles' motor activation pool [28].

C. Data Analysis

Recruitment curves were constructed by plotting the peak twitch forces as a function of stimulus strength. To allow for comparison of recruitment curve slopes presented in this paper with those from other investigators, the recruitment curves were normalized to their maximum (plateau) force and the stimulus strength was expressed in terms of charge. The slope was calculated by performing a linear regression on the first dynamic portion of the recruitment curve (between the point when force was first detected and the point where the curve first began to plateau). The "point when force was first detected" was the first point on the force trace that was larger than the mean +3 SD of the background (or baseline) level acquired 200 ms immediately prior to the delivery of the stimulus [28]. The "point where the force first began to plateau" was the point at which the force trace traversed 90% of the amplitude of the first plateau in a given curve.

Time-to-peak or contraction time, defined as the time required for the muscle force to reach its peak from the time it crossed the background force level (generally around 18–20 ms after delivering the stimulus), was measured for each of the twitches forming the recruitment curves [28]. To analyze motor unit recruitment order as a function of stimulus strength, each twitch was normalized to its peak and the twitch duration at the 40% normalized force level was measured. This level was chosen to minimize the amount of noise interference in the measurements. Twitch durations within each recruitment curve were then plotted as a function of stimulus strength and a linear

regression analysis was performed. The slope and statistical significance of the relationship between twitch duration and stimulus strength were determined for each recruitment curve.

III. Results

A. Twitch Characteristics

The distribution of twitch times-to-peak is shown in Fig. 1. Quadriceps and triceps surae/plantaris had similar, unimodal distributions of twitch time-to-peak, while tibialis anterior had, on average, longer times-to-peak and a bimodal distribution. Time-to-peak did not vary significantly with stimulus strength at any of the sites tested.

When measuring the normalized twitch duration as a function of stimulus strength from a single stimulation site, any one of three relationships emerged: 1) twitch duration significantly ($p < 0.05$) *decreased* with increasing stimulus strength, 2) twitch duration significantly ($p < 0.05$) *increased* with increasing stimulus strength, and 3) there was no significant effect of stimulus strength on twitch duration. Fig. 2 gives typical examples from the quadriceps muscle group demonstrating these three relationships. Each row of figures corresponds to stimulation of a single site in the quadriceps activation pool. In the absence of a rationale for using a more complex relationship, a linear fit was chosen for describing and comparing the three twitch duration–stimulus strength relationships. Fig. 2(A) shows all the twitches obtained by stimulating one site in the quadriceps motor activation pool at various stimulus strengths. Each twitch was normalized to its peak and its duration was measured at the 40% level. The twitch durations are plotted as a function of stimulus strength in Fig. 2(B) as is the linear regression curve for this relationship. In this case, twitch duration significantly decreased with increasing stimulus strength and, as expected, peak twitch force increased with decreasing twitch duration [(Fig. 2(C))]. Fig. 2(D) and (G) show the twitches obtained by stimulating two different sites in the quadriceps motor activation pool. Fig. 2(E) shows that the twitches in Fig. 2(D) significantly increased in duration with increasing stimulus strength, while Fig. 2(H) demonstrates that Fig. 2(G) twitch durations had no significant dependence on stimulus strength. Fig. 2(F) shows that twitches in Fig. 2(D) were primarily produced by fast motor units whose peak force increased as a function of stimulus strength and Fig. 2(I) demonstrates that a mixture of fast and slow motor units were activated by stimulating this site with no particular dependence on stimulus strength in correspondence to what is observed in Fig. 2(H).

Table I summarizes the frequency of occurrence of the three twitch duration–stimulus strength relationships in quadriceps, tibialis anterior and triceps surae/plantaris: twitch durations for at least two thirds of the sites significantly decreased or were not significantly affected by stimulus strength, implying a prevalence of near normal or mixed motor unit recruitment order. All the stimulated sites in the quadriceps, tibialis anterior and triceps surae/planaris activation pools exhibiting a negative twitch duration–stimulus strength relationship showed a negative peak twitch force–twitch duration relationship where the peak force was smaller for wider twitches. Sites exhibiting

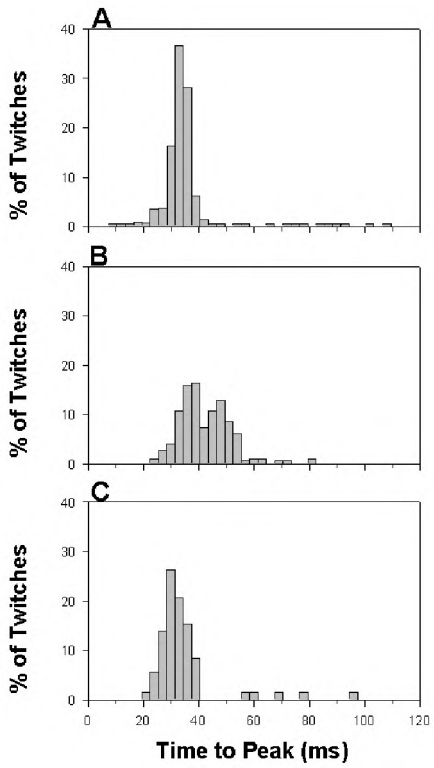

Fig. 1. Distribution of twitch times-to-peak at different stimulus strengths for the (A) quadriceps, (B) tibialis anterior and (C) triceps surae/plantaris muscles. The quadriceps distribution represents twitches obtained from 43 sites in four animals (total of 647 twitches), 17 sites in four animals (total of 235 twitches) for tibialis anterior, and 6 sites in four animals (total of 73 twitches) for triceps surae/plantaris. For each twitch, time-to-peak reflects the time needed for the muscle force to reach its maximum value starting from the point the force crosses the background level. Time-to-peak mean and S.E. values: (A) 33.0 ± 0.4 ms, (B) 41.0 ± 0.9 ms, and (C) 36.0 ± 2.6 ms.

positive twitch duration–stimulus strength relationship predominantly demonstrated steep peak force– twitch duration profiles [(e.g., Fig. 2(F))], indicating that similar types of motor units were being activated. On the other hand, sites exhibiting no twitch duration–stimulus strength relationship showed a lack of correspondence between peak force and twitch duration. Though measurements of twitch duration in this study were obtained at the 40% level of normalized twitch contractions, the observed effects were not dependent on the specific level chosen to make the comparisons. Therefore, while the absolute twitch duration differences for varying stimulus strengths may be larger at lower levels of normalized twitch contractions, the general effect of stimulus strength on twitch duration remains the same.

B. Recruitment Curves

Examples of recruitment curves obtained from quadriceps, tibialis anterior and triceps surae/plantaris are shown in Fig. 3. These examples typify what was seen in all animals and were obtained from spinal cord sites distributed throughout the activation pools. Quadriceps and triceps surae/plantaris recruitment curves showed considerable variability in their slopes, while tibialis anterior possessed more uniform and shallower recruitment slopes. The quadriceps recruitment curve slopes ranged from

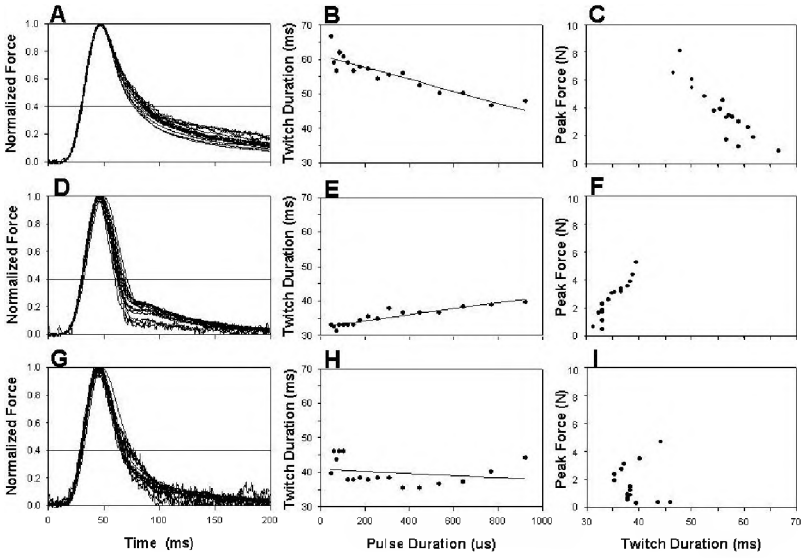

Fig. 2. Twitch responses from three different quadriceps stimulation sites. A, D, and G show superimposed recruitment curve twitch waveforms normalized to their peak amplitudes. B, E, and H show twitch duration (measured at the 40% level, as indicated by the darkened line in A, D, and G) as a function of stimulus strength (pulse duration in μs). The plots show a significantly ($p < 0.05$) negative (A and B), a significantly ($p < 0.05$) positive (D and E) and a nonsignificant (G and H) relationship between twitch duration and stimulus strength. Slopes (ms/μs) and r^2 values: (B) -0.018, 0.81; (E) 0.0088, 0.86; and (H) -0.0031, 0.048. C, F and I are plots of the peak force (in Newtons) of each of the twitches in A, D, and G, respectively, versus their corresponding twitch duration measured at the normalized 40% level.

TABLE I
RELATIVE ABUNDANCE OF DIFFERENT RELATIONSHIPS BETWEEN TWITCH DURATION AND STIMULUS STRENGTH FOR THREE MUSCLE GROUPS

	QUADRACEPS $n = 43$	*TIBIALIS ANTERIOR* $n = 17$	*TRICEPS SURAE/ PLANTARIS* $n = 6$
Decrease	35%	47%	0%
Increase	26%	18%	33%
No effect	39%	35%	67%

Shown are the relative frequencies with which twitch durations showed a statistically significant ($p < 0.5$) decrease, increase, or no change with increasing stimulus strength. N gives the number of motor activation pool sites (in four animals per muscle) from which the data were obtained.

0.51 to 38.0 and had mean and standard error of 7.9% ± 1.3% Plateau Force/nC. Tibialis anterior slopes ranged from 1.2 to 6.7 and had mean and standard error of 2.6% ± 0.34% Plateau Force/nC, and triceps surae/plantaris slopes ranged from 1.4 to 25.0 and had mean and standard error of 8.5% ± 3.6% Plateau Force/nC. Recruitment slopes were statistically independent of the plateau normalizing forces (linear regression, $p > 0.05$).

The quadriceps muscle group generated the highest absolute twitch plateau forces, followed by triceps surae/plantaris and tibialis anterior, respectively. The plateau recruitment forces for quadriceps ranged from 0.71 to 20.0 N, with a mean ± standard error of 20.6% ± 2.7% of the maximum twitch force for whole nerve stimulation. Triceps surae/plantaris plateau recruitment forces ranged from 0.75 to 6.5 N, with a mean ± standard error of 5.5 ± 1.5% of the maximum twitch force for whole nerve stimulation. Tibialis anterior plateau recruitment forces ranged from 0.55 to 5.6 N, with a mean ± standard error of 12.4% ± 1.8% of the maximum twitch force for whole nerve stimulation. Maximum twitch forces for quadriceps, triceps surae/plantaris and tibialis anterior obtained by whole nerve stimulation were 60, 58, and 29 N, respectively.

Recruitment curve slopes and twitch recruitment plateau forces as a function of twitch duration–stimulus strength relationships are shown in Fig. 4 for the quadriceps, tibialis anterior and triceps surae/plantaris muscle groups. There was no statistically significant difference between either of these parameters within a given muscle group as a function of the twitch duration–stimulus strength relationship.

IV. DISCUSSION

A. Twitch Characteristics

The time-to-peak results presented here match the temporal characteristics of fast muscle twitches [32]–[35]. Though the quadriceps and triceps surae/plantaris muscle groups contain both fast and slow muscles, the contribution of the slow muscles was not evident when measuring twitch time-to-peak because the faster contracting components dominated the initial

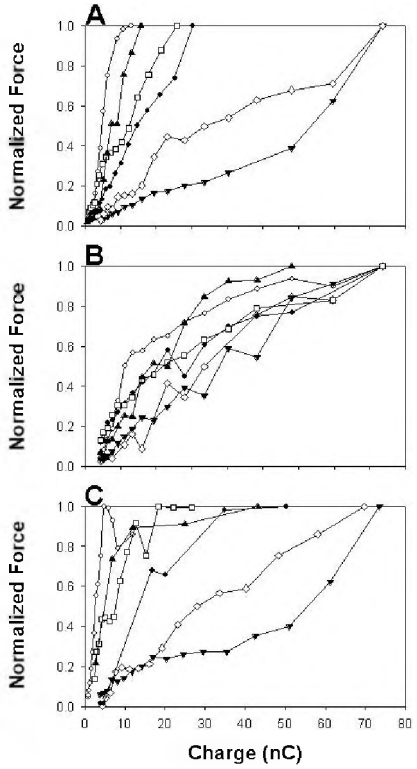

Fig. 3. Sample recruitment curves obtained from twitches elicited by stimulating 6 typical sites in each of the quadriceps (A), tibialis anterior (B) and triceps surae/plantaris (C) activation pools in the ventral lumbo-sacral spinal cord. The curves were normalized to their peak values. Slope (Normalized Force/nC) and peak force (N) in the symbol order ○; ▲; □; •; ◇; ▼): (A) 0.18, 2.17; 0.13, 3.09; 0.069, 3.19; 0.036, 4.68; 0.018, 10.03; 0.0091, 13.42; (B) 0.067, 2.33; 0.027, 2.43; 0.017, 3.26; 0.020, 5.64; 0.018, 2.47; 0.015, 1.99; (C) 0.25, 5.37; 0.12, 2.01; 0.065, 1.98; 0.045, 0.75; 0.019, 4.13; 0.014, 6.46.

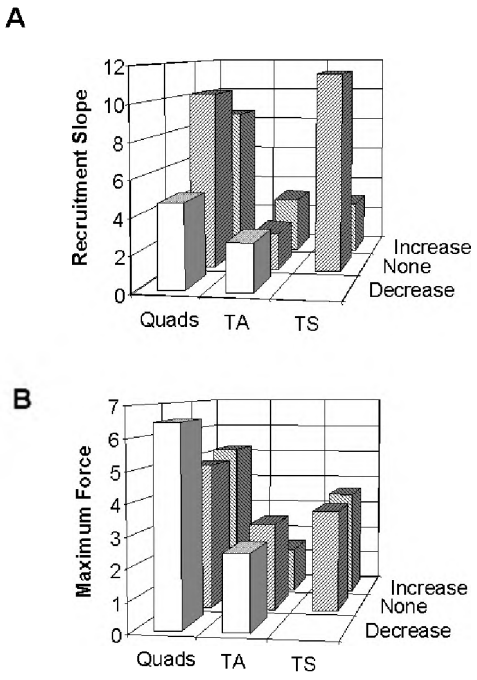

Fig. 4. Mean recruitment curve slope (A, in units of percentabe of plateau force per μC,) and mean twitch recruitment plateau force (B, in Newtons) as a function of twitch duration–stimulus strength relationship for the quadriceps (Quads, $n = 43$), tibialis anterior (TA, $n = 17$) and triceps surae/plantaris (TS, $n = 6$) muscle groups. There was no statistically significant difference in slope or plateau force as a function of the twitch duration–stimulus strength relationship.

peak force of the twitch. However, the contribution of the slow muscle fibers became clear when twitch durations were measured. If only fast-contracting components contributed to the generated force, the twitch durations would have been consistently short for all stimulus strengths. In contrast, we found that twitch durations varied as a function of stimulus strength, indicating a contribution from both fast and slow muscle fibers in the contractions.

Other studies have used the duration of normalized twitches as an indicator of recruitment order [17], [34]. A positive, monotonic relationship between the duration of the normalized twitch and stimulus strength indicates a reversed recruitment order of motor units: faster units are recruited first followed by slower units as the stimulus strength increases. A negative monotonic relationship between the duration of normalized twitch and stimulus strength, on the other hand, indicates a close to physiological recruitment order of motor units in which smaller units are activated first followed by faster units. Our spinal cord stimulation results demonstrated a greater likelihood for mixed and near normal physiological recruitment of motor units than the classical reversed recruitment order associated with electrical stimulation of fibers in peripheral nerves (Table I).

The reason mixed and near normal physiological recruitment order were predominant in our results is primarily because the stimulating electrode provided focal stimulation of the motor neurons. Focal stimuli lead to steep current field curvatures [36] close to the electrode tip which allow for activation of both large and small motor neurons in the vicinity of the electrode before recruitment of large neurons farther away from the electrode [28], [37]. Based on the distribution of small to large motor neurons in a lumbar ventral horn segment and the distribution of large to small motor neurons in a lumbar ventral root [38], the expected probability of activating small to large motor units is roughly 2 to 1 with focal stimuli in the ventral horn. Spielmann *et al.* [39] have presented evidence that, with extracellular stimulation, the threshold current required for sustained firing is not significantly different for fast and slow motor unit cells. These observations are consistent with our finding that about 70% of the stimulated sites in the motor activation pools showed either normal physiological recruitment of motor units or unbiased recruitment of fast and slow units.

B. Recruitment Curves

While the slope of the recruitment curves obtained from tibialis anterior were relatively uniform, the quadriceps and triceps surae/plantaris recruitment curves exhibited a larger range of slopes. The variation in quadriceps and triceps surae/plantaris recruitment slopes could be due to the presence of a topographical segregation of the various compartments of the two muscles within their motor activation pools [40]–[44]. The various

compartments of these muscles may be composed of different fiber types and can perform distinctively different functions in the limb. Qualitative observations during the experiments noted that contraction was largely limited to only one portion of the quadriceps when a single site was stimulated, and that as more caudal locations in the pool were activated, different parts of the quadriceps were activated in an orderly manner. This observation could not be further studied in the present experiments since additional dissection of the muscles and their tendons would have been required. Tibialis anterior consists of two compartments with two distinct representations in its spinal cord motor nucleus [45]. Therefore, the bimodal distribution of times-to-peak we observed could indicate the presence of two regions within the motor activation pool representing the different tibialis anterior compartments. The ability to primarily activate specific muscle compartments by stimulating selected regions in the muscle's motor activation pool could have beneficial application in the field of functional neuromuscular stimulation.

In order to compare recruitment curve slopes obtained in this study to those acquired through peripheral nerve stimulation, several references were consulted [14], [15], [34], [46]–[48]. Out of these references, only Durfee and MacLean [34] and Gruner and Mason [48] used stimulation paradigms and force measurement techniques similar to the ones utilized in this study. Tibialis anterior and triceps surae/plantaris recruitment curves from these two papers were normalized to their plateau values and the stimulus strength was expressed in terms of charge. The recruitment curve slopes were calculated as described above in the Methods section, and the range and mean $\pm$ S.E. values were determined. Tibialis anterior recruitment slopes from Durfee and MacLean ranged from 5.0 to 6.7 and had mean and standard error of 5.8% $\pm$ 0.43% Plateau Force/nC, while triceps surae/plantaris recruitment curve slopes from Gruner and Mason ranged from 0.46 to 19 and had mean and S.E. of 7.0% $\pm$ 3.1% Plateau Force/nC. Slopes obtained in the present study with spinal cord stimulation for these two muscles thus overlapped the ranges of slopes reported for the same muscles with peripheral nerve stimulation. However, because motor pool stimulation does not fully recruit the muscle from a single site, spinal cord stimulation provides finer control of muscle force than does peripheral nerve stimulation. Due to the lack of reports on feline quadriceps recruitment curves, we were unable to compare the muscle's recruitment curve results in this study to those obtained by others.

The peak recruitment forces obtained by single point spinal cord stimulation in previously conducted spinal-cord mapping experiments [28] ranged from 1.3% to 73% of the maximal twitch force obtained by whole nerve stimulation. Plotting the cumulative distribution of maximum twitch forces generated when individual sites were stimulated with 600-μs long biphasic pulses and pulse amplitudes of 100 μA or less (Fig. 5) shows that the majority of sites in a given pool generate relatively low twitch forces. Thus, multiple electrodes would need to be implanted in a single motor activation pool to obtain maximal muscular contraction.

C. Electrode Arrays

Using generated *twitch* force as the only criterion for choosing an appropriate number of electrodes to be implanted

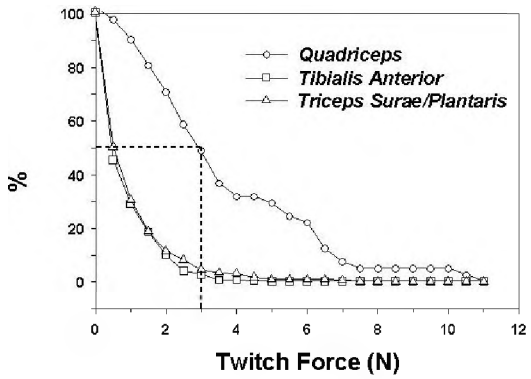

Fig. 5. Cumulative distribution of maximum twitch forces in the quadriceps, tibialis anterior and triceps surae/plantaris elicited by single point stimulation in their respective activation pools. Data obtained from a previously conducted study [28]. The stimulus amplitude used at each site was the maximum current (up to a limit of 100 μA) that produced contraction of the target muscle in isolation. The dashed lines indicate that 50% of the activation pool locations produced 3 N or less when the maximum stimulus level was delivered. $n = 41$ sites in four animals for quadriceps, 417 sites in six animals for tibialis anterior, and 274 sites in six animals for triceps surae/plantaris.

in the quadriceps, tibialis anterior or triceps surae/plantaris motor activation pool, and keeping in mind that simultaneous dual channel stimulation produces a greater force than the sum of the forces generated through stimulation of each of the channels individually [15], [25], arrays of 4, 6, and 14 electrodes would be recommended for stimulation of quadriceps, tibialis anterior and triceps surae/plantaris motor activation pools, respectively. These numbers assume that from 70% to 80% of the maximum force would be obtained by the summation of forces generated at each site when the stimulus is rotated through the electrodes such that each electrode is stimulated individually, and the remaining 20%–30% of the force is generated when multiple electrodes are stimulated simultaneously [20], [25]. When trains of stimuli are used, significantly larger tetanic forces are generated by the activated muscle or muscle group in comparison to the twitch forces reported in this study [25], [49]. Furthermore, in a chronic study in which electrodes were implanted in intact, freely moving cats for six months, fused contractions generated by stimulating through individual electrodes were capable of lifting the animals' hindquarters [26].

Stimulating through a distributed set of electrodes implanted in a given motor activation pool would have several benefits, including finer control of force generation and fatigue resistance. Finer control of muscle contraction is possible with multiple electrodes because varying stimuli can be delivered to the different electrodes, thereby optimizing the desired output of a given muscle. Furthermore, since the muscle response to a constant stimulus may vary from one pulse to the next [11], stimulation through a population of electrodes implanted in a given motor activation pool has the advantage of producing a more stable muscle response by statistical averaging. With more than one electrode in each motor activation pool, the amount of muscle fatigue associated with conventional peripheral elec-

trical stimulation methods can be reduced by two mechanisms. First, instead of stimulating the same set of motor units continuously, the stimuli are rotated among the different electrodes in a single pool, distributing the mechanical work among different motor units in a specific muscle. Second, since the rate of fatigue is related to the rate of firing of a neuron, by stimulating through several electrodes one can decrease the rate of firing of individual neurons in a pool by stimulating each electrode at a fraction of the fusion frequency while still producing a fused, tetanic contraction. This has already been demonstrated by stimulating the peripheral nerve [19], [20], [50] as well as the spinal cord by our group [25].

In summary, we have demonstrated here and in the companion paper that selective activation of functional muscle groups in the hindlimb of cats can be obtained through spinal cord microstimulation [28]; that stimulation of the ventral lumbo-sacral spinal cord can produce a more physiological order of recruitment of motor units than does peripheral nerve stimulation; and that graded control of muscle force is possible. These findings indicate that spinal cord stimulation has the potential to restore functional motion and could have numerous applications in future neuromuscular stimulation systems. Based on the relative arrangement and geometry of motor activation pools [28], force recruitment characteristics obtained through spinal cord stimulation, and interactions between electrodes implanted at varying distances within the spinal cord [25], we have provided elsewhere specifications for a stimulating electrode array suitable for implantation in the lumbosacral spinal cord for the purpose of restoring mobility following a spinal cord injury [25].

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