Selective Activation of Muscle Groups in the Feline Hindlimb Through Electrical Microstimulation of the Ventral Lumbo-Sacral Spinal Cord

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***Abstract*—Selective activation of muscle groups in the feline hindlimb by electrical stimulation of the ventral lumbo-sacral spinal cord was investigated. Spinal cord segments L5 to S1 were mapped using a penetrating tungsten needle electrode. Locations that produced isolated contraction of quadriceps, tibialis anterior or triceps surae/plantaris muscles when stimulated with a current of 40 μA or less, and in which spread of activity to other muscles was not detected after increasing the stimulus to at least twice the threshold level, were defined as belonging to the target muscle's "activation pool." The quadriceps activation pool was found to extend from the beginning of L5 to the middle of L6. The tibialis anterior activation pool extended from the beginning of L6 to the middle of L7, and the triceps surae/plantaris activation pool extended from the caudal end of L6 to the beginning of S1. The three activation pools were located in Rexed motor lamina IX and their spatial organization was found to correspond well with that of the anatomically defined motor pools innervating the same muscles. The spatial and functional segregation of motor pools manifested at the spinal cord level can have direct applications in the areas of functional electrical stimulation and motor control.**

***Index Terms*—Functional electrical stimulation, motor pools, spinal cord stimulation.**

I. Introduction

PARALYSIS induced by an acute spinal cord injury leaves the limb muscles and many of their innervating motor neurons below the level of the lesion intact, but disrupts communication between the brain and the peripheral nervous system [1]–[3]. In the absence of spinal cord regeneration, artificial means have been developed for restoring function to paralyzed limbs and organs. Electrical stimulation of peripheral motor nerves and spinal sacral roots for restoring mobility and effecting micturition in paraplegia, as well as diaphragm pacing in quadriplegia, has been extensively investigated [4]–[13]. This technique, known as functional neuromuscular stimulation (FNS), uses motor point or cuff electrodes to stimulate nerve fibers innervating various muscles. Though some success has been attributed to current FNS systems, several shortcomings have overshadowed their effectiveness [14], [15]. These shortcomings include premature lead breakage due to the implantation of stimulating electrodes near or in moving target tissue [15]; dependence of muscle response on location of the electrodes relative to the motor point, which results in unpredictable force recruitment profiles [16]; and muscle fatigue due to the reversed recruitment order of motor units and prolonged stimulation of the same subset of motor units [17].

Some of the problems associated with peripheral nerve FNS systems have recently prompted at least one group of researchers to implant electrodes in the lumbar roots, a location far away from contracting muscles [18]. Yet, the lack of selectivity in muscle activation when stimulating whole roots has been a confounding factor in restoring functional mobility using this approach.

We proposed the use of spinal cord stimulation in FNS primarily for two reasons [19]–[24]: The spinal cord is distant from contracting muscles, so electrodes implanted therein will not be subjected to damaging stresses and strains due to movement of the target tissue [25]. The limited spinal cord movement within the spinal column has recently been verified in a chronic study in which electrodes were implanted in intact, actively moving animals for 6 months [26]. The lumbo-sacral spinal cord which houses the cell bodies of motor neurons innervating the muscles of the lower extremities is compressed, thereby allowing the activation of essentially all lower extremity muscles by implanting electrodes in a relatively small and protected region.

In establishing the feasibility of producing functional motion using a spinal cord FNS system, three conditions need to be met. First, the system should have the ability to selectively activate single muscles or synergistic muscle groups. Second, the system should allow for smooth and graded control of force generated by the activated muscle(s). Third, the system should have the capability to reduce the rate at which the activated muscles fatigue.

In this paper, we focus on the effectiveness of spinal cord stimulation in activating specific muscles or muscle groups in isolation. The companion paper [27] discusses force recruitment through spinal cord stimulation. Reduction of muscle fatigue using spinal cord stimulation has been reported elsewhere [23], [24].

The motor nuclei of neurons innervating hindlimb muscles in the cat have been extensively investigated using chromatolysis [28], [29], Nissl [30] or horseradish peroxidase staining [31]–[36] as cell markers of motor neurons in the ventral horn of the mammalian lumbo-sacral spinal cord. Romanes [28] demonstrated that motor neurons innervating specific feline hindlimb

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muscles are arranged in discrete columns in the spinal cord ventral horn, but commented that intermingling of motor neurons innervating various muscles could not be ruled out. However, in a sagittal spinal cord section through the center axis of the medial gastrocnemius cell column, Burke *et al.* [31] suggested the presence of "relatively cell-sparse regions dorsal and ventral" to the medial gastrocnemius column, separating it from cells of other columns. Furthermore, Iliya and Dum [32] demonstrated that the motor neurons innervating tibialis anterior in the cat form a distinct pool in the spinal cord that is not contaminated by motor neurons innervating other pretibial flexor muscles.

The invasion of motor nuclei by neurons innervating different muscles could occur in two forms. First, motor nuclei could contain cell bodies of motor neurons innervating more than one muscle. Second, excitable fibers of neurons innervating a certain muscle could travel through regions occupied by motor nuclei innervating other muscles. While the lack of intermingling of neuronal cell bodies innervating tibialis anterior has been indicated [32], contamination of motor nuclei has not yet been fully resolved, leaving the presence of spatial and functional segregation on the spinal cord level questionable for FNS applications.

In this study, we investigated whether selective muscular activation occurs when populations of neurons in the ventral lumbosacral spinal cord of cats are directly activated through electrical microstimulation. While anatomical spinal cord motor nuclei studies have been concerned with analyzing motor pools in terms of location of cell bodies, the focus of this work is on the existence and nature of activation pools in the lumbo-sacral spinal cord. We define activation pools as regions in the spinal cord gray mater from which electrical stimulation evokes contraction of individual muscles or muscle groups in isolation. The existence of activation pools could provide the basis for spinal cord stimulation in FNS applications. This is the first full report on lumbosacral mapping using electrical microstimulation for the purpose of designing spinal cord-based FNS system for controlling the knee and ankle.

II. METHODS

A total of 29 adult cats (2.7 kg or larger) were used in this study. Acute lumbo-sacral spinal cord fine mapping experiments were performed on eighteen cats. The cats were divided into three groups of six, with each group dedicated to investigating the existence and nature of the quadriceps, tibialis anterior or triceps surae/plantaris activation pool, respectively. Incomplete maps were obtained in one tibialis anterior and one triceps surae/plantaris experiment and are not included in the results. Coarse maps in which four activation pools were mapped at the same time (hamstrings, quadriceps, tibialis anterior and triceps surae/plantaris) were obtained from 11 animals.

The complexity of the preparative surgery, the extensive amount of data collected, and the need to wait long enough between stimuli to avoid muscle fatigue meant that the experiments would typically last in excess of 36 h. To maintain a viable, stable preparation for this length of time, the overriding consideration in the experimental setup was to minimize the disruption of the blood supply to the nerves and muscles of the leg and spinal cord.

A. Animal Preparation and Experimental Setup

Anesthesia was induced with an intraperitoneal injection of sodium pentobarbital (40 mg/kg) and maintained with a 1 : 10 lactated ringers dilution of the anesthetic which was administered as needed through the cephalic vein. Each animal was placed on a heated plate and its body temperature was maintained near 37.5 °C. Two hip pins and a spinal clamp for rigidly holding the spinous process of vertebra L3 were used (Fig. 1), and a laminectomy was performed to expose spinal cord segments L4–S2. Note that the segments of the spinal cord lumbar enlargement in a cat (L5–S1) comprise a 3 cm-long region covered by a single vertebra (L5) [37]. The dura mater was opened using iridectomy scissors and reflected to the right side of the spinal cord.

For the fine mapping experiments bone pins were placed in the medial proximal surface and medial malleolus of the tibia to allow for isometric muscular force measurements. An additional pin in the lateral epicondyle of the femur was needed to prevent rotation about the iliac crest pins and hip. The placement of the femoral pin caused minimal muscle disturbance (if any) in all animals. The pins and footpad transducer placed the hip, knee and ankle at 90° angles. The patellar ligament was detached from its point of insertion and attached to a force transducer (model SM-25, Interface, Scottsdale, AZ). The patellar transducer was used to quantify the force generated by the quadriceps muscle group when the quadriceps activation pool was under investigation, and to detect stimulus spread to the quadriceps muscle group when the tibialis anterior or triceps surae/plantaris activation pools were mapped. The tibialis anterior and Achilles/plantaris tendons were left intact when the quadriceps activation pool was mapped, but each was detached from its point of insertion and attached to a force transducer (model SM-25 for Achilles/plantaris tendon and model MB-5 for tibialis anterior tendon, Interface, Scottsdale, AZ) when the activation pool of their respective muscle(s) was studied. The recordings from the force transducer attached to the muscle of interest were further processed to quantify force recruitment as a function of stimulus strength (see the companion paper [27]).

Bipolar intramuscular EMG electrodes were placed close to the motor points in biceps femoris and semimembranosus/semitendenosus muscles. Each electrode in a pair of intramuscular EMG electrodes was prepared by passing a fine wire, insulated except for a 1 mm tip, through a 28-gauge hypodermic needle. The electrodes were placed in the muscle 5 mm apart. Signals in each electrode were recorded relative to the hypodermic needle shield. EMG activity in a muscle was detected by differential recording between the paired electrodes.

The design and placement of these electrodes was such that their ability to detect muscle fiber action potentials within the muscle they were placed in was comparable to the sensitivity of the force transducers used to detect muscle force, while at the same time they did not pick up measurable crosstalk from neighboring muscle groups when the latter were stimulated with maximal, single pulse stimuli delivered to the spinal cord. The former relied on the random distribution of muscle fibers of single motor units in the muscle, and the latter relied on the common mode rejection properties of differential recordings. The EMG recordings were used to detect the presence of activity in muscles

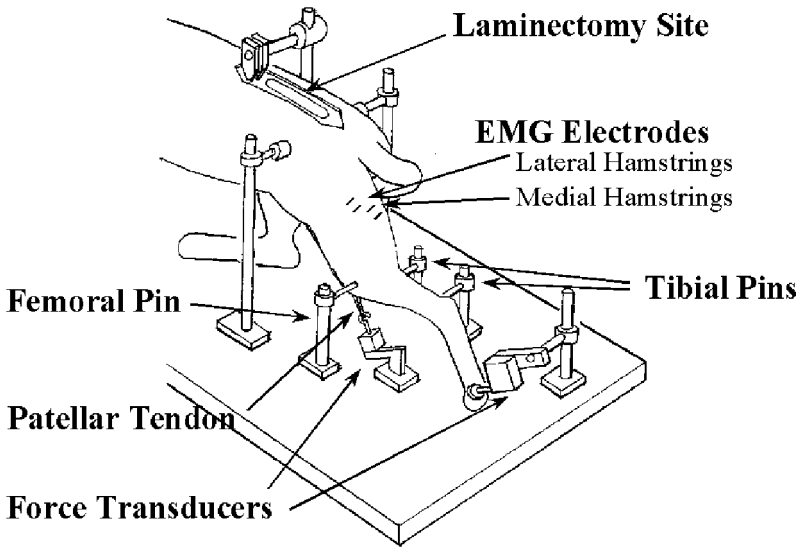

Fig. 1. Experimental setup for mapping the quadriceps activation pool in the cat. A force transducer was attached to the patellar tendon to measure the isometric force generated by quadriceps contraction. A combination of transducers and EMG electrodes were used to detect activity in the remaining muscles of the leg when stimulus spread to motor neurons innervating other muscles occurred. When tibialis anterior or triceps surae/plantaris activation pools were mapped, their respective tendons were detached from their points of insertion and attached to a force transducer.

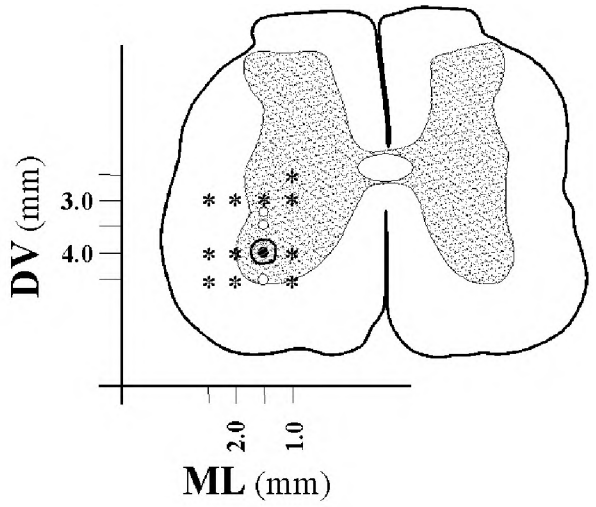

Fig. 2. Cross section from the caudal end of the quadriceps activation pool illustrated in Fig. 3. The asterisks refer to locations where no muscular activity was detected when a 40-μA stimulus was delivered. The white circles refer to locations where activity in the target muscle was detected with stimuli of 40 μA or less, but the stimulation range was less than 2 (i.e., selective activity in the target muscle was not maintained when the stimulus was increased to twice the threshold current level). The black circle refers to the location where activity in the target muscle was detected with a stimulus 40 μA and the stimulation range was $\geq$2. The hatched area surrounding this point shows the outline of the activation pool at this level.

other than a target muscle, and were not further processed (i.e., no attempt was made to further quantify the EMG activity nor to use it for estimating the amount of generated hamstrings force).

A force transducer (model MB-5, Interface, Scottsdale, AZ) was placed on the animal's footpad to detect contraction of muscles controlling the ankle and the paw. Plantarflexion contractions of the ankle deflected the transducer upwards in the sagittal plane, while dorsiflexion contractions deflected it downwards. Similarly, paw flexion deflected the transducer upwards while paw extension deflected it downwards. In preliminary studies, contraction of muscles anterior and posterior to the tibia was not found to completely cancel the forces in transducers attached separately to each set of muscles: therefore, the use of a single footpad force transducer which eliminated the disruption of vessels and muscle tendons was deemed appropriate and adequate for monitoring ankle and paw movements. As with the EMG recordings, the output of this transducer was used to detect contractions in muscles other than a muscle of interest and the signals were not further processed.

With this setup, contractions in muscles controlling the ankle and paw (i.e., all shank muscles) were monitored through the footpad transducer. The hamstring EMG electrodes and the patellar ligament force transducer allowed for monitoring of activity in the main muscles of the thigh. However, this setup did not allow discrimination between mono- and biarticular muscles within these groups. To do so would have required a more extensive dissection of the leg, which would have compromised the integrity of the preparation over the duration of an individual experiment.

B. Stimulation Protocol and Data Acquisition

Both stimulation of the spinal cord and recording of muscle activity were performed using an IBM compatible 80486 computer. The computer generated stimuli were sent through a digital-to-analog converter to a voltage controlled constant current source prior to delivery to the stimulating electrode. Activity from force transducers and EMG electrodes was digitized at 4 kHz for 200 ms.

A 100-μm diameter tungsten rod (AM Systems, Everett, WA), insulated with epoxy except for the electrolytically sharpened tip (50-μm exposed tip, impedance 25–50 kΩ), was mounted in a three-dimensional (3-D) micromanipulator and used to stimulate the ventral lumbo-sacral spinal cord. The electrode was vertically advanced through the dorsal horn and mapping of the ventral horn progressed in 0.25–0.5-mm steps

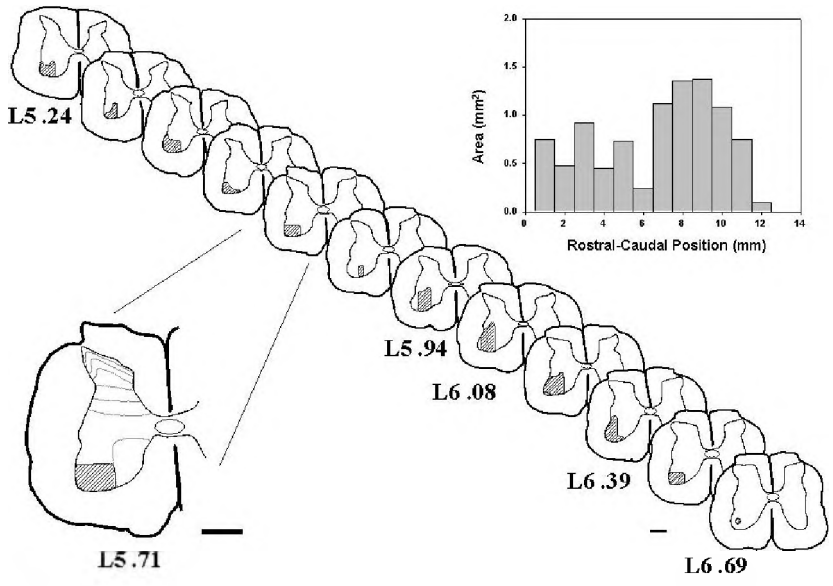

Fig. 3. Example of a typical quadriceps activation pool. The spacing between the cross sections is 1 mm. Segment labels refer to the location of the cross sections relative to the rostral end of each segment: e.g., L5.24 means that the cross section was obtained from segment L5 and was located 24% of the way between the segment's rostral and caudal ends. The first cross section is the rostral level at which the quadriceps activation pool was first detected. The last cross section marks the caudal end of the pool. The graph in the upper right shows the pool's cross sectional area at each level. The inset on the left outlines Rexed's lamina at the indicated level [43] and [58]. Scale bars: 1 mm.

in the dorsal-ventral and medial-lateral dimensions and in 1 mm steps in the rostral-caudal dimension. Increment steps in the three dimensions were determined from preliminary mapping experiments [19]. They were also determined from spinal cord microstimulation studies in which effective current spread through a single electrode, force summation obtained through multielectrode stimulation and amount of tissue displacement due to electrode array implantation were investigated with regards to potential FNS applications [24]. An 18-gauge metal hypodermic needle was placed in the right latissimus dorsi muscle and served as the return electrode. At each location, single 600-μs-long cathodic first, biphasic pulses with 500-μs interphase intervals and varying pulse amplitudes were delivered, and force generation in the target muscle (quadriceps, tibialis anterior or triceps surae/plantaris) was recorded. If a contraction was detected in the target muscle, the threshold current for generating muscle force, as defined below, was then determined. The pulse amplitude was then increased until either activity in another muscle was detected, or an amplitude of 100 μA was reached. The stimulation range (maximum current before spread of activity to other muscle groups relative to the threshold current) was calculated. The stimulation protocol continued until stimulation of new spinal cord locations no longer produced activity in the target muscle. Throughout the duration of the experiment, the viability of each preparation was tested by periodically stimulating various spinal cord locations mapped early in the experiment and comparing the resulting muscle responses. In all cases, muscle responses obtained later in the experiments were within 10% of those obtained earlier.

At the end of the experiment, 70-μm electrolytic lesions (70–90 μA for 30 s) were placed in the spinal cord to serve as location markers. The animals were deeply anesthetized, injected with heparin, and perfused through the heart with a buffered, 3.7% formaldehyde fixative using our standard laboratory procedures [38]–[40]. The stimulated region of the spinal cord was removed and the ventral and dorsal rootlets were used to verify the location and extent of the stimulated lumbo-sacral segments. The spinal cord was then sliced in 25-μm transverse sections. The electrolytic lesions were located and the sites of spinal cord stimulation were determined. Electrode tracks within a spinal cord cross section were parallel to each other as would be expected when using a stereotaxic setup as the one used in these experiments. Photographs of the cord sections were taken and digitized using AutoCad LT.

C. Detection of Activity

For online detection of muscle activity, the EMG signals were bandpass filtered (10–10 000 Hz), amplified 1000 times, rectified and divided into 15-ms bins. The mean signal amplitude in each of the bins was compared to the background (or baseline) level of the corresponding channel acquired 200 ms immediately prior to the delivery of the stimulus. Presence of activity was established if the mean rectified EMG in any bin was higher than mean +3 SD of baseline activity. Similarly, the outputs from the force transducers were amplified 1000 times and divided into 25 ms bins and the presence of muscle contraction was established if the mean signal amplitude in any bin was larger than the mean +3 SD of the corresponding force channel's background level. Though the criteria for detection of force and EMG activity were well within limits established in the literature (e.g., Sainburg *et al.* [41]), these criteria almost certainly meant that threshold represented multi- rather than single-motor unit activity. However, as shown in the companion paper [27], threshold did represent a very low level of force production.

D. Data Processing

Once the images of the spinal cord cross sections were digitized, all the stimulation sites were identified as shown in Fig. 2. If a location produced activity in the target muscle with a threshold current of 40 μA or less and had a stimulation range of at least 2 (i.e., selective activation of the target muscle was maintained after the stimulus was increased to at least twice the threshold current level), the location was said to be part of the target muscle's "activation pool." A stimulation range of at least 2 was chosen to allow for adequate force recruitment as a function of stimulus strength [27]. A threshold current of 40 μA was chosen based on safe electrical stimulation criteria for the electrode dimensions used in these experiments (surface area around 5600 μm^2) and on the need to have a stimulation range of at least 2 and a maximum stimulation current of 100 μA [42]. Electrical stimulation safety criteria in the central nervous system were predominantly determined in cortical tissue. In the absence of similar published studies in the spinal cord, it was assumed that the reaction of the spinal cord gray mater to electrical stimulation would be similar to that of cortical tissue. The term "activation pool," therefore, refers to all the spinal cord gray mater locations at which activity was detected in the target muscle in isolation, using the criteria described above. A small percentage (<5%) of spinal cord locations that met the activation pool stimulation criteria were located in the white mater. Those locations were identified during the histological analysis of tissue and were disregarded (i.e., excluded from the activation pools). This was primarily done to reflect the clinical reality of spinal cord injuries where descending and ascending tracts in the white mater are usually disrupted. By disregarding all white mater locations, some locations from which motor neuron axons were activated might have been inadvertently lost.

The outline of the activation pool in each cat was marked on cross sections spaced 1 mm apart by drawing a line around the points forming the pool. The line was drawn such that it fell midway between the points inside the pool and those outside the pool. Using this technique, the stimulated portion of the spinal cord was reconstructed and the activation pool of the muscle was determined. The dorsal-ventral, medial-lateral and rostral-caudal extents of each pool were measured and the pool volume calculated.

E. Coarse Mapping

To determine the relative arrangement of the main knee and ankle flexor and extensor muscle activation pools, coarse spinal cord mapping experiments were completed on 11 adult cats. Sodium pentobarbital anesthesia was induced and maintained as described above. In these experiments, the animal was positioned in the Kopf spinal unit, and its left hindlimb was allowed to move freely above the heated plate. Spinal cord segments L4–S2 were exposed and mapping of the left side of the spinal cord proceeded in 1 mm increments in the dorsal-ventral, medial-lateral and rostral-caudal dimensions using a tungsten needle electrode. The stimuli consisted of trains of pulse amplitude modulated, rectangular, 200-μs duration pulses delivered at 50 Hz for 500 ms. These trains produced tetanic contractions that allowed the use of palpation and visual inspection to detect activity in the quadriceps, hamstrings, tibialis anterior and triceps surae/plantaris muscles [19]. Thresholds determined by palpation and visual inspection were ± 10 μA within those determined by EMG activity recorded through intramuscularly implanted electrodes [26]. If at any site hindlimb contractions could not be localized to a single muscle, that spinal cord site was considered as not being part of an activation pool. Activation pools were defined using the threshold current and stimulation range criteria presented above for the fine mapping experiments. For each cat, 3-D graphs combining the four pools were constructed to allow for proper visualization of the relative spatial arrangement of the pools in the spinal cord.

It is important to note that the focus of this set of experiments was to determine the relative arrangement in the lumbo-sacral spinal cord of the activation pools controlling the main knee and ankle flexor and extensor muscles, not to determine in detail the boundaries of the pools. The use of muscle activity detection through palpation and visual inspection was necessary to allow for completion of the experiments while the preparations were still viable (36 h or less).

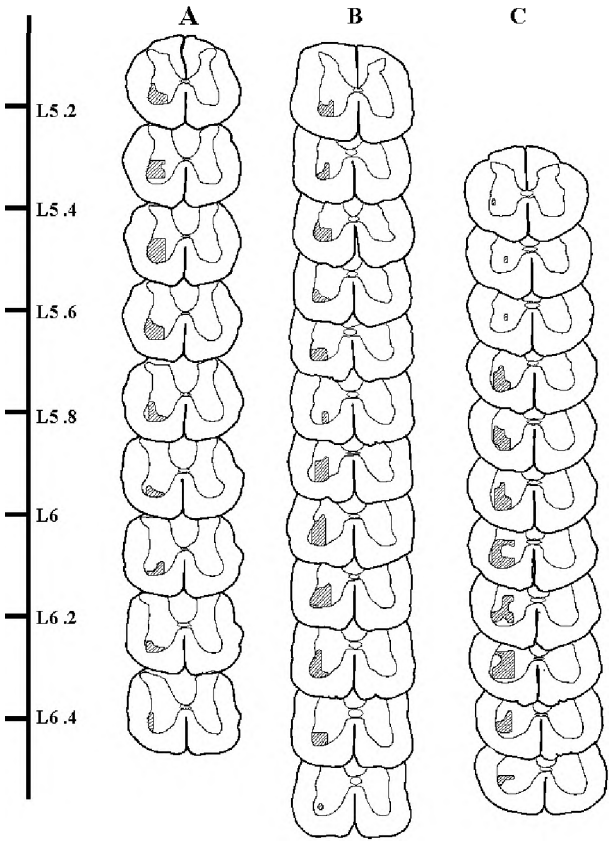

Fig. 4. Variability between quadriceps activation pools. Shown are quadriceps activation pools from the animal illustrated in Fig. 3 (B) and two other cats (A and C). The pools are representative of all the quadriceps activation pools mapped in this study. Each pool is displayed by dimensioning it relative to the dimensions of the spinal cord segments from which it was obtained, rather than by absolute size. The scale in the figure shows the pools' segmental level location: e.g., L5.2 indicates a location 20% caudal to L5's rostral end.

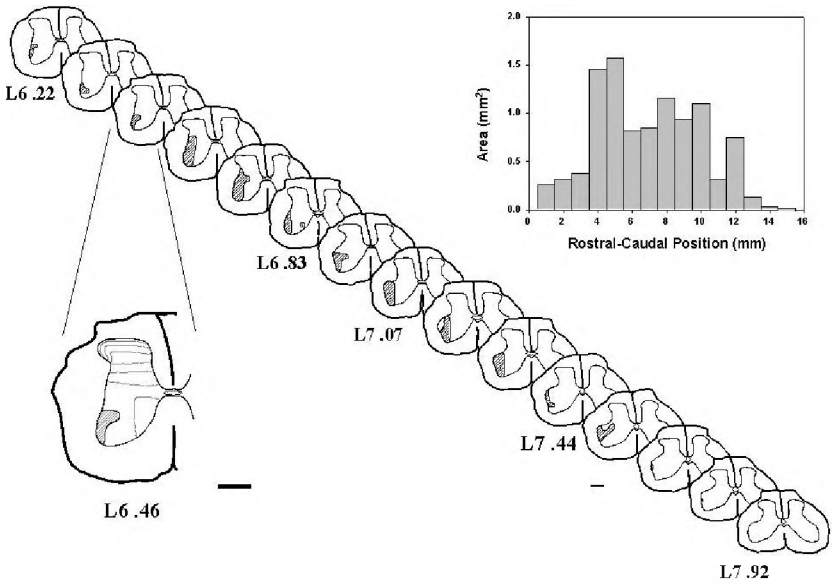

Fig. 5. Example of a typical tibialis anterior activation pool. Format as Fig. 3.

III. Results

A. Anatomical Organization of Activation Pools

An example of a typical quadriceps activation pool is shown in Fig. 3. The cross sections are 1 mm apart and were obtained from lumbar segments L5 and L6. The first cross section marks the most cranial level at which the quadriceps activation pool was detected and the last cross section marks the caudal end of the pool. Cross section labels refer to their location relative to the rostral end of the lumbar spinal segment from which they were obtained. The hatched region represents the activation pool at that level.

In the example shown in Fig. 3, the quadriceps activation pool was centered around the L5/L6 junction and extended over nearly three quarters of both L5 and L6 segments. The lower left corner of the figure provides an enlargement of cross section with an outline of the Rexed laminae [43]. In all the cross sections the pool was located in Rexed motor lamina IX. The upper right hand inset is a plot of the quadriceps activation pool cross sectional area along its rostral-caudal dimension. The first bar in the graph represents the area of the hatched region in the first cross section of the pool, while the last bar represents the area of the hatched region in the last cross section. The graph demonstrates that the pool cross sectional area was not constant along its length: rather, the pool had alternating regions of increasing and decreasing cross sectional area, giving it an overall "bead-like" appearance. The quadriceps activation pool's bead-like shape was apparent in all six animals, with four pools exhibiting a narrowing toward the middle of their rostral-caudal axis and two possessing narrow regions at their rostral and caudal ends.

Fig. 4 shows the quadriceps activation pool in Fig. 3 along with pools from two other animals. The pools are representative of the quadriceps activation pools mapped in this study. In this figure and in Figs. 6 and 8, the maps of an individual are scaled by spinal cord segment, not absolute distance. The figure illustrates that the rostral-caudal extent of the quadriceps activation pools was consistent, as was their location in the ventral gray mater of the cord. Note that though the cross sectional area of the pools changed along their rostral-caudal excursion, the pools

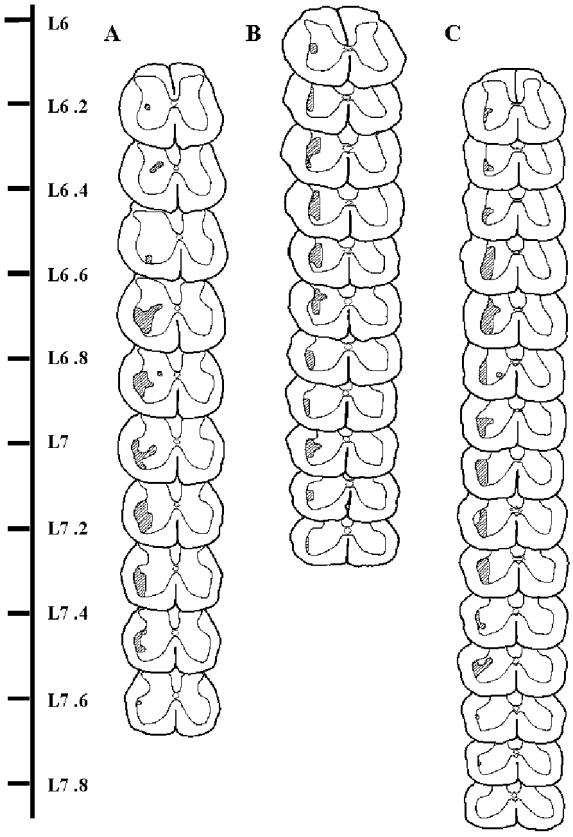

Fig. 6. Variability between tibialis anterior activation pools. Format as in Fig. 4.

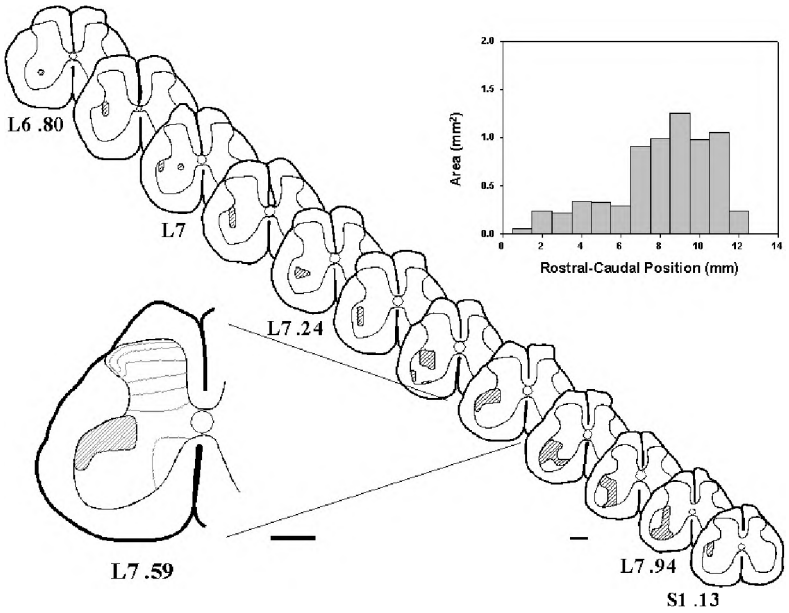

Fig. 7. Example of a typical triceps surae/plantaris activation pool. Format as Fig. 3.

were consistently located in lamina IX. On average, the quadriceps activation pools started at L5.19 (i.e., 19% of the way between the beginning and end of L5) and extended to L6.52.

An example of a tibialis anterior activation pool is shown in Fig. 5. As in Fig. 3, the cross sections are 1 mm apart and the hatched regions show the activation pool at the level of each section. In this example, the pool was found to span the caudal three quarters of segment L6 and almost the full length of L7. Similar to the quadriceps activation pool, the tibialis anterior pool was located in Rexed motor lamina IX. The change in cross sectional area of the tibialis anterior activation pool along its rostral-caudal extent gave it a general bead-like appearance that had narrowing regions toward the rostral and caudal ends of the pool. The bead-like shape of the pool was consistent in all five cats.

Fig. 6 shows the tibialis anterior activation pool in Fig. 5 along with pools from two other animals. The three pools are representative of the variability observed between all tibialis anterior pools obtained in this study. The figure shows while the pools originated from the same rostral lumbar level, some variability was present in their caudal termination. On average, the tibialis anterior pools extended from L6.10 to L7.59. They were consistently found to lie in the lateral portion of the ventral gray mater and were always in lamina IX. Compared to the location of the quadriceps activation pools, the tibialis anterior pools were more caudal in the lumbar spinal cord, more lateral, and extended slightly more dorsally.

Fig. 7 shows an example of a triceps surae/plantaris activation pool using the same format described above. The pool occupied a small portion of the caudal end of L6, the entire L7 segment, and a small portion of the rostral end of S1, and was located in Rexed lamina IX. The cross sectional area of the pool varied along the rostral-caudal axis and also had a bead-like appearance.

Fig. 8 shows the triceps surae/plantaris pool of Fig. 7 along with pools from two other animals. The pools in Fig. 8 are representative of all five triceps surae/plantaris pools obtained in this study. A noticeable variability between tricepse/plantaris pools obtained from different animals was in the location of the rostral end of the pool. The cross sectional area of the pools demonstrated a general bead-like appearance with frequent narrowing around the center of the pool. On average, these pools, which extended from L6.83 to S1.36, were located medial and caudal to the tibialis anterior pools, though the two pools shared parts of lumbar segments L6 and L7.

Table I provides a comparison of the locations and relative dimensions of the three activation pools. Of these measures, the most striking differences between activation pools were in their segmental levels. This is more clearly shown in Fig. 9. The figure was constructed from pool sites obtained by coarsely mapping the left side of the spinal cord at 1 mm increments in three dimensions, and includes the hamstring group which was not studied with the fine mapping described above. The tick marks are 1 mm apart and the intersection of the three axes is on the spinal cord midline. The vertical axis shows the location of the pools relative to the dorsal surface of the spinal cord; the axis leaving the plane of the paper shows the location of the pool relative to the spinal cord midline; and the horizontal axis shows rostral-caudal position.

The figure illustrates that the quadriceps pool is positioned more rostrally than the other pools. The tibialis anterior pool is more laterally located, and the hamstrings pool extends more caudally than the remaining pools. The triceps surae/plantaris pool, under-represented in this example, is situated medial and caudal to the tibialis anterior pool and caudal to the quadriceps pool. The hamstrings pool has a long fusiform shape with its widest region lying mainly in L7 and its narrow rostral and caudal ends extending to L6 and S1, respectively. Aside from exhibiting some shifting in the rostral-caudal dimension, the rel-

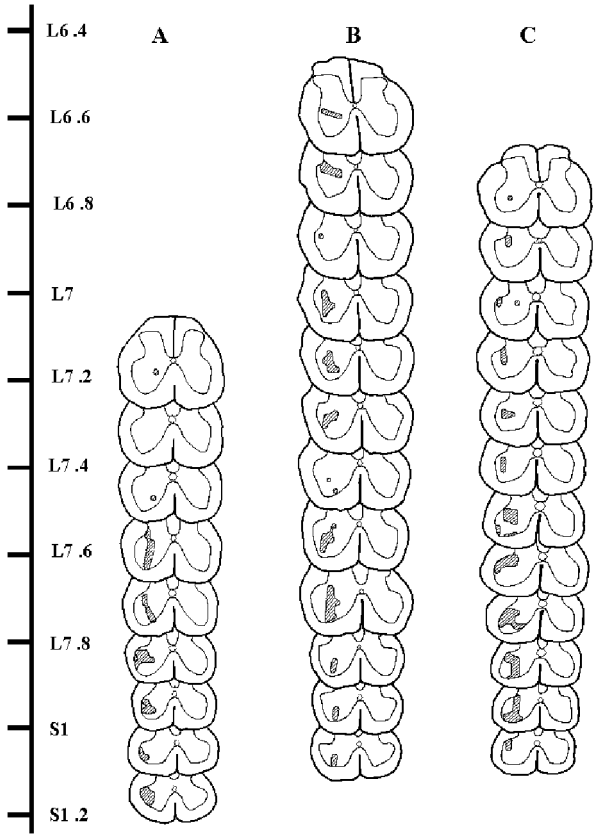

Fig. 8. Variability between triceps surae/plantaris activation pools. Format as in Fig. 4.

TABLE I
RELATIVE LOCATION AND DIMENSIONS OF QUADRICEPS (Q), TIBIALIS ANTERIOR (TA) AND TRICEPS SURAE/PLANTARIS (TS) ACTIVATION POOLS IN THE LUMBO-SACRAL SPINAL CORD

Parameter	*Relationship*
craniality	Q >> TA >> TS
laterality	TA > TS >> Q
ventrality	Q >> TA = TS
length	Q = TA = TS
width	TS = Q > TA
height	TA >> TS >> Q
volume*	TA = Q = TS

Pools are listed in the order of the magnitude of the respective parameter. Statistical significance: >>, $p < 0.01$; >, $p < 0.05$; =, $p > 0.05$ (Student t-test, $\alpha = 0.05$).

*Activation pool volume was determined by summing the pool cross-sectional areas along their rostral–caudal extension.

ative spatial arrangement of the four pools shown in Fig. 9 was consistent between animals [19].

B. Electrophysiological Characteristics of Activation Pools

Fig. 10 gives the cumulative distribution of threshold levels for the quadriceps, tibialis anterior and triceps surae/plantaris activation pools. The pulse width of the rectangular biphasic stimuli was held constant at 600 μs and the interphase interval was 500 μs. The majority of locations in the activation pools required low stimulus levels to activate their respective muscles. Mean and standard error threshold current values for quadriceps, tibialis anterior and triceps surae/plantaris activation pools were $13.9 \pm 0.6\,\mu$A, $15.9 \pm 0.4\,\mu$A, and $15.5 \pm 0.6\,\mu$A, respectively.

Fig. 11 shows the distribution of stimulation ranges in the three pools. For all three pools, the stimulus amplitude could be substantially increased beyond the threshold level before spread of activity was detected. Mean and standard error stimulation range values for the quadriceps, tibialis anterior and triceps surae/plantaris activation pool were 7.9 ± 0.4, 7.5 ± 0.3, and 5.0 ± 0.2, respectively.

IV. DISCUSSION

A. Activation Pool Location and Profile

The quadriceps, tibialis anterior and triceps surae/plantaris activation pools were located in Rexed motor lamina IX in the ventral lumbo-sacral spinal cord. The location of the pools was consistent relative to the spinal cord midline and dorsal surface, but some variability was noticed in the location of the pools' rostral and caudal boundaries. This variability could be due to differences in ventral root contributions to the lumbo-sacral plexus of cats which have conventionally classified the animals as pre or post fixed [28]. Yet, even with the rostral-caudal "shifting" of pools, the spatial arrangement of the activation pools relative to each other in the lumbo-sacral spinal cord was consistent between animals. This is of great importance for a spinal cord FNS system designed for restoring mobility following a spinal cord injury. It demonstrates that there is little variability between animals in the location of activation pools relative to each other. Therefore, once a single activation pool is located, the location of the remaining pools may be promptly determined.

The location and spatial organization of the hamstrings, quadriceps, tibialis anterior and triceps surae/plantaris activation pools were found to coincide well with the location of the motor pools innervating the same muscles, as determined through chromatolysis and horseradish peroxidase studies [28], [29], [31], [32], [36], [44], [45]. Moreover, dimensions of the activation pools seemed to correlate well with published motor pool dimensions. For example, mean and standard error values for the medial-lateral, dorsal-ventral and rostral-caudal extents of the triceps surae/plantaris activation pool, scaled to reflect the average size of all cats in this study, were 0.6 ± 0.05 mm, 1.0 ± 0.1 mm, and 11.4 ± 0.3 mm, respectively. These were similar to values obtained from dimensional measurements of the lateral-gastrocnemius/soleus motor pool (0.6 ± 0.1 mm width, 0.8 ± 0.1 mm height, and 9.9 ± 0.9 mm length) performed by Van Buren and Frank [29] using retrograde chromatolysis as a cell body marker. Locations within the dorsal and intermediate regions of the gray mater did elicit muscle contractions when electrically stimulated. But, these interneuronal locations did not meet the activation pool criteria set forth in this study and

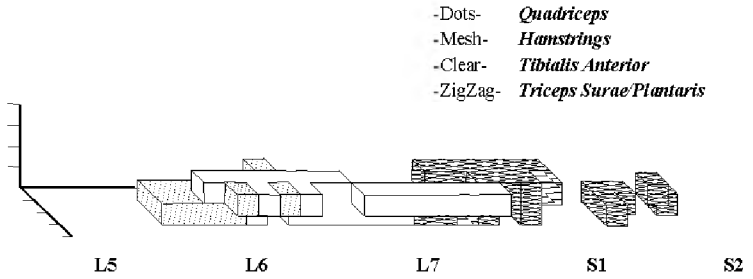

Fig. 9. Three dimensional representation of hamstrings (volume covered by crossed meshwork), quadriceps (dots), tibialis anterior (clear) and triceps surae/plantaris (zig-zag lines) activation pools in the left side of the ventral lumbo-sacral spinal cord. The plane formed by the dorsal-ventral (vertical) axis and rostral-caudal (long horizontal) axis falls on the midline of the cord. The plane formed by the medial-lateral (short horizontal) axis and the rostral-caudal axis is at the same depth as the bottom of the pools. Tick marks are 1 mm apart, and segment labels are positioned at the beginning of the corresponding spinal segment.

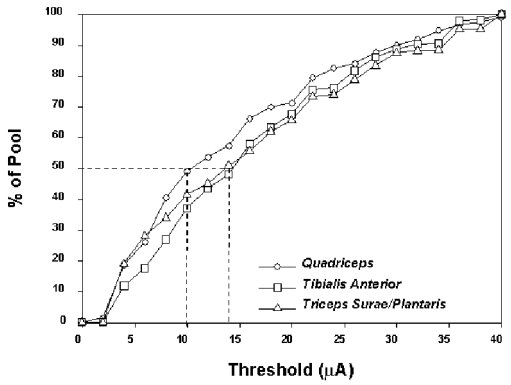

Fig. 10. Threshold stimulus levels. Shown are the cumulative distributions of stimulus levels in the quadriceps, tibialis anterior and triceps surae/plantaris activation pools at which activity was first detected in each of the respective target muscles. Dashed lines indicate that half of the sampled quadriceps activation pool locations had threshold currents of 10 μA or less, while half of the sampled tibialis anterior and triceps surae/plantaris activation pool locations had threshold currents less than 15 μA.

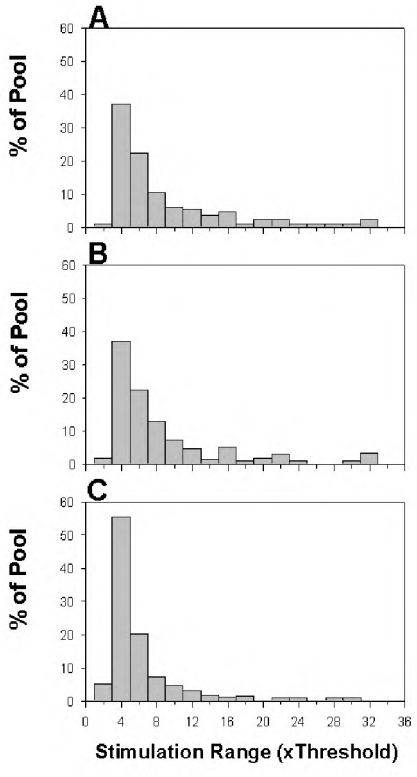

Fig. 11. Distribution of stimulation ranges in all sampled locations within the (a) quadriceps, (b) tibialis anterior, and (c) triceps surae/plantaris activation pools. Stimulation ranges are expressed as the ratio of the current at which contractions were detected in hindlimb muscles other than the target muscle (or 100 μA, whichever was lower) to the threshold current.

were therefore disregarded. The majority of interneuronal locations were activated with stimulus currents >40 μA, possibly due to the effect of sodium pentobarbital anesthesia on their level of excitability. Interneuronal locations that were activated with 40 μA or less did not meet the range criterion, possibly due to the role of some of these locations in interconnecting multiple motor pools. Selective and synergistic activation of muscles by microstimulating the intact, unanesthetised spinal cord of chronically implanted animals is discussed elsewhere [26].

The cross-sectional area of the activation pools varied along their longitudinal axis, giving them a general bead-like shape. Although we cannot prove that this is not an artifact of our sampling method and the technique used to outline the pool perimeters, the cross sectional area versus distance along the cord curves of the activation pools are similar to the cell density graphs constructed by Romanes [28] for motor pools innervating quadriceps, tibialis anterior and triceps surae/plantaris. A similar bead-like appearance of individual motor pools was also reported by Van Buren and Frank [29] and Burke *et al.* [31]. Furthermore, the general appearance of the combined map of activation pools shown in Fig. 9 coincides with the beaded shape of the segment L6 motor column presented by Testa [30].

The resemblance between activation and motor pools, in terms of their location in the spinal cord, dimensions and general structural appearance, and the low threshold currents needed to elicit muscle contraction, indicate that the electrical stimulation was primarily activating axon-hillocks (initial axonal segments of motor neurons) or motor neuron cell bodies, in the ventral horn [46]. The presence of activation pools, therefore, suggests the presence of spatially segregated clusters of motor neurons and fibers in the spinal cord that innervate individual muscle groups and are not contaminated by fibers

innervating other muscles. The relatively large stimulation ranges further supports the lack of contamination of the neural clusters by fibers innervating nonhomonymous muscles.

Since the activation pools in the cat closely correspond to spinal cord motor pools, it is likely that the relative organization of activation pools is the same for other mammalian species such as the rabbit [47] and the human [44], with the main difference being the rostral-caudal location of the pools relative to the spinal cord segments, implying that functional segregation is also maintained in other mammalian species.

B. Functional Implications

Our results demonstrate that the activation pools in the lumbo-sacral spinal cord are spatially and functionally segregated such that when they are electrically stimulated in the anesthetized or the unanesthetised, decerebrate cat [24], individual muscle groups in the hindlimb are selectively activated. Though the mapping in this study concentrated on finding locations in the spinal cord from which independent control of the main knee and ankle flexor and extensor muscles could be achieved, similar results would be expected for muscles controlling the hip.

Although the proposed stimulation site is novel, much of the existing work on peripheral stimulation for FNS can be applied to spinal cord stimulation. In particular, control strategies, including operation of biarticular muscles, developed for use intramuscular or nerve cuff electrodes, should be applicable to spinal cord FNS [48].

The relatively large stimulation range observed in our experiments suggests that spinal cord stimulation could produce smooth and graded muscle contractions. This is confirmed in the companion paper [27]. Specifications for an electrode array to be chronically implanted in the spinal cord electrode have been proposed based on the dimensions of the activation pools in the spinal cord, the force generated through spinal cord stimulation relative to maximum muscle force, and the extent of stimulus spread as a function of current amplitude [24].

The spinal cord in various vertebrate species contains complex circuitry responsible for producing involved motor outputs such as locomotor pattern generation and phasic-limb positioning [49]–[55]. Giszter *et al.* [56] have shown that stimulation of premotoneuronal networks produces a repertoire of "natural" or stereotyped movements in the frog's hindlimb involving multiple muscles. Such movements were triggered by stimulating through single electrodes implanted in dorsal and lateral 'neuropil' regions of the lumbar spinal cord [56]. Whether this would occur in bipedal mammals, such as humans, is problematical. The current study emphasized selective activation of individual functional muscle groups by stimulation of the spinal cord ventral horn gray mater. Such emphasis stems from the need to generate novel movement combinations and corrections in FNS applications. For example, selective activation of individual muscles would be desirable in situations such as standing up from a wheelchair and taking one or two steps to reach something, to use the toilet, or to get into bed.

Based on the relative arrangement and geometry of activation pools in the lumbo-sacral spinal cord, the force recruitment characteristics obtained through spinal cord microstimulation [27], interactions between electrodes implanted at varying distances in the spinal cord [24] and amount of tissue displacement due to electrode implantation [57], we proposed specifications for a spinal cord electrode array suitable for implantation in the lumbo-sacral spinal cord for the purpose of restoring mobility [24].

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