Selective Activation of Functional Muscle Groups through Stimulation of Spinal Motor Pools

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Abstract-**A microelectrode was used to stimulate motor neurons in the lumbo-sacral spinal cord of adult cats. Consistent with spinal cord anatomical studies, we found that the motor neurons responsible for activation of individual muscle groups are situated together in specific areas of the cord, forming motor pools. Localized spinal cord stimulation of these motor pools enables selective activation of individual muscle groups. By modulating the magnitude of stimulation at different sites in the motor pools, we should be able to selectively activate different muscle groups to produce desired levels of contraction and controlled limb movements.**

I. INTRODUCTION

Paralysis caused by spinal cord injury leaves the limb muscles and their innervating motor neurons intact below the level of the lesion. However, nerve impulses from the brain are unable to transverse the injured portion of the spinal cord to stimulate the motor neurons which activate the various muscle groups. We suggest that mobility can be restored to paralyzed individuals by artificially stimulating these motor neuron cell bodies in the spinal cord.

In order to restore meaningful mobility to paralyzed individuals, activation of single muscle groups must be controlled. Anatomical studies conducted by George Romanes [1,2] indicate that the motor neurons innervating a given hindlimb muscle are grouped together in the lumbo-sacral segment of the spinal cord forming a motor pool. In this study, we examined the feasibility of selectively stimulating individual motor pools with electrodes placed in the lumbo-sacral gray matter.

To accomplish this, we mapped the lumbo-sacral portion of the spinal cord to determine the exact location (depth and position in two dimensions along the length of the spinal cord) of the different motor pools. We then determined the threshold currents (the smallest currents eliciting muscle contraction) and the muscle groups involved at specific locations in the spinal cord. We also determined the stimulus intensity range over which only a single muscle group was activated at each site.

II. METHODS

Adult cats were anesthetized with sodium pentobarbital and held in a position allowing free movement of the hip, knee and ankle joints. The lumbar spinal column was stabilized with clamps, and a laminectomy was performed to expose the lower lumbo-sacral region of the spinal cord. A tungsten microelectrode was used to map the spinal cord by mounting it in a micromanipulator. A reference point on the midline of the spinal column was identified, and the spinal cord was stimulated at 1 mm increments relative to the established reference point using currents ranging up to 150 μA. Muscle groups contracting due to stimulation at these locations were noted. Both the magnitude of the threshold current and the stimulation range over which only one muscle group was activated were determined.

III. RESULTS AND DISCUSSION

Combined results from motor pool mappings of the lumbo-sacral spinal cord of five cats are shown in Figure 1. These graphs show the sites at which single muscle groups were activated. Only the points with threshold currents $\leq$ 20 μA, and stimulation ranges $\geq$ 5 times the threshold current are plotted in Fig. 1A. Raising the threshold current limit to $\leq$ 40 μA (Fig. 1B) increased the number of sites at which different muscle groups were activated, and generated a motor pool pattern that was consistent for all threshold levels beyond 40 μA.

These results demonstrate that functional muscle groups can be selectively activated by stimulating the gray matter of the spinal cord. The contraction strength of the muscle groups can be controlled by varying the amplitude of the stimuli applied at these sites and the number of electrodes stimulated.

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IV. CONCLUSION

Spinal motor pool stimulation utilized as a means of restoring mobility to paralyzed individuals requires a complete array of electrodes as shown in Figure 1. This array would consist of distributed sets of electrodes that activate individual motor pools. By using a distributed set of electrodes in a given motor pool, the strength of a muscle contraction can be controlled in two ways: (1) by changing the number of electrodes stimulated, and (2) by regulating the stimulus intensity through a specific electrode. Stimulation of the spinal motor pools also diminishes the amount of muscle fatigue associated with electrical stimulation by allowing rotation of the mechanical work throughout the different parts of the muscle [3]. Finally, the relative immobility of the spinal cord should minimize the degree of electrode encapsulation.

These findings establish a basis for the development of a multi-electrode neuroprosthetic device to be implanted in the spinal cord for stimulation of lumbo-sacral motor pools. A controlled and coordinated stimulation of these motor pools would activate only desired muscle groups, providing a means to generate meaningful limb joint movement. Before such a device can be developed, more experiments must be conducted to expand and refine the results presented here. The rostral distribution of the motor pools must be determined more precisely and the relationship between stimulus intensity and muscle force needs to be quantified.

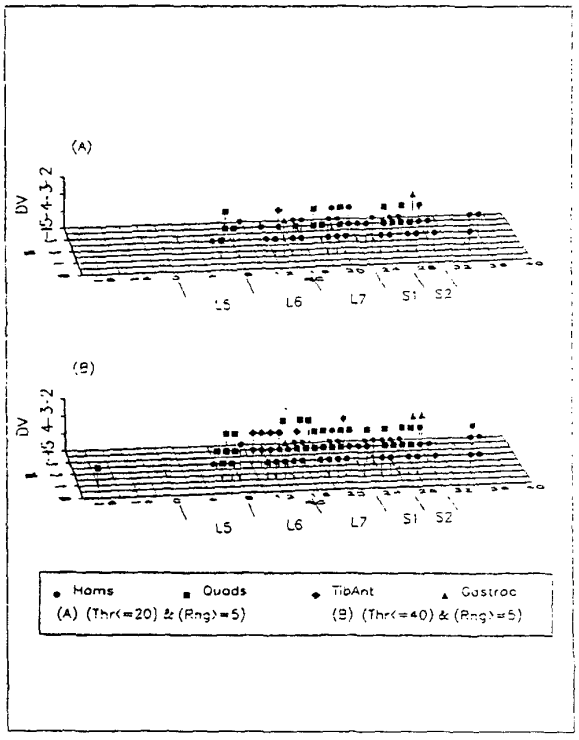

Fig. 1. Stimulation sites at which single muscle groups were activated. The three axes refer to the rostral-caudal (RC), the medial-lateral (ML) and the dorsal-ventral (DV) dimensions of the spinal cord. Muscles studied were the hamstring group (Hams), quadriceps group (Quads), lower leg anterior muscle group (TibAnt) and calf muscle group (Gastroc). (A) Threshold currents $\leq$ 20 μA and stimulation ranges $\geq$ 5x Threshold. (B) Threshold currents $\leq$ 40 μA and stimulation ranges $\geq$ 5x Threshold. The stimuli frequency was 50 Hz and the stimulus pulse duration was 200 μs.

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