Selective activation of muscles using peripheral nerve electrodes

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Abstract—*The feasibility of two methods for selectively activating muscles with peripheral nerve electrodes has been investigated. One method for achieving selectivity is to place a cuff electrode around the nerves to each group of synergistic muscles to be stimulated. A second method is to stimulate through pairs of electrodes selected from a multielectrode array placed around a common nerve trunk. Both methods have been tested in experiments conducted on four dogs. It was shown that the first method, cuff electrodes placed on individual motor branches, is an effective technique for selective activation. Thresholds of motor fibres lying outside of, but adjacent to, cuff electrodes are much greater than the stimulus amplitudes required to maximally stimulate motor fibres contained within the cuff electrode. Good results were obtained with a multielectrode array in two animals, but results were poor in a third dog. Electrode position and contact with the nerve were found to be important factors in achieving good selectivity.*

Keywords—*Electrical stimulation, Multielectrode arrays, Nerve electrodes, Selective stimulation*

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1 Introduction

IMPLANTED neuromuscular stimulators have been used to correct footdrop in 31 hemiplegic patients by stimulating the peroneal nerve and thereby activating muscles that dorsiflex the foot (WATERS *et al.*, 1975; MCNEAL *et al.*, 1977). The implanted hardware comprised a passive radiofrequency receiver placed in the medial thigh with a flexible lead wire extending to a cuff electrode that was wrapped around branches of the peroneal nerve just below the knee. A review of the long-term results of this clinical series was recently completed (WATERS *et al.*, 1985). Ten units still implanted in the surviving patients were functional 9–14 years after implantation.

One problem encountered with some of these patients was excessive inversion or eversion of the foot during dorsiflexion. Four muscles innervated by the peroneal nerve normally act synergistically to dorsiflex the foot. Two of these muscles also invert the foot while the other two evert the foot during dorsiflexion. In those patients in which a problem was observed, one of these two groups of muscles was apparently stimulated excessively, resulting in unbalanced dorsiflexion. This occurred despite wrapping the cuff electrode around selected branches of the peroneal nerve and demonstrating that balanced dorsiflexion of the foot was achieved during the surgical procedure.

It was felt that this method of correcting footdrop would be significantly enhanced if there was a way to electronically balance the contribution of these two groups of muscles postimplantation. Two methods of balancing the foot were proposed. One was to use a dual-channel receiver with two electrodes, one wrapped around motor branches to the two muscles that dorsiflex and invert the foot and the other wrapped around the branches to the muscles that dorsiflex and evert the foot. By adjusting the relative intensities of the two channels, correct dorsiflexion could be achieved. The second method considered was to use a single insulating sleeve wrapped around all four motor branches with an array of small electrodes positioned inside the sleeve†. Given a method for postsurgically selecting any of the electrodes to be the cathode and a second to be the anode, it should be possible to find a combination that produces the desired response.

Some results have already been reported that suggest the feasibility of the second concept. CALDWELL (1971) placed up to eight electrodes (each a 0·25 mm diameter, 1 mm long platinum wire) around the sciatic nerve of rabbits. Electromyographic (EMG) activity of the gastrocnemius and anterior tibialis muscles (both innervated by branches of the sciatic nerve) was recorded from a pair of wires inserted into each muscle. He reported that a combination of stimulating electrodes could usually be found to produce a contraction of one muscle without activating the other. EMG data presented, however, was limited to one rabbit, and no specifics of stimulus amplitude and electrode positions were given.

A six-electrode array (three stimulating and three earth electrodes) was used by PETROFSKY (1979) to selectively activate three distinct populations of neurons within cat sciatic nerve. Equipotential lines drawn from experimentally obtained data were shown to trisect the sciatic nerve into three similar pie-shaped sections; the implication being that neuronal populations in each of these sections could be selectively activated by stimulation through one of the three active electrodes. Single-fibre EMG data did indeed show that approximately one-third of 55 muscle fibres of the medial gastrocnemius were activated by each of the three stimulating electrodes with virtually no overlap; i.e. each

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†In this paper, 'cuff' and 'sleeve' are both used to describe an insulating cylindrical sheath placed around a peripheral nerve. For clarity, 'cuff' is used for the monopolar and bipolar configurations and 'sleeve' is used in conjunction with a multielectrode array

motor unit was excited by stimulation through one electrode but not excited by stimulation through the other two. These results would be compatible if the motoneurons innervating the medial gastrocnemius were distributed throughout the sciatic nerve so that one-third of the neurons were within the excitation zone of each of the three stimulating electrodes; however, this is not the case. Motoneurons of the medial gastrocnemius are localised within the sciatic nerve to one or a few fascicles (see, e.g. SUNDERLAND, 1968). This problem is not addressed by the author.

The purpose of the present study was to test the feasibility of selectively activating independent muscles with peripheral nerve stimulation using both of the methods described above. The muscles studied were those that flex and extend the ankle. Chronic and acute studies involving four dogs were conducted. Methods and results of these studies are presented. The implications of using each method to produce balanced dorsiflexion of the human foot are discussed.

2 Methods and procedure

Four mongrel dogs between 20 and 27 kg were used in this study. All animals were initially anaesthetised with intravenous Surital‡ (sodium thiamylal) for intubation and transferred to Penthrane§ anaesthesia (methoxyflurane) for the remainder of the procedure.

In one animal, a sterile technique was used to expose the sciatic nerves bilaterally from the midthigh to the popliteal fossa. The posterior tibial and peroneal branches were identified. Two bipolar cuff electrodes were implanted in the left leg, one around the posterior tibial nerve and the other around the peroneal nerve. The electrodes were flattened multistranded platinum wire 1·5 mm in width running parallel to each other with 4 mm separation inside a silicone rubber flap that was 11 cm wide*. When wrapped around the nerve, two circumferential bands were thus formed inside an insulating cuff. To guard against damaging the nerve the cuff electrodes were wrapped loosely around the nerve; the inner diameter of the electrode being approximately 50 per cent greater than the diameter of the nerve. Both electrodes were located above the knee just below the point where the nerves bifurcate from the sciatic nerve. At this location, both nerves are in close proximity to each other so that the exterior of each electrode was in contact with the adjacent nerve. Two monopolar cuff electrodes (a single multistranded wire inside a 7 mm wide flap) were positioned in the same way around the peroneal and tibial nerves in the right leg. Leads from all four electrodes were passed subcutaneously to a common point on the back. Excess lead wire was coiled and placed in a subcutaneous pocket. All incisions were closed and the animal was awakened. Twelve weeks later, the animal was reanaesthetised and the back incision was reopened for testing.

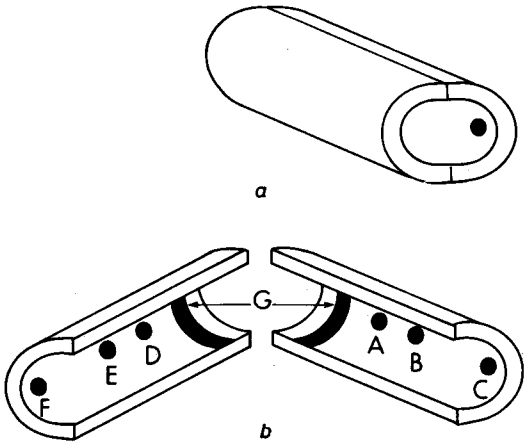

Fig. 1 *Multielectrode array inside an insulating sleeve used to test the selectivity of various electrode configurations: (a) closed as it would be when placed around the nerve and (b) opened to expose the electrodes. Dimensions, materials and procedures used to position the array on the nerve are described in the text*

†*Parke-Davis trademark*

§*Abbot Laboratories trademark*

**Manufactured by Medtronic, Inc., Minneapolis, MN*

In three other dogs, who were sacrificed at the end of the procedure, a nonsterile technique was used to similarly expose only the left sciatic nerve. A cylindrical plastic sleeve containing seven electrodes (Fig. 1) was positioned around the sciatic nerve proximal to the point of bifurcation into the posterior tibial and peroneal nerves. The sleeve, machined from Delrin†, was 8 mm in diameter and 18 mm long. The inner channel of the sleeve was elliptical in cross-section with dimensions of 3 × 4 mm. Six of the electrodes were circular silver electrodes 1 mm in diameter. Electrodes A, B and C were located on one half of the sleeve with a 3 mm spacing between the centres of A and B and a 6 mm spacing between the centres of B and C. Electrodes D, E and F were identically spaced on the opposite half of the sleeve. Electrode G was a silver band 1 mm wide that completely encircled the nerve when the two halves of the sleeve were sutured together around the nerve. The centre of the band was 3 mm from the centres of electrodes A and D. The multielectrode array was positioned for maximal selectivity by observing the EMG response when stimulating through selected electrode pairs. This position was determined at the beginning of the experiment and was not changed after data collection was initiated. After positioning the sleeve, the incision was closed for the duration of the experimental tests.

In all four dogs, bipolar wire electrodes were placed in each of four muscles of the leg for recording EMG activity. The wire was nylon-coated stainless steel 0·05 mm in diameter with approximately 2 mm at the tip deinsulated. Two of the muscles in which EMG was recorded, the gastrocnemius and soleus (ankle extensors), are innervated by the posterior tibial division of the sciatic nerve. The other two muscles, the anterior tibialis and peroneus longus (ankle flexors), are innervated by the peroneal branch. EMGs were recorded from all four muscles while stimulating through various combinations of electrodes. All tests were conducted while the animals were anaesthetised. In the chronic dog experiment, this was performed 12 weeks following implantation to allow tissue reaction to the cuff electrodes to stabilise.

In each case, the stimulus amplitude was increased to eight times the minimum motor threshold of the four muscles or until all four muscles were stimulated supramaximally. The pulse duration was fixed at 0·2 ms and the repetition rate was one pulse per second. The stimulator, built in our laboratory, was capacitively coupled and produced monophasic constant-current pulses.

All EMG signals were recorded using differential preamplifiers (Tektronix FM-122) and recorded on a Honeywell Visicorder. EMG responses to pulses of constant amplitude were very consistent and were either biphasic or triphasic in form. At each stimulus level, the maximum peak-to-peak value of the EMG was recorded and used as a relative measure of motor activity.

3 Results

In the chronic dog experiment, maximal stimulation of motor fibres of the nerve contained within any one of the four

†*DuPont trademark*

cuff electrodes was achieved without exciting neighbouring nerves outside the cuff. The range of stimulus amplitudes necessary to activate each muscle group (ankle flexors or extensors) using each of the four electrodes is shown in Fig. 2. The stimulation ranges are indicated by the shaded regions of the horizontal bars (cross-hatching for flexors and diagonal lines for the extensors). Each range is bounded on the left by the minimum stimulus amplitude which elicits a detectable EMG and on the right by the minimum amplitude at which the peak-to-peak EMGs of both muscles in the group were at least 80 per cent of the supramaximal value.

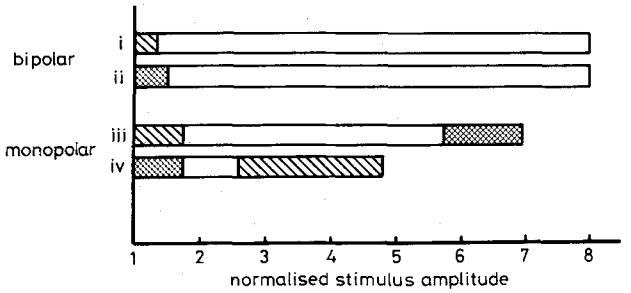

Fig. 2 *Stimulation ranges (0 to 80 per cent of maximum EMG) for the ankle extensors and flexors are shown when using each of four cuff electrodes: (i) bipolar electrode on tibial n., (ii) bipolar electrode on peroneal n., (iii) monopolar electrode on tibial n. and (iv) monopolar electrode on peroneal n. In each case, the stimulus amplitudes are normalised so that the minimum motor threshold is 1·0*
▨ *extensors* ▩ *flexors* □ *no overlap*

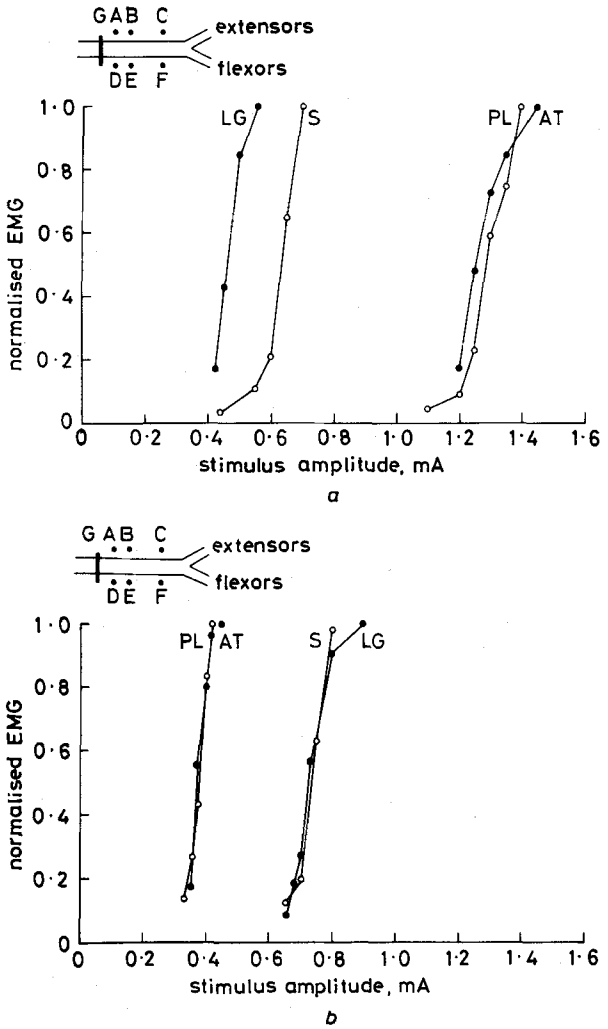

Fig. 3 *Normalised EMG plotted as a function of stimulus amplitude using the multielectrode array and (a) electrodes B and C for stimulation and (b) electrodes E and F for stimulation. The distal electrodes C and F were cathodic*

The value 80 per cent was used because it is more sharply defined than the point of maximal stimulation. In each case, the data were normalised so that the minimum motor threshold was 1·0.

The selectivity of the bipolar electrodes was particularly outstanding. No EMG activity was observed in the muscles innervated by the nerve lying just outside the electrode even when the stimulus amplitude was increased to eight times the minimum motor threshold of the nerves inside the cuff. The monopolar configuration was less selective, but equally as good from a functional standpoint. Using the monopolar electrode wrapped around the nerve branches innervating the ankle extensors, the motor threshold of the flexors was 3·3 times the amplitude required to elicit 80 per cent of the maximal EMG in the extensors. This ratio was 1·5 for the other monopolar electrode.

When using the bipolar configuration, the distal electrode was always the cathode. During monopolar stimulation, the electrode inside the cuff was the cathode, and a stainless-steel disk 2·5 cm in diameter placed under the skin of the animal's back was the anode.

Data recorded from one electrode combination of the multielectrode array in one of the three acute dogs (dog 2) is shown in Fig. 3 in which normalised peak-to-peak amplitudes of EMGs recorded from the four muscles are plotted as a function of stimulus amplitude. Stimulation through electrodes B and C (6 mm spacing), oriented on the side of the sciatic nerve containing the posterior tibial branch, produced maximal stimulation of both ankle extensors at a

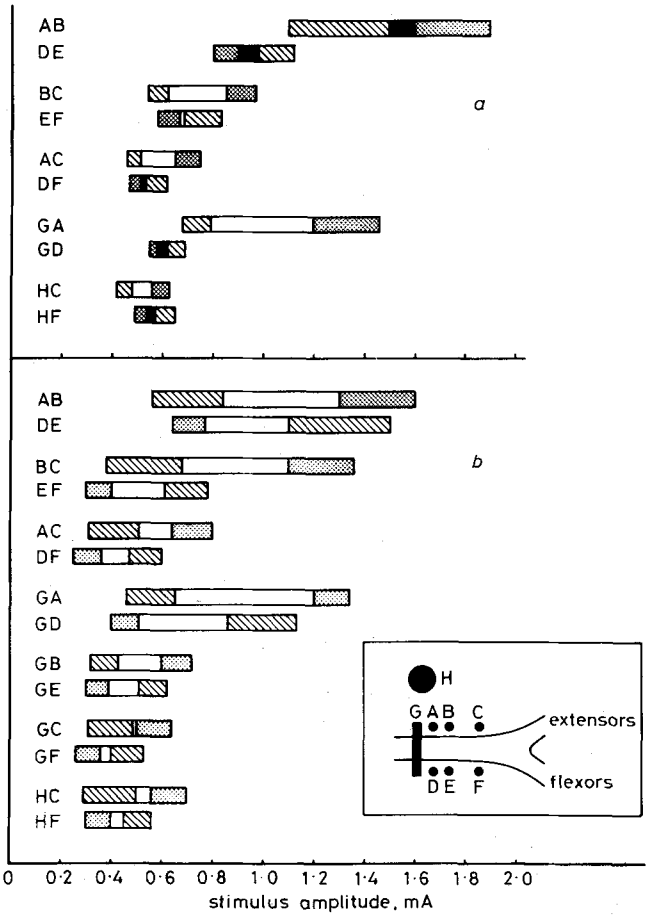

Fig. 4 *Stimulation ranges (0 to 80 per cent of maximum EMG) for the ankle extensors and flexors are shown when using various combinations of electrodes in the multielectrode array. The electrodes used in each case are shown at the left. The first and second letters identify the anode and cathode, respectively; (a) dog 1, (b) dog 2*
▨ *extensors* □ *no overlap*
▩ *flexors* ■ *overlap*

stimulus amplitude of 0·7 mA, well below 1·0 mA, which was the motor threshold of the ankle flexors (Fig. 3*a*). Using electrodes E and F on the opposite side of the nerve, the ankle flexors were maximally stimulated at an amplitude of 0·45 mA, again well below the 0·6 mA motor threshold of the antagonist muscles (Fig. 3*b*).

Data for these and a number of other electrode combinations are summarised in Fig. 4 for two of the acute dogs. As in Fig. 2, the range of stimulus amplitudes for each muscle group extends from the motor threshold to 80 per cent of the maximum peak-to-peak EMG. In this case, however, the abscissa is not normalised, and so the values of the stimulus amplitude required for excitation with each electrode combination are clearly shown. For electrode configurations in which the stimulation ranges of the flexors and extensors overlap, the overlapping region is indicated by black shading.

The electrode array was oriented so that the band (electrode G) was proximal to the other electrodes. Electrode configurations tested were two circular electrodes on the same side of the nerve with interelectrode spacings of 3, 6 and 9 mm and the band electrode with one circular electrode with spacings of 3, 6 and 12 mm (only the 3 mm spacing was tested in dog 1). In all cases, the distal electrode was selected to be the cathode. A monopolar configuration, in which a circular electrode was used as the cathode and the anode was a stainless-steel disk 2·5 cm in diameter (electrode H) placed under the skin in the animal's back, was also tested.

In dog 1, separation of the extensor and flexor responses is seen in all cases in which the cathode is on the side of the sciatic nerve containing the tibial branch (electrodes A, B or C) except for configuration AB (Fig. 4*a*). The results were not as good when the cathode was on the opposite side near the peroneal branch (electrodes D, E or F). Complete separation is seen only for configuration EF. Nonseparation is clearly illustrated by the solid black shading.

It is interesting that the stimulation ranges of the extensor muscle group are lower when the cathode is on the 'flexor' side of the nerve for the cases in which electrode separation is 3 mm (configurations AB, DE and GA, GD). Since these cases involve only electrodes at the proximal end of the sleeve, it may be that the peroneal and tibial branches were not well oriented with the array at the proximal end.

The results are much better with dog 2. Separation of the extensor and flexor responses is seen with every electrode configuration tested (Fig. 4*b*). As expected, selectivity was enhanced when the electrodes were closely spaced (configurations AB, DE and GA, GD). The poorest results were obtained when the band was used with a circular electrode at a spacing of 12 mm (GC, GF) and with the monopolar configuration (HC, HF). Thresholds are significantly higher for the 3 mm spacings, and so a 6 or 9 mm spacing may be preferred as a compromise that provides good selectivity and low stimulation ranges.

The results were not good in the third acute dog. In this animal, it was impossible to position the electrode array to obtain stimulation of one group (extensors or flexors) without stimulating the other group. In this animal, the nerve was smaller than in the other two dogs and fit loosely in the array.

4 Discussion

The ability of the cuff electrode to stimulate peripheral nerves inside the cuff without stimulating nerves outside the cuff was nicely demonstrated by this study. Four cuff electrodes, two bipolar and two monopolar chronically implanted for three months, maximally stimulated muscles innervated by motor fibres inside the cuff without exciting motor fibres lying just outside the insulating cuff. It should, therefore, be quite easy to obtain balanced dorsiflexion of the foot by wrapping one electrode around nerve branches innervating muscles that dorsiflex and invert the foot and a second electrode around branches that dorsiflex and evert the foot. A balance control to vary the relative stimulus amplitude to both electrodes should allow total control over the full range from inverted to normal to everted dorsiflexion.

The feasibility of using an array of electrodes contained in a single insulating sleeve to selectively stimulate the ankle flexors and extensors has also been demonstrated. A completely successful outcome was achieved in only one of three dogs, but in that one case excellent selectivity was demonstrated for a number of electrode configurations.

Two factors appeared to be extremely important in achieving selective stimulation with the multielectrode array: electrode position and direct electrical contact with the nerve. While positioning the electrode array, it was subjectively observed that results were altered significantly as the array was rotated around the nerve. Even with careful positioning of the array, poor results were obtained if the electrodes were not very close to or in direct contact with the nerve. This was evident with dog 3. In this case, the sciatic nerve was significantly smaller than the inner opening of the array, and it was impossible to maintain contact between the nerve and both sides of the array. The poor results achieved may have been attributable to this.

On the basis of these studies, it is possible to conclude that two closely spaced electrodes, properly positioned near the nerve, can be used to excite a population of nerve fibres close to the electrodes without exciting populations at a distance. The required separation between the populations to be stimulated and those not to be stimulated was not determined in this study. The sciatic nerve was used because it is organised into separate tibial and peroneal bundles; thereby ensuring that motoneurons innervating the ankle extensors would be close to electrodes on one side of the multielectrode array and motoneurons innervating the ankle flexors would be close to electrodes on the opposite side of the array. How well these results can be generalised to other cases is not known.

If selective stimulation is to be achieved, the results of this study suggest that an electrode array of closely spaced electrodes should be placed around the peripheral nerve so that each electrode is in close contact with the outer surface of the nerve. Various combinations of electrodes could then be tested to determine the degree of selectivity achievable at different stimulus intensities. Electronically, this could be done quite easily postimplantation with electronic switching using a digitally coded radiofrequency signal to select electrode combinations. The difficulty would be in designing a sleeve that maintained all electrodes in contact with the nerve without constricting the nerve or its blood vessels. Implantation techniques for cuff electrodes still follow the procedure advocated by GLENN *et al.* (1970) in which the electrode is positioned loosely around the nerve to permit postoperative swelling of the nerve and perineural tissue without compressing the nerve. Obviously, new ideas and techniques will be required to achieve intimate contact between electrodes and peripheral nerve in chronic applications.

While a multielectrode array like the one described above may permit selective stimulation of populations of nerve fibres near the perimeter of the nerve, selective activation of fibres near the centre of the nerve may be possible only with electrodes which penetrate the epineural sheath surrounding the nerve. Two types of penetrating electrodes have been

proposed for peripheral nerve stimulation. One is an eight-electrode stimulation array developed for implantation in the eighth cranial nerve for an auditory prosthesis (WHITE, 1980). A second electrode that has been tested in animals is a coiled wire electrode that is drawn into the nerve with a 1·7 cm long 30 gauge needle (BOWMAN and ERICKSON, 1985). Penetrating electrodes have also been used for intracortical (SCHMIDT and MCINTOSH, 1979) and spinal cord stimulation (NASHOLD *et al.*, 1972).

In the footdrop application, a nonpenetrating electrode array inside a sleeve surrounding the common peroneal nerve should be capable of producing balanced dorsiflexion. It is not necessary in this application to achieve total separation of the stimulation ranges of the muscles that invert and evert the foot; only a proper balance between these two muscle groups is required. Given a number of electrodes inside the sleeve (probably no more than three to six would be required) and a method to select any two of these as the anode and cathode, it should be possible to find at least one combination that results in a balanced foot.

In summary, the feasibility of using cuff electrodes or a multielectrode array to balance foot dorsiflexion has been demonstrated. The approach of wrapping two cuff electrodes around selected branches of the peroneal nerve and using a dual-channel stimulator would appear certain to achieve the desired result. Use of an electrode array would require a more complex electrode. Positive results are likely but would not be guaranteed.

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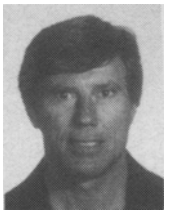
Authors' biographies



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