Biomechanical Response in the Ankle to Stimulation of Lumbosacral Nerve Roots with Spiral Cuff Multielectrode

—Preliminary Study—

Roman BOŠNJAK, Vinko V. DOLENC, and Alojz KRALJ*

*Department of Neurosurgery, University Hospital Center, Ljubljana, Slovenia;
Faculty of Electrical Engineering, University of Ljubljana, Ljubljana, Slovenia

Abstract

Biomechanical response in the ankle to tetanic stimulation of the lumbosacral root was investigated to assess the potential for lower limb functional neurostimulation. Myotomal response in the leg was measured as the three-dimensional isometric torque in the ankle after extradural tetanic stimulation of the L3–S1 roots exposed surgically for herniated disc removal in five patients. The cuff multielectrode was employed to investigate functional topography of the roots by monopolar, bipolar, and tripolar electrode configurations. Four response patterns in the direction of three-dimensional torque vectors were observed. The L-5 and S-1 roots had the same response pattern, but S-1 roots produced stronger torques. Dorsiflexion torque was not obtained by stimulation of L-5 roots despite coactivation of the tibial anterior and peroneal muscles. Dorsiflexion torques were produced only by stimulating the L-4 roots. More selective bipolar and tripolar stimulations recruited force at higher thresholds and less gain. Additionally, some muscles were not activated by tripolar stimulation of the same root. In one L-4 root, the torque at lower electrical threshold was replaced by inverse torque at higher threshold, providing indirect evidence that different muscles may have motoneuron populations that differ in diameter or location within the root. Although dorsiflexion and plantarflexion torques are functional per se, they are accompanied by foot inversion and leg rotation torques (as well as proximal muscle contractions). Further experimental investigations on direct extradural stimulation of lumbosacral roots, either single or in combination, are recommended to explore the potential of lumbosacral nerve root stimulation for restoration of leg function.

Key words: lumbosacral root, electrical stimulation, functional electrical stimulation, neurophysiology, contraction force, torque

Introduction

Restoration (or enhancement) of (residual) locomotion in upper-motoneuron-injured patients can be achieved by electrical stimulation of paralyzed muscles or peripheral nerves with superficial or implantable electrodes.[2,5,10,11,15,22,27] The difficulty in daily placement of numerous electrodes and also achieving selective and reliable muscle contraction (especially of deep-seated muscles) by superficial electrodes can sometimes be solved by implantation of epineural,[10,22,24,27] intraneural[20] or indwelling intramuscular,[15] or epimisial electrodes.[21] All current methods and types of implanted electrodes for ar-

tificial restoration of motor control have subjective, surgical, and technical obstacles.[11,22,25,26] Breakage of long conductor cables and electrode dislocation of multichannel implantable electrode systems demand repeated servicing accompanied by extensive surgical interventions.[2,15,22,25,26]

Stimulation of the peripheral nerves at their most proximal parts, in the region of the cauda equina or extrathecal nerve roots, may allow control of the whole lower limb musculature from a single confined intraspinal space. However, interfascicular plexification of peripheral nerves and roots demands more selective ways of stimulation of strictly confined regions in the nerve trunk or root to study the functional topography.

The multicontact spiral cuff electrode can activate

discrete populations of nerve fibers by creating a highly focal electric field within the nerve trunk employing electrode configurations other than monopolar cathodic stimulation.[21,24,28,32,33] Separation of foot dorsiflexion from plantarflexion was possible using the cuff multielectrode in the animal ishiadic nerve.[19,28] However, the functional topography of the lumbosacral roots has not been studied with the spiral cuff multielectrode.

There are a limited number of studies of direct electrical stimulation of surgically exposed roots (extradurally[6,16,29] or intradurally[9,23,25,26]) or spinal nerves by less invasive transcutaneous needle near-nerve stimulation.[12–14,18,31] Direct stimulation studies of spinal roots and spinal nerves have confirmed modern concept of distribution of segmental motor innervation and the concept of multiple innervation of most muscles.[9,23,26,29] However, the biomechanical response of myotomal muscles at high power levels cannot be predicted from such electrodiagnostic data or clinical deficit studies. In voluntary contraction, a group of synergistic muscles can be selectively activated. In whole root stimulation, all agonist and antagonist muscles of the myotome are activated together. The net torque, direction of movement, and joint stiffness depend not only on the cross-section area and innervation ratio of the antagonist and agonist but also on the moment arms, complex geometry of the joints, intrinsic muscle properties, pre-stretch of muscles, trajectory of muscle contraction force, and many other variables.

Interest in the biomechanical response to direct stimulation of lumbosacral roots has arisen from recent trends in lower limb functional neuromuscular stimulation promoted by technological progress in seeking multifunctional restoration by means of implantable and multichannel programmable stimulators and electrode development.[5,11,21,22,25] The potential of stimulation of the lower lumbar nerve roots for restoration of leg function at the dural root sleeve[34] has not yet been explored in humans.

This preliminary study measured three-dimensional (3D) ankle torques to test different coactivation patterns of leg muscles due to monopolar, bipolar, and tripolar stimulation of L3–S1 roots. This new approach allows study of the internal topography of the lumbar spinal roots based on their functional response to direct electrical stimulation.

Methods

The 3D isometrical torques in the ankle were measured during extradural stimulation of the L3–S1 roots (n = 7) with a multielectrode spiral cuff. The roots were exposed at surgery for removal of her-

niated disc. Only patients with lumboishialgic syndrome and minimal or absent clinical and neurophysiological signs of motor root injury were operated on after unsuccessful conservative treatment of at least 3 months duration. Muscular force in the ankle was graded M5–M4+ on manual testing. All patients had root compression due to herniated disc confirmed by myelography and computed tomography. Patients with chronic root lesions, neuromuscular disorders, systemic diseases, and ankle injuries were excluded. The subjects were informed of the procedure and signed informed consent forms. The research and the text of the informed consent were approved by the Slovene Official Committee for Medical and Ethical Matters.

Total intravenous anesthesia with propofol (50–100 mg/kg/hr) and fentanyl (1–3 μg/kg/hr) was induced and maintained by intravenous drip infusion. A single bolus of the short-lived relaxant vercuronium (half-time 15 min) was given to the patient for easier endotracheal intubation at induction of
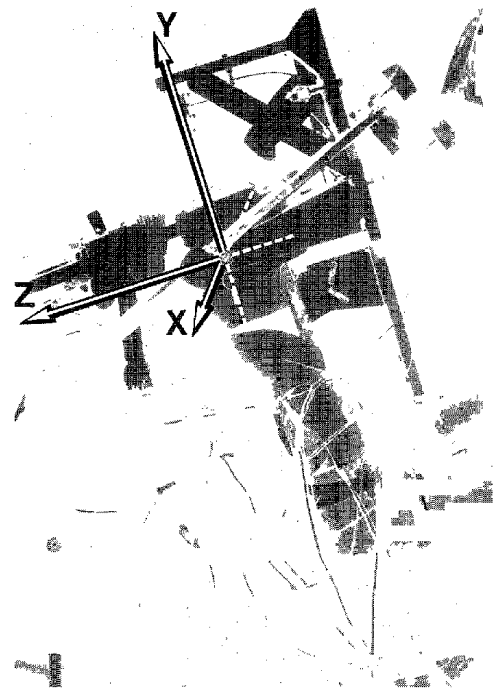
Fig. 1 Patient position and device placement for intraoperative detection of three-dimensional ankle torques, Mx, My, and Mz, caused by direct stimulation of nerve roots with a cuff multielectrode. X denotes the orthogonal axis of plantarflexion/dorsiflexion of the foot; Y, foot and leg internal/external rotation; and Z, foot inversion/eversion.

anesthesia and at least 60 minutes before root stimulation.

The patient was put in the prone position with hip flexion of 40° and knee flexion of 90°. An L-shaped brace, firmly attached to the operating table by a grid, was placed from above onto the dorsal side of the leg and sole to obtain the 3D torque in the ankle (Fig. 1). The brace for 3D ankle torque measurements was developed in collaboration with the Laboratory for Biocybernetics (head L. Vodovnik, Eng., Ph.D.), Faculty of Electrical Engineering, University of Ljubljana and Institute Josef Stefan, Ljubljana, Slovenia. The details of the brace construction are explained elsewhere.[30] The reproducibility of the device was not less than 97.2%, linearity was ±5%, and sensitivity was 100 g. The 3D ankle torque (M) was expressed as the orthogonal torque value in the X, Y, and Z axes of the ankle. $+Mx$, $+My$, and $+Mz$ denote the orthogonal torques in the direction of dorsiflexion of the foot, the foot and leg external rotation, and the foot eversion. $-Mx$, $-My$, and $-Mz$ denote the orthogonal torques in opposite directions.

Fenestration was performed under the operating microscope. Hemilaminectomy was performed only in Patients 1 and 4 because of sequestrated disc material and two roots were exposed and stimulated. The correct intervertebral level was checked by diascopy in all patients. After herniated disc removal, the cuff multielectrode was wrapped snugly around the decompressed spinal root for stimulation.

The self-curling spiral cuff was fabricated by modifying the method of Naples et al.[21,22,24,33] The bilayered silicone rubber cuff included 12 recessed poles of 3 × 1 × 0.035 mm platinum plates (99.99% purity), each with a separate insulated lead. The internal diameter was 5 mm to fit the range of diameters for the human L-5 and S-1 roots. The distance between the platinum plates was 0.8 mm. The cuff width was 7 mm. Each silicone rubber layer was 0.1 mm thick. The cuff multielectrode was manufactured by J. Rozman, Eng., Ph.D., Center for Implantable Technology and Sensors, Ljubljana, Slovenia. Fabrication of the cuff electrodes is explained in detail elsewhere.[21,24,33]

The classical form of the cuff was modified by the first author for the purposes of this study by appending the "tongue" and the "tail" to the cuff to enable safe wrapping and final positioning of the cuff around the root in the deep operative field (Fig. 2 upper). A curved ligature passer (Yasargil Model FD270; Aesculap, Tuttlingen, Germany) was used to draw a surgical thread under the root first. The thread was previously stitched to the tail of the cuff.
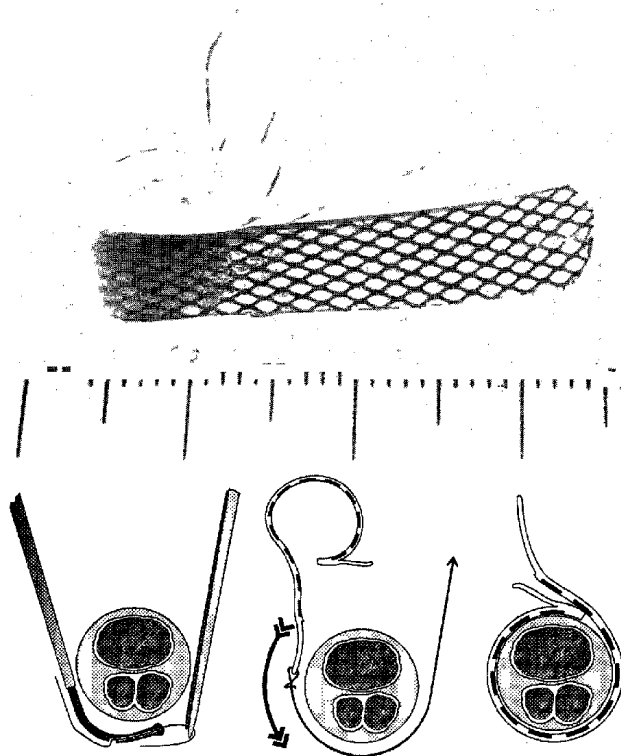
Fig. 2 Multielectrode spiral cuff (upper) and the technique for convenient and safe cuff placement around the dural root sleeve (lower).

The cuff was then gently pulled by the thread under the root from the lateral to medial side of the root and allowed to curl snugly around the root (Fig. 2 lower). By manipulating the tongue and tail of the cuff with two bipolar forceps the final orientation and adaptation of the cuff on the root was possible in this very small and very deep operative field. The first innermost electrode of the cuff was always placed on the dorsal top of the root at the 12 o'clock position as shown in Fig. 2. Generally, 9–10 stimulating electrodes were in contact with the whole circumference of the root. The final position of the cuff was secured with wet cotton and the operative field was irrigated with 0.95% saline solution.

Monopolar stimulation used each electrode as the stimulating cathode. The needle of a surgical wire suture was used as the common neutral anode and was inserted into the capsule of facet joint. The 12 leads were then consecutively connected to the constant current stimulation unit of a Neuropack Four Mini Model MEB-5304K (Nihon Kohden, Tokyo). Only cathodes with biomechanical response

thresholds <1 mA (or more in some roots) were tested completely by a train of 20 monophasic rectangular impulses at 20 Hz in 0.2 mA steps from the threshold to saturation of the biomechanical response. The tetanic force of the 20 Hz train was 92–100% compared to 30 Hz train and fatiguing was minimized. The pulse duration was 0.05 msec.

Bipolar stimulation was performed in two roots, and tripolar stimulation in one root. Only one cathode (with the lowest activation threshold) per root was tested with bipolar and tripolar stimulation. Neighboring electrodes were employed as anodes for bipolar and tripolar (a central cathode and an anode on each side) stimulation.

Bipolar surface detection of compound muscle evoked potentials (CMAP) was achieved by a pair of Ag-AgCl electroencephalography (EEG) disc electrodes (Evoked EEG Electrode Kit NE-121J; Nihon Kohden) or a pair of self-adhesive electrodes (Pals 879100R; Axelgaard Manufacturing Co., Fallbrook, Calif., U.S.A.). These electrodes were placed 2 cm apart over the bellies of the muscles tibialis anterior, peroneus longus, gastrocnemius medialis, and lateralis, hamstrings, quadriceps, and gluteus maximus. Indwelling 80 μm wire electrodes with noninsulated tips were used only for the posterior tibial muscle under sterile conditions. CMAPs were detected at 50–100 μV/div, bandpass 20 Hz–3 kHz, sweep time 30 seconds. Each of the seven channels of the amplifier was individually amplified according to signal strength after pre-test stimulation. There was a pause of at least 1–1.5 minutes between each electrode position testing during storage of digitized data on the computer hard disk. The stimulation and detection units were optically isolated from the main electrical power.

Anesthesia induction, patient positioning, surface electrodes, and leg brace placements took altogether 40–45 minutes, and surgery required an additional 20–30 minutes. The testing protocol took 30–40 minutes. There was a pause of at least 3 minutes between each stimulus train. Each train was triggered in a free-hand mode.

Results

Roots were most excitable on their ventral aspect. The threshold for the biomechanical response at the ventrally located cathodes was <1.6 mA, except for 3 mA in the L-4 root of Patient 2. Lateral to the optimal stimulation site, the thresholds to evoke ankle torques ≥1 Nm increased steeply. Generally 4–8 cathodes were tested per root. This produced a family of 4–8 sigmoid curves of torque recruitment per root. The recruitment curve from the lowest

threshold cathode had the steepest slope. Torque detection preceded detection of electromyographic (EMG) activity. The EMG activity of each recorded muscle started simultaneously at nearly identical threshold values and saturated quickly. More laterally positioned cathodes (away from the lowest threshold cathode) had higher thresholds for detecting CMAPs.

Four patterns of biomechanical response according to torque vector orientation were obtained upon monopolar stimulation of roots L3–S1 (Fig. 3). The L-5 and S-1 roots produced the same response. Dorsiflexion torque (+Mx) was caused by stimulation of the L-4 root, but not the L-5 root.

Monopolar, bipolar, and tripolar stimulation were comparatively tested in Patient 3 at the same cathode position (Fig. 4). Recruitment curves of each orthogonal torque started at higher thresholds and their slope was less by bipolar and tripolar stimulation. The EMG activity of all recorded muscles occurred simultaneously at proportionally higher thresholds. In addition to the decreased CMAP amplitudes and increased thresholds, EMG activity of some muscles (hamstrings and tibialis posterior) was not detected by tripolar as compared to bipolar and monopolar stimulation. Recruitment was not tested to suprathreshold levels in this case.

Plantarflexion torque (−Mx) was inverted to dor-
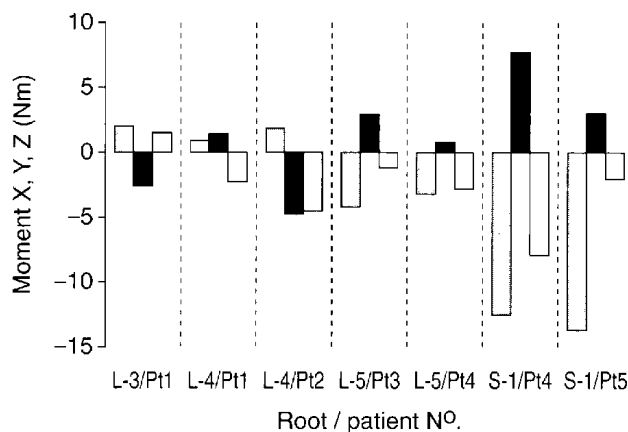
Fig. 3 Biomechanical response patterns in the ankle caused by direct stimulation of roots L3–S1 presented as triplets of orthogonal isometric torques, X (shaded bars), Y (closed bars), and Z (open bars). Maximal torques in five patients are shown. X, Y, and Z bars in the triplets denote torque (M) direction: +Mx, dorsiflexion; +My, external rotation of foot and leg; +Mz, eversion; −Mx, plantarflexion; −My, internal rotation of foot and leg; −Mz, inversion.
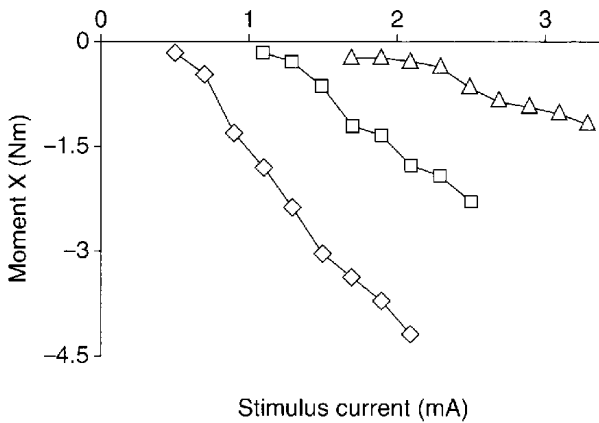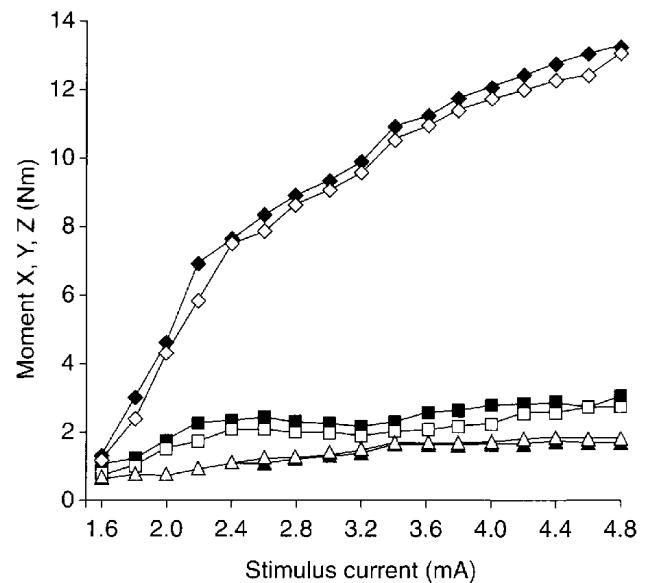
Fig. 4 Influence of bipolar (□) and tripolar stimulation (△) on recruitment of isometrical ankle torque in Patient 3. Only the Mx torque is shown for clarity. ◇: monopolar stimulation.
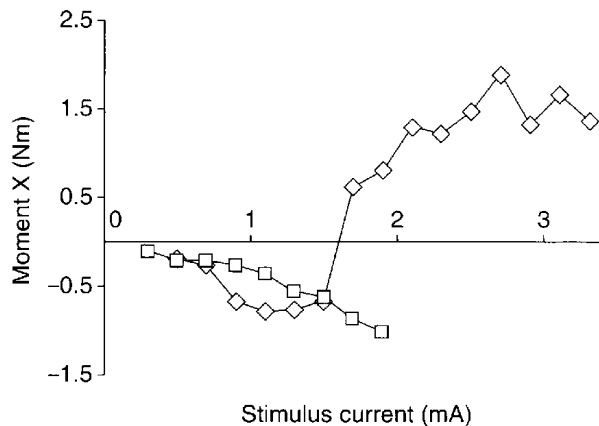
Fig. 5 Inversion of Mx torque vector by monopolar stimulation (◇) in Patient 2. □: bipolar stimulation.

Fig. 6 Three-dimensional ankle torque values caused by extradural root stimulation by cuff multielectrode at the beginning (closed symbols) and at the end (open symbols) of measurements (test-retest in Patient 5). ◇, ◆: recruitment curve of X torques; □, ■: recruitment curve of Y torques; △, ▲: recruitment curve of Z torques. Torque direction is not shown.

siflexion torque (+Mx) in Patient 2 when strong EMG activity in the anterior tibial muscle appeared at the threshold value of 1.6 mA (Fig. 5). However, bipolar stimulation at the same location of that root produced only plantarflexion torque up to 1.8 mA and no electric activity had appeared in the tibialis anterior muscle, but stimulation was not performed higher than 1.8 mA.

The biomechanical responses observed upon root stimulation with multicontact spiral cuff were very consistent. The reproducibility of responses was tested only in Patient 5 at the E10 cathode position (Fig. 6). During a 12-minute period the root was fully tested at locations E10, E11 (broken), E12, and E9 in steps of 0.2 mA. Good reproducibility of

results and only minimal cumulative fatigue was found.

Discussion

The spiral cuff multielectrode wrapped around the dural sleeve enables electrical stimulation of discrete populations of nerve fibers under the electrode.[19,21,22,24,28,32] Low electrical thresholds at ventrally positioned cathodes are consistent with the ventral position of the anterior roots in the dural sleeve.[1,7] Sensory roots occupy double the cross-section area in the dural sleeve compared to motor roots.[3,7] Tetanic stimulation from the dorsal site of the root will thus not produce motor response, but will produce reflex responses in single pulse stimulation and in paraplegics.[26]

Comparison of the ratios of individual torques versus stimulus current indicates that at maximum forces they are practically the same for each cathode position. Only the thresholds of activation of muscles vary with cathode position. Mx, My, and Mz torques recruit proportionally at each cathode position, but slower at cathode positions lateral to the cathode with the lowest threshold of the root.

We conclude that nerve fibers related to any lower limb muscle are distributed randomly in the ventral part of the root or that selectivity of monopolar stimulation was insufficient to activate different populations of nerve fibers within the root. However, replacement of a torque at lower electrical thresholds by inverse torque at higher thresholds may be indirect evidence that different muscles have motoneuron populations that differ in diameter or location within the root (Fig. 5). Large motoneurons are excited at lower currents than smaller ones. Torque redirection is expected only upon stimulation of roots that innervate predominantly dorsiflexors, like L-4 and L-5, but not S-1. This phenomena of movement redirection has already been noted upon intradural stimulation of some anterior roots.[26]

Bipolar stimulation offered qualitatively similar results to monopolar stimulation in Patient 3. Torques were weaker at higher thresholds (Fig. 4), but the same muscles were active. Tripolar stimulation did not activate some of the muscles (hamstrings and tibialis posterior; data not shown) at all. The superior selectivity of transverse tripolar stimulation over bipolar and monopolar ones has been computer modeled.[4] However, the potential of tripolar stimulation for spatially selective activation of discrete populations of nerve fibers within the root should be tested to suprathreshold levels in more patients in the future.

The biomechanical response in the ankle due to L-5 root stimulation was not the same as that expected from segmental innervation tables or electrophysiological studies.[12,22,29] Based on electrophysiological data and clinical deficit studies, the L-5 root is expected to cause foot dorsiflexion and the S-1 root to cause foot plantarflexion on stimulation.[9,25] Electrophysiological parameters can be completely misleading when stimulation was submaximal and nontetanic or based only on comparisons of amplitudes of muscle evoked potential.[9,25]

Foot dorsiflexion torques were present only upon L-4 root stimulation (Fig. 3). In L-4 root stimulation, the true foot dorsiflexors (tibialis anterior, peroneus tertius, extensor hallucis longus, extensor digitorum longus) are unopposed by the triceps surae, tibialis posterior, flexor hallucis longus, and flexor digitorum longus muscles. In L-5 root stimulation, the tibialis anterior and peroneal muscles were coactive, but their action was surpassed by the stronger foot plantarflexors. Because the triceps surae muscles have a biomechanical advantage due to long leverage, a small electrical activity can be accompanied by strong plantarflexion torques in the ankle. Although response pattern upon L-5 and S-1 root

stimulation was the same (plantarflexion + leg lateral rotation + foot inversion), net torques tended to be much stronger upon S-1 than L-5 stimulation (Fig. 3).

The X-torques caused by L-4 and S-1 root stimulation are sufficient for foot clearance at toe-off phase and for push-off phase and body propulsion in simple hybrid walking of selected patients with spinal cord injury.[2] However, they are accompanied by inversion torques and leg external rotation torques (Fig. 3). Leg external rotation torques are produced by the lateral hamstrings and peroneal muscles. These torques were overestimated in our study because of the flexed knee position and foot immobilization during measurements. Strong hip abduction upon L-5 and knee flexion upon S-1 stimulations were observed.

Patients with disc herniation have a pre-existing injury of the root due to compression by the extruded disc material, and unavoidably interfered with the results. There is no single parameter for grading root injury from chronic compression[16] or retraction.[17] To minimize the influence of root compression injury, only patients with minimal or absent clinical and electrophysiological signs were selected. However, quantification of the injury by amplitude of muscle-evoked potentials is impossible because the exact innervation pattern of the individual root is unknown in each individual. However, prolonged latency of muscle-evoked potential and higher threshold are correlated with root injury.[16,17]

Extradural sites[1,3] might provide a more stable and safe location for chronic implantation than intradural sites.[5,25,26] The dura of the sleeve shows less inflammatory reactivity than epineurium to artificial material. However, reoperations have shown strong adhesions are present epidurally, extending from the paravertebral space. In contrast to intradurally placed electrodes,[5,26] the epidurally placed cuff is much less mobile and is supposed to provide more stable responses over longer time periods. Intradural booklet electrodes cannot be secured to the gracile and free floating rootlets and the thresholds vary over time.[26] Arachnoidal adhesions may make removal of the electrodes from the dural sac impossible in case of malfunction due to electrode encapsulation or meningitis without destroying the rootlet. Serious mechanical injury to the intradural anterior rootlets may occur at surgical implantation.[26] Spread of excitation to other roots is unlikely upon extradural whole root stimulation. Current intensities of more than 20 mA produce excitation spread to other roots epidurally.[8] The present study found saturation of ankle torques at

<5 mA in all roots and no cross talk between roots was observed. Finally, not all roots must be stimulated as not all muscles need to be superficially stimulated for simple hybrid walking.[11] Every surgeon is aware of the difficulties in identifying ventral roots in the cauda equina to their exit levels,[1] especially in a single level upper-lumbar laminectomy.[26] Root identification problems, posture-related reflex responses, and excitation spread to other roots (as well as biological variability) may explain the somewhat different responses in the ankle caused by anterior L-5 root stimulations[5,26] in spastic humans and extradural stimulation of whole L-5 roots in our study.

The cuff electrode provided a stable interface between the electrode and the excitable tissue and a stable recruitment pattern in the present study. We did not notice any additional morbidity from cuff placement or stimulating current. The multielectrode cuff is a valuable research tool for studying the functional topography of the root in a living human. Further experimental studies will be necessary to evaluate the capacities for extrathecal stimulation of lumbar roots, single or in combination, for restoration and enhancement of locomotion in patients with upper-motoneuron-injury with functional electrical stimulation.

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Address reprint requests to: R. Bošnjak, M.D., Department of Neurosurgery, University Hospital Center, Zaloška 7, 1525 Ljubljana, Slovenia.

Commentary

The important fact to learn in this article is that extradural placement of a spiral or circular cuff is not only feasible but effective and stable over a long time. When indeed, the problem is confined to a single nerve root, the circular placement of multiple electrodes can provide very effective stimulation to involve only the sensory aspect of the root. Within a single nerve root, the sensory components occupy twice as much of the cross sectional area. In addition, they clearly lie dorsal. So with multiple electrodes, bipolar stimulation can indeed provide selective responses. This would avoid any changes in other roots within the cauda equina. The authors are encouraged to continue their work. Obviously certain movement disorders and pain disorders will utilize these techniques in the future.

Thomas B. DUCKER, M.D.
Department of Neurological Surgery
Johns Hopkins University
and University of Maryland
Maryland, U.S.A.

The authors describe a technique, utilizing a multicontact spiral cuff electrode, to stimulate the nerve trunk or root selectively. This paper offers hope that further studies on this technique may help us to refine stimulation procedures in restorative neurosurgery. The authors also report a technique, employing biomechanical responses of the joint, for the determination of myotomal topographic representations of stimulated spinal roots. While the electromyographic (EMG) technique has commonly been employed for evaluating motor nerve function, monitoring of actual biomechanical responses is far more reliable.[1] Since recent advances in neurosurgical anesthesia have enabled stable muscle activity to be maintained intraoperatively, it may be that this kind of monitoring technique can be further refined and utilized more frequently in the future.

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Yoichi KATAYAMA, M.D.
Department of Neurological Surgery
Nihon University School of Medicine
Tokyo, Japan

These authors propose an interesting new approach to study internal topography of lumbar spinal roots using three types of extradural stimulation and measuring three-dimensional (3D) ankle torque. A cuff electrode was wrapped around the decompressed spinal root for monopolar, bipolar, and tripolar stimulation. Both 3D ankle torque and compound muscle activity from several muscle groups of the leg were measured. Results of the study revealed various response patterns, indicating that the ventral aspect of the nerve root was most excitable at stimulation levels of 1.6 to 3 mA. There were some inconsistencies of response to the three different polarities of stimulation. In addition, the results are scattered because data collection from all subjects was not systematic. The highest specificity of response arose from the tripolar stimulation technique. However, during locomotion, the sequence of muscle recruitment to be

carried out may require that two adjacent electrodes be stimulated simultaneously. This renders the tripolar technique impossible, as an electrode cannot be used as a cathode and anode at the same time and use of two adjacent electrodes as cathodes causes the specificity of stimulation to be lost. In addition, because of the variability of conditions causing leg dysfunction, including spinal cord injury, stroke, chronic nerve root compression, and the accompanying muscle deterioration, we are interested in knowing how subjects will be selected for application of this technique. For example, the stimulus threshold of chronically compressed nerve roots significantly exceeds those of normal roots and can exceed 10 mA,[1] levels of stimulation not used by Bosnjak et al. If higher stimulus levels are required, then cross talk among cuff electrodes may occur. All these factors combined with the large inter-individual differences in nerve root topography make this method extremely complex, and it will be interesting to see whether this technique holds the same promise as other methods. From this reviewers' point of view, a substantial amount of additional research is required to determine which combination of electrodes, stimulus levels, and sites results in a systematic and predictable response. However, the authors should be congratulated for proposing an interesting method for extradural stimulation of nerve roots, thus avoiding some of the problems caused by chronic intradural placement. We look forward to further research following this preliminary study, and to ways of resolving some of the complex problems mentioned by the authors.

Reference

1) Holland NR, Lukaczyk TA, Riley LH III, Kostuik JP: Higher electrical stimulus intensities are required to activate chronically compressed nerve roots. Implications for intraoperative electromyographic pedical screw testing. Spine 23: 224–227, 1998

Robert W. KEITH, Ph.D.
and Angela BOTTLEY, B.S.
Department of Otolaryngology
University of Cincinnati College of Medicine
Ohio, U.S.A.
John M. TEW, Jr., M.D.
Department of Neurosurgery
University of Cincinnati College of Medicine
Ohio, U.S.A.

Biomechanical response to ankle tetanic stimulation of the lumbosacral root was investigated to assess the potential for lower limb functional neurostimulation. Myotomal response in the leg was measured as the three-dimensional isometric torque in the ankle after extradural tetanic stimulation of the L3–S1 roots exposed surgically for herniated disc removal in five patients. They observed that the L-5 and S-1 roots had the same response pattern, but S-1 roots produced stronger torque. Dorsiflexion torque was not obtained by stimulation of L-5 roots despite coactivation of the tibial anterior and peroneal muscles. Only stimulating L-4 roots produced dorsiflexion torque. The authors concluded that although dorsiflexion and plantarflexion torques are functional per se, they are accompanied by foot inversion and leg rotation torques. Basically we share the same impression that the placement of electrodes around lumbar roots and stimulation might be efficient in patients with upper motor-neuron injury. However, such an invasive experiment during lumbar disc surgery aimed at functional recovery would not be approved anywhere in Japan.

Tadashi KOJIMA, M.D.
Department of Neurosurgery
Mie University School of Medicine
Mie, Japan

This unique clinical study shows us the important neuroanatomical and neurophysiological fact that a single joint motion is not simply correlated with single nerve function, but is based on remarkably complicated motor innervation. The authors are trying to quantify the myotomal response of the dorsiflexion or plantarflexion in the ankle in which those movements were often accompanied by foot inversion and leg rotation torques.

The most important issue in this study is how this methodology can be put into clinical practice. In the single spinal root, there are many nerve fibers which innervate different muscles. Direct stimulation study has shown that the antagonist of muscles innervated by some fibers in a spinal root is also innervated by other fibers in the same spinal root. The spiral cuff multielectrode developed by the authors may be very effective for stimulation of the each small fiber groups in the root, and this methodology can be used as a diagnostic tool to evaluate the precise functional status of the root. For the development of neuroprostheses for the restored function of the extremities after spinal cord injury or cerebral stroke, much accumulation of knowledge regarding the biomechanical response to stimulation of the spinal root is important.

Toshisuke SAKAKI, M.D.
Department of Neurosurgery
Nara Medical University
Nara, Japan