
FUNCTIONAL ELECTRICAL STIMULATION AND SUPPRESSION OF SPASTICITY FOLLOWING SPINAL CORD INJURY*

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IT IS WELL KNOWN THAT AFTER the upper motor neuron has been damaged by injury or disease of the spinal cord or brain, the lower motor neuron may continue to work independently without cerebral control and to produce involuntary movements of the paralyzed limbs. Understanding of this involuntary motor activity, i.e., spasticity, is limited, but it is known to be influenced by certain factors (Table I) intrinsic to the central nervous system, i.e., inhibition and facilitation, the pathologic lesion itself, and the influence of chemicals. It may also be affected by extrinsic factors, mostly nociceptive stimuli from various organ systems. Sometimes this involuntary activity may be excessive and result in severe chronic, tonic spasticity that makes all movements and activities difficult or impossible, and at other times it may result in sudden severe spasms that throw the person off balance with only minimal or no apparent stimulus. Most people with spasticity, fortunately, have less of a problem: deep tendon reflexes are exaggerated and reactive muscle activity occurs mostly upon sizeable stimulation.

For a long time clinicians have been battling unsuccessfully to suppress severe spasticity to increase comfort and function, while, during the last decade, almost paradoxically, researchers have been trying to harness involuntary motor activity for a useful purpose. What follows is a brief status report on these two different clinical tasks, i.e., suppression of severe spasticity by new technology and functional electrical stimulation. Both tasks are highly relevant to most physiatrists.

MANAGEMENT OF SPASTICITY BY INTRATHECAL BACLOFEN

Spasticity has never been elegantly defined, but Lance's definition¹ is better than most: "A motor disorder characterized by a velocity dependent increase

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TABLE I. SPASTICITY: INFLUENTIAL FACTORS

A. Intrinsic to nervous system
1) Physiologic facilitation/inhibition
2) Pathologic lesion: type, location, etc.
3) Chemical influences
B. External to nervous system
1) Urinary tract infections, stones, etc.
2) Bowel impaction, hemorrhoids, etc.
3) Pressure sores
4) Tight garments, wheelchairs, etc.
5) Muscle and joint lesions: Contractures, tears, sprains, etc.
6) Other: Heterotopic ossification, deep vein thrombosis, etc.

in tonic stretch reflexes (muscle tone) with exaggerated tendon jerks resulting from hyper-excitability of the stretch reflex, as one component of the upper motor neuron syndrome." More important than definition is recognition that spasticity caused by cerebral lesions in many ways differs from spasticity caused by spinal cord lesions, or myelopathy. These may differ with respect to the clinical presentation as well as with respect to the response to different medications.

It has long been recognized that severe spasticity may interfere with function and comfort. Many attempts have been made to find an effective way to suppress spasticity without generating major damage to the nervous system and without losing important reflex functions. One problem that has constantly hampered clinical research efforts has been inability accurately and reliably to assess and measure spasticity. Many assessment tools have been devised (Table II) with various degrees of subjectivity/objectivity and ease of application, but few investigators seem to agree which method is scientifically most sound. It has at times appeared best to use a number of scales simultaneously and to average all the results. One scale, however, appears to be emerging in many clinical studies as the most commonly used assessment tool, i.e., the Ashworth Rigidity Scale, which often is used in combination with the Spasm Frequency Score.² Both tools are highly subjective.

The management approach to spasticity involves several steps (Table III). Treatment methods vary widely in terms of invasiveness, neurological damage, and risk to the patient. This paper will only address treatment with the medication that is probably most commonly used to treat spasticity, i.e., baclofen (4-amino-3(4-chlorophenol)-butanoic acid, Lioresal (TM)). Since its introduction in the 1970s baclofen, given orally, has proved an effective medication in the treatment of spasticity secondary to myelopathy, i.e., spinal cord injury, multiple sclerosis, syringomyelia, etc. In contrast, it is clinically relatively ineffective in the treatment of spasticity caused by cerebral lesions.

TABLE II. SPASTICITY: ASSESSMENT METHODS

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- 1) Questionnaire for self-assessment
 - Count spasms
 - Grade spasticity and spasms
 - Interference with activities of daily living, comfort, etc.
 - 2) Clinical examination
 - Grade muscle tone (e.g. Ashworth scale)
 - Deep tendon reflexes:
 - Grade amplitude of muscle contraction
 - Grade force of tendon tap
 - Count clonic contractions
 - Joint range of motion assessment
 - Grade flexion withdrawal response
 - Assess function (activities of daily living, ambulation)
 - Measure joint angle at appearance of stretch reflex
 - 3) Dynamometry
 - Measure force required to overcome muscle resistance
 - 4) Electrophysiological tests
 - Surface electromyography to monitor spasms
 - Electrical stimulation of nerve, muscle, or tendon
 - Grade muscle force, amplitude, relaxation time
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TABLE III. SPASTICITY: MANAGEMENT STEPS

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- 1) Establish diagnosis and severity
 - 2) Consider indications/contraindications
 - 3) Prevent and treat nociceptive stimuli
 - 4) Rehabilitation techniques:
 - Muscle stretching program
 - Wrapping, casting, splinting, bracing
 - Physical exercise: Neurofacilitation, endurance
 - Position and posture
 - Modalities: Heat, cold, stimulation
 - 5) Nerve blocks: Motor point, nerve, root
 - 6) Medications
 - 7) Surgical procedures
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Thousands of patients in the United States are receiving treatment with oral baclofen. Unfortunately, oral baclofen, even when exceeding the maximum recommended daily dose of 80 mg per day, fails to control spasticity in 25–30% of cases. It has been stated that “the main reason for failure appears to be the low concentration of the drug and similarly of other anti-spastic agents at the site of action within the CNS after systemic administration.”³

Baclofen is much more effective if applied in high concentrations locally to the spinal cord and cauda equina.³ This can be accomplished by administering the drug by means of a programmable implanted pump via a catheter to the lumbar subarachnoid, i.e., the intrathecal space.

A recent study described 20 patients with disabling spasticity and spasms

caused by spinal cord injury and multiple sclerosis despite intake of oral baclofen, 40–200 mg per day.² Intrathecal administration of baclofen objectively reduced muscle tone in all patients and diminished spasms in 18 or 19 patients. Subjectively, function and comfort improved. No drowsiness or confusion occurred and no infections relating to this treatment were observed. However, two catheters became dislodged, one pump failed, and one patient experienced pain at implantation site. This method thus appears to provide an effective suppression of severe spasticity with fewer side effects.

Before implantation of the pump, each patient should be evaluated carefully and further trial with oral medications attempted if indicated. If judged a proper candidate for intrathecal baclofen, the patient is admitted to the hospital, a bolus of intrathecal baclofen given by lumbar puncture and, if effective and without side effects, the pump is inserted. Postoperatively the most effective infusion rate needs to be determined before discharge. Periodic returns for radio frequency monitoring and refilling of the pump are scheduled once a month initially. It is of particular interest that the amount of intrathecal baclofen required for effect is only a fraction of that required by oral administration, usually one tenth to one milligram per day, which may explain the fewer side effects.

FUNCTIONAL ELECTRICAL STIMULATION

Electricity has been used in medicine for centuries for various clinical purposes. Indeed, electricity is one of the principal physical agents utilized by physical medicine. While there are multiple purposes for the use of electricity, my topic is limited to “restoration of limb function.”

Functional electrical stimulation has a history of at least 30 years. In the mid 1950s Liberson, a physiatrist in Connecticut and later in Hines, IL, started simple clinical experiments on his patients where he used electricity to stimulate muscles in both the upper and lower extremities to obtain gross motions, i.e., wrist extension, gross grasp, and ankle dorsiflexion.⁴ Several investigators took interest in his work and a few years later in Cleveland, Ohio, another physiatrist, Charles Long, a recognized expert in hand rehabilitation, designed “an electrophysiologic splint for the hand” in which he used electrical stimulation to obtain extension of the fingers within a basic wrist hand orthosis equipped with an automatic spring for closure.⁵ These early efforts, however, were limited by many technological shortcomings. By the late 1960s considerable testing and associated research was underway in at least two American institutions, i.e., Case Western Reserve university in Cleveland and Rancho Los Amigos Rehabilitation Center in Downey, Cali-

TABLE IV. FUNCTIONAL ELECTRICAL STIMULATION SYSTEM:
MAJOR COMPONENTS

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|---|
| 1) Electrical stimulator, multi-channel |
| 2) Energy source |
| 3) Computer for open or closed loop control (hardware/software) |
| 4) Wires and electrodes (surface/implanted) |
| 5) Sensors: Force impact, joint angle, muscle fatigue, etc. |
| 6) Organism—body part receiving stimulation |
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fornia. With rapid progress in computer technology and microprocessing, new clinical opportunities opened for functional electrical stimulation. It was speculated that walking could be accomplished for spinal cord injured individuals by stimulation in proper sequence all the muscles used during the ordinary gait cycle. During the mid 1970s two new groups became rather prominent in functional electrical stimulation research, one in Ljubljana, Yugoslavia, and the other at Wright State University in Dayton, Ohio. One had in the early 1980s, grabbed national attention, both in medical circles, but particularly in the media, which of course dramatized this technology and inappropriately raised the hopes of the disabled. Premature as all this publicity may have been, it generated a spurt of interest and inflow of research funds into the field of functional electrical stimulation that has helped to advance its technological side considerably.

In recent years functional electrical stimulation technology has been used to improve limb function in three major areas: upper extremities for grasp and release, lower extremities for ambulation, and lower extremities for active exercise to improve physical fitness and health. The major components of such a system are listed in Table IV. In each of these categories, great needs for research still exist but as a physician I believe that in particular the response of living organisms to prolonged electrical stimulation has to be better investigated before such systems become clinically useful and marketable. This research needs to focus both on the muscle response and the entire physiological response to prolonged exercise.

FUNCTIONAL ELECTRICAL STIMULATION FOR UPPER EXTREMITIES

Cervical spinal cord injury causes paralysis of the upper and lower extremities. Paralysis of the upper extremities most consistently involves the hands and thus limits the individual's functional skills and vocational potential. Physiatrists have traditionally focused on improving upper extremity functions through several different approaches, i.e., teaching new techniques, strengthening residual muscles, maintaining joint range of motion, providing

TABLE V. UPPER LIMB FUNCTIONAL ELECTRICAL STIMULATION: SELECTION CRITERIA⁵

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- 1) Quadriplegia C5 and C6, lower motor neuron preserved at C7,8
 - 2) Skin sensation in hand
 - 3) Good vision
 - 4) No voluntary muscles available for transfers to create grasp and release
 - 5) Medically and neurologically stable
 - 6) Stable trunk while sitting in wheelchair
 - 7) High motivation for improvement of hand function
 - 8) Realistic and emotionally stable
 - 9) At least one year and post injury
 - 10) Strong family support
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orthotics and adaptive equipment, surgical reconstruction, and, most recently, by functional electrical stimulation.

Fundamentally, there are two key components of upper extremity function, i.e., positioning of the arm in space and grasping and releasing objects from the hand. One or both of these components may be lost with cervical spinal cord injuries, and traditional rehabilitation methods may not provide adequate restoration of function.

In 1963 Long first described a system for upper extremity functional electrical stimulation.⁵ Where surface electrical stimulation provided finger extension, an orthosis provided stabilization of the wrist, thumb, and interphalangeal joints, and a spring at the metacarpal-phalangeal joints generated a flexion torque. Using chin switch the patient controlled the stimulation. Unfortunately, due to rapid muscle fatigue and the uncosmetic appearance of the device, it was rejected by most users. Regardless of the relatively poor early success, upper extremity functional electrical stimulation research continued. The technology has vastly improved, and today many individuals with high quadriplegia, mostly those with neurological levels at C5 and C6, have been successfully fitted with upper extremity functional electrical stimulation systems. The patient criteria for upper limb stimulation are quite specific (Table V),⁶ and functional restoration requires both surgical expertise and, for the patient, lengthy training (Table VI).

The desired functional movements with such systems are hand grasp/release, although elbow flexion and extension may also be desired in some cases. Control of muscle force upon contraction is regulated by recruitment modulation, most commonly controlled by the duration or width of the primary stimulus pulse. The hand muscles are thus activated either in a synergistic or an antagonistic pattern to move the fingers through the desired trajectory. Different voluntary command sources may be used to control the entire coordinated movement, but one group of investigators has found that

TABLE VI. UPPER LIMB FUNCTIONAL ELECTRICAL STIMULATION: PROCESS

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- 1) Selection of appropriate candidate
 - 2) Establish accurate functional goals
 - 3) Electrode implantation and stabilization
 - 4) Initial training and programming
 - a) Electrical exercise program
(8 hrs/day at 12.5 hz)
 - b) Prehension patterns developed
 - c) Control parameters developed
 - 5) Training in functional activities
 - 6) Evaluation and follow-up
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for this purpose contralateral shoulder movement is optimal: rapid, precise, and repeatable.⁶ Here a position transducer is placed on the contralateral shoulder. Voluntary shoulder motions are transduced to a chest-mounted shoulder position sensor, where they are converted to logical and proportional signals. Surgically implanted (percutaneous) electrodes are preferable to superficial or surface electrodes, but the electronic receiver/stimulator has heretofore been placed external to the body except for one reported case, where it was surgically implanted.

In some quadriplegic subjects upper limb surgical reconstruction with tendon transfers and anastomosis and arthrodeses of certain finger joints has been long shown clinically to augment function. Such reconstruction recently has also been used in combination with functional electrical stimulation. Here spastic muscles paralyzed by upper motor neuron lesions and lying close to flaccid paralyzed muscles are used for tendon transfers in a manner identical to the traditional transfer of tendons from voluntary contracting muscles. These muscles are subsequently stimulated electrically in a similar fashion as the other spastic muscles for functional purposes.

FUNCTIONAL ELECTRICAL STIMULATION FOR AMBULATION

One of the earliest applications of functional electrical stimulation was to provide an electrical stimulus to ankle dorsiflexors in a hemiplegic extremity during the swing phase of gait. It was not until the 1970s that work was started to enable paraplegics to walk by means of electrical stimulation. During the 1980s, as systems improved, hundreds of paraplegic individuals in the United States and abroad have learned to walk by this means.

The clinical requirements of a complete system are described in Table VII.⁷ Unfortunately, no system as yet meets adequately all requirements, and therefore no system has yet been marketed for clinical use. In concept, functional electrical stimulation systems for ambulation may differ in several

TABLE VII. FUNCTIONAL ELECTRICAL STIMULATION AMBULATION:
CLINICAL REQUIREMENTS

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- 1) Safety: No burns, fractures, infections, etc.
 - 2) Reliability: No failure of parts of system
 - 3) Function: Speed, distance, different surfaces
 - 4) Low energy cost
 - 5) Easy to use: Maintenance, don/doff, training
 - 6) Cosmetic
 - 7) Acceptable cost
 - 8) Patient clinically appropriate
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ways with respect to the components used. Electrodes may be either surface or percutaneous intramuscular. Most have found that percutaneous intramuscular electrodes are preferable because they reduce the number of electrodes required, give better muscle selectivity, especially of deep muscles, provide more consistent muscle response, and cause less skin irritation. Percutaneous electrodes, unfortunately, also have several problems. Marsolais⁷ has reported a 45% failure rate three months after insertion and 60% in six months as well as infections and occasional burns. Control may be either an open or closed loop. In an open loop control system, preprogrammed patterns of electrical stimulation are generated for a specific function and for a specific individual, but there is no automatic correction for changes in muscle contraction and environment. In a closed loop control system, the computer receives feedback information from sensors about a particular motion and institutes remedial action or gives a warning if motion is not possible. Several systems offer a manual control over certain movements, frequently by switches attached to the walker. The number of channels used may vary between four and 48 although most commonly either four or eight channels for muscle stimulation have been used. The number of preprogrammed physical activities also may vary widely. Some only allow a single activity, whereas more sophisticated systems may allow as many as 24 different activities, i.e., standing, walking, climbing and descending stairs, different exercises to perform, etc. Sensory feedback may be obtained simply by using residual sensory functions, i.e., visual auditory, vestibular, vibration, etc. or, in more sophisticated systems, by placing artificial sensors in the paralyzed limbs that can feed back information regarding joint positions and pressure on the limb to the computer. Orthoses of different designs are used today by most of the systems to provide joint stability, to prevent injuries, to reduce oxygen consumption, and to increase control and to reduce the number of electrodes required. The orthoses may vary in design from a simple ankle-foot orthosis to a full-length leg brace, e.g., the reciprocal gait orthosis.

Gait aids, i.e., canes, crutches or walkers, are usually required since good standing and ambulation balance cannot be provided by functional electrical stimulation even with sensors and close loop control. Initially, most systems rely on walkers for balance.

To provide effective functional ambulation by means of electrical stimulation, Marsolais⁷ has described numerous clinical concerns that need to be addressed. **Safety:** Burns have occurred both with superficial and percutaneous electrodes. With the latter, the burns usually happen when there is a break of connectors between the percutaneous electrode and the external stimulator. Fractures of bones are rare, but have occurred. No major falls while ambulating have been reported. **Reliability:** The electrical stimulus must be consistently effective and generate the proper amount of muscle contraction. Thus, failure of either parts of the system or of the total system should not occur. **Function:** To ambulate functionally, the patient has to be able to obtain an acceptable speed of gait, to be able to travel significant distances, and to negotiate different surfaces, i.e., stairs and inclines. The usual speed of ambulation has been reported to be between 12–18 meters per minute⁸ with a maximum speed of 50–60 meters per minute in outstanding individuals. The usual reported distance traveled on level surfaces is 100–200 meters with maximum distance approximately 400 meters.⁷ Most functional electrical stimulation systems are programmed for ambulation on level surfaces, although the more sophisticated systems allow patients to ascend and descend stairs and inclines. Walking parallel to an incline, however, presents a major problem. **Energy cost:** It has been found that oxygen consumption during both standing and walking with functional electrical stimulation systems is two or three times higher than similar activities for nondisabled people.⁹ This, however, is no higher oxygen consumption than that measured for paraplegics using knee-ankle-foot orthoses (long leg braces) and crutches for ambulation. Additionally, it appears that as the speed of functional electrical stimulation ambulation increases there is little change in the oxygen consumption.⁹ Thus, functional electrical stimulated walking does seem to compare favorably to ambulation with long leg orthoses and crutches. **Ease of use:** Care of percutaneous electrode sites may often take as much as 30 minutes daily, and the application of the system takes on the average 15 minutes.⁷ Before being able safely to use the systems, four to six weeks of intensive training is required. Although many components of the system have been miniaturized, the size of the system is still significant and may interfere with performance of various activities. A total failure of the system is relatively infrequent. Cosmesis is improving but still not adequate. Cost is still unknown, but predictably will

TABLE VIII. FUNCTIONAL ELECTRICAL STIMULATION AMBULATION:
PATIENT CRITERIA

1) Paraplegia with upper motor neuron lesion (T4-T11)
2) Impaired sensation
3) Spasticity minimal or moderate
4) Joint range of motion within normal limits
5) Good health
6) Psychologically appropriate

be high, given the need for bilateral leg orthoses in addition to the functional electrical stimulation system and to legal liability issues that have to be addressed before marketing.

Patient selection requires that certain criteria be met (Table VIII). Patients with T4-T11 lesions are the ideal candidates, but unfortunately these represent a small minority of all patients with spinal cord injuries. Quadriplegics and those with flaccid paralysis in general would not qualify. Quadriplegics constitute approximately 55% of the spinal cord injured population, and thoracolumbar fractures resulting in lower motor neuron lesions add approximately 20%. Thus, paraplegics with T4-T11 level cord lesions would constitute no more than 25% of the entire spinal cord injured population.¹⁰ Obviously, not every T4-T11 paraplegic would be able to use the system because of the various exclusion criteria, i.e., lower motor neuron lesion, age, obesity, joint contractures, spasticity, medical problems, poor response to electrical stimulation and inadequate motivation. The potential user population for functional electrical stimulation ambulation systems thus is relatively small.

In one study⁸ all 500 spinal cord injured patients admitted during a nine-year period were evaluated for functional electrical stimulation use and a system prescribed and customized when indicated. Of this group, 76 patients (15.2%) were selected, 26 with incomplete cord lesions and 50 with complete lesions between T4 and T12. Only half or 25 patients with complete cord lesions were able to walk by this means. Of these, nine patients stopped using the system for ambulation but 16 patients remained ambulatory, representing only 3.2% of the total number of spinal cord injured patients admitted. The study did not specify what happened to the patients with incomplete lesions who used the system. Given the current state of technology, it thus appears that only the exceptional paraplegic will be able to use these systems for community ambulation.

FUNCTIONAL ELECTRICAL STIMULATION EXERCISE FOR FITNESS

Functional electrical stimulation has found its widest clinical use as means to provide strengthening and endurance exercise for muscles paralyzed by

upper motor neuron lesions to improve physical fitness and health. This is still controversial because of the high cost of training and of the device and because many of the claimed clinical and functional benefits have not been adequately documented.

The question may be raised why clinicians should prescribe this form of treatment for spinal cord injured patients. Physiatrists and allied health rehabilitation specialists have not always been consistent in what they say and do, and they are not always the unbiased advocates for physically disabled people that they believe they are. Physiatrists are usually quick to prescribe appropriate exercise and fitness programs for their patients without paralysis, but with different musculoskeletal symptoms or evidence of cardiovascular deconditioning, and usually obtain good results. On the other hand, physiatrists usually say to patients newly paralyzed by injury or disease of the nervous system, "We will strengthen your voluntary muscles, we will teach you self care skills, we will provide equipment for you and we will passively stretch your paralyzed limbs to prevent contractures." Exercise for comfort, fitness, and health is rarely mentioned.

This is a disturbing attitude and suggests a lack of concern, shallow thinking, or even discrimination given the obvious needs of this disabled population. Every day, it seems, evidence is mounting that even modest physical exercise can improve health and increase longevity. Large population studies have been published in prestigious journals¹¹ and abstracted in major newspapers. Benefits of even modest physical exercise long suspected are now recognized and, in many aspects, proved. No group of people, generally young and healthy, spends a greater part of their lives being sedentary than people with spinal cord injuries. Quadraplegics and paraplegics also may suffer from various symptoms of inactivity (Table IX), become ill, and even die from diseases linked to sedentary life. Their main cause of death is no longer renal failure but pulmonary and cardiovascular conditions.¹⁰

It is well known that endurance exercise that activates the largest muscle mass is the optimal exercise to induce cardiovascular fitness and most of its documented health benefits. While upper extremity exercises for spinal cord injured people may be of considerable value, i.e., arm cranking and wheelchair racing, it is probable that lower extremity exercise through functional electrical stimulation may be preferable because it involves larger muscle mass and does not stress the upper limbs and thus does not contribute to the development of degenerative conditions in the upper limbs, i.e., osteoarthritis, tendinitis, bursitis, carpal tunnel syndrome, etc., all conditions that commonly reduce function for individuals with spinal cord injuries.

TABLE IX. SPINAL CORD INJURIES: DECONDITIONING AND DEGENERATIVE EFFECTS

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- 1) Reduced cardiovascular fitness
 - 2) Reduced respiratory function
 - 3) Reduced serum high density lipoproteins
 - 4) Reduced lean body mass, obesity
 - 5) Reduced bone density, osteoporosis
 - 6) Reduced muscle bulk, strength, endurance
 - 7) Reduced endorphin production
 - 8) Reduced self image, stress tolerance
 - 9) Reduced insulin sensitivity
 - 10) Altered reflex activity: somatic, autonomic
 - Muscle tone
 - Bowel and bladder function
 - Vasomotor response
-
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My colleagues and I have been advocating and providing lower limb functional electrical stimulation exercise for individuals with spinal cord injuries for the last six years and have performed two controlled studies to assess some of its beneficial effects.^{12,13} In these studies, multistage stress tests were performed on a number of spinal cord injured individuals with both para- and quadriplegia while they were cycling on the functional electrical stimulation ergometer, during various stages of their training.

In general, results indicate that the parameters for aerobic capacity were significantly increased in all subjects with training as indicated by increased endurance for propelling the exercise cycle at higher resistance, increased heart rate at maximum oxygen consumption, and increased oxygen consumption. The quadriceps muscle bulk increased while muscle contraction became slower as assessed by twitch time tests. This test indicates an alteration from fast Type II (white) to slow Type I (red) muscle fibers and thus increased aerobic capacity of the muscle. Computer tomographic scans of the femurs did not show increased bone mass but did show increased muscle mass with less fat infiltration.

Despite improvement of the various parameters of exercise this improvement occurred slowly and was quite limited as compared with reported results in able-bodied individuals. Resistance on the ergometer increased but never exceeded one kilopond even after more than three months of therapy, far less than would be expected of a nondisabled individual on a progressive exercise bicycle program. The total lower extremity work during ergometry, however, was similar to upper extremity work reported in other¹⁴ studies on quadriplegics, but not paraplegics, performing maximum upper extremity exercise, indicating that there may be a common limiting factor for both upper and lower extremity exercise for people with high cord lesions.

Fatigue in the muscles occurred at every phase in the program when the anaerobic threshold was reached. This may be due to lactic acid accumulation resulting from insufficient oxygen supply to the exercising muscles. The reasons for insufficient oxygen supply to the exercising muscles are unclear, but it is probable that at least in individuals with high cord lesions, venous return to the heart is inadequate due to poor peripheral compensatory vasoconstrictions, and thus stroke volume and cardiac output is diminished. This hypothesis is supported by the finding that oxygen pulse is reduced, but oxygen pulse is a measure which expresses the combined effects of stroke volume and venous oxygen gradient. It does not appear that the respiratory dysfunction limits the exercise capacity in people with spinal cord injuries.

It is still unclear what these findings exactly mean in terms of lower extremity exercise for people with spinal cord injuries. Suffice it to say that significant training effect can be achieved even in individuals with high cord lesions. This effect may be sufficient for health benefits, but inadequate to sustain the great amount of work required during community ambulation with functional electrical stimulation systems or with orthotic devices only.

In closing, I reemphasize my basic belief that the relatively modest training effect of functional electrical stimulation exercise indeed is extremely important and will contribute to better health, fewer medical problems, and greater longevity of people with spinal cord injuries, just as scientific studies have shown that a modest regular exercise program helps people not physically disabled. This is no new discovery. Hippocrates already made this observation. The public considers this common sense, i.e., exercise is good for you, but physicians have been officially skeptical due to apparent lack of scientific data, but privately most have shared this belief and exhibit it in their lifestyles. It is our task as physiatrists to provide further scientific proof for the various health benefits of exercise for everyone, including those with physical disabilities.

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