The Use of a Four-Channel Electrical Stimulator as an Ambulatory Aid for Paraplegic Patients

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This article reports the use of electrical stimulation to provide paraplegic patients with complete lesions of the spinal cord the ability to rise from sitting to standing, to maintain a standing position, and to walk with a reciprocal gait. Four channels of electrical stimulation are sufficient for synthesis of a simple reciprocal gait pattern in these patients. During the double-stance phase, knee extensor muscles of both knees are stimulated, providing sufficient support for the body. Only one knee extensor muscle group is excited during the single-stance phase. The swing phase of the contralateral lower extremity is accomplished by eliciting the synergistic flexor muscle response through electrical stimulation of afferent nerves. The transition from the double-stance phase to the swing phase is controlled by two hand switches used by the therapist or built into the handles of the walking frame or crutches for use by the patient.

Key Words: Electric stimulation, gait, paraplegia.

Functional electrical stimulation (FES) of paralyzed muscles of the lower and upper extremities is not a new rehabilitation approach. Until recently, however, FES has seldom been applied to paraplegic patients with functionally complete transections of the spinal cord. The reason FES has not been used to a great extent is that the severe locomotor disability of paraplegic patients creates difficult problems for both therapists and engineers to solve.

So far, using FES to restore locomotor abilities in paraplegic patients with complete lesions has been attempted in only a few rehabilitation centers. Wilemon et al. implanted stimulating electrodes in both femoral and gluteal nerves to obtain contraction of knee and hip extensor muscles. A paraplegic patient with lesions at the T5 level was able to stand and even walk with both legs extended with the help of crutches and ankle-foot orthoses. Five-channel and six-channel stimulation systems were implanted in paraplegic patients with T7- and T12-level lesions by Brindley et al. Different branches of the femoral nerve were stimulated to obtain “electrical splinting” of the knee, allowing walking for 5 to 15 minutes. All of these previous reports of the use of FES for paraplegic patients with complete lesions have been limited to descriptions of swing-to or swing-through gaits.

The purpose of this article is to report the use of FES as an “electrical orthosis” to provide paraplegic patients with complete lesions the ability to rise from sitting to standing, to maintain a standing position, and to walk with a simple reciprocal gait pattern. The flexion response for this gait was obtained through afferent nerve stimulation. Another benefit of the application of FES to the paraplegic patients was to help prevent the negative consequences of immobilization, such as orthostatic hypotension, osteoporosis, and a tendency to develop contractures and decubiti.

PATIENT SELECTION

The candidates for FES treatment were patients with spastic paraplegia from complete spinal cord
lesion. Sensory and muscle strength testing together with routine EMG examination was performed to determine that the lesion was functionally complete.

The criteria for patient selection also include the following: the patient's agreement; absence of contractures, heterotropic ossifications, pressure sores, or thrombophlebitis; and good psychosocial condition (successful collaboration with therapist and engineer, adaptation to the disability, understanding of the purpose and the expected benefits of FES). The most crucial contraindications for FES application during standing or walking are contractures and ossifications preventing the positioning of a joint at the desired angle. Pressure sores often result in heightened spasticity hindering smooth movements during walking. The sores can also prevent attachment of electrodes to the skin. Regarding the psychosocial condition, the patients who have not yet adapted to their disability or who expect too much from FES are not good candidates for the FES program and they often abandon FES after returning home.

The patients who received FES treatment received all the exercises and therapies that are ordinarily used at the rehabilitation center.

**PRELIMINARY TRAINING PROGRAM**

Because several months had passed after the injury, the paraplegic patients had to undergo a strengthening program for disuse atrophy of thigh muscles. Our strengthening program consisted of applying cyclic electrical stimulation to the knee extensor muscles, resulting in isotonic contractions. Surface electrical stimulation of knee extensor muscles was delivered through large (6 × 4 cm) stainless steel sheet-metal electrodes covered with water-soaked foam rubber. The stimulation periods of four seconds were followed by a pause of eight seconds. The electrical pulses used were rectangular and monophasic. A stimulation frequency of 20 pulses per second (Hz), a pulse duration of 0.3 msec, and a stimulation amplitude of sufficient intensity to bring the legs into full extension were used.

During the training, the patients were positioned supine with both lower extremities semiflexed to approximately 30 degrees by a pillow under the knees. During the first week of the program, the FES sessions lasted a half-hour a day, five days a week. As a result of this FES training program, the muscle force was increased and the muscle fatigability was lessened. Because of this, a half-hour of FES was added each week thereafter. The FES muscle strengthening was usually divided into two or three sessions a day, which together did not exceed three hours. The effects of FES training were tested and assessed through isometric knee-joint torque measurements.

**STANDING-UP AND STANDING TRAINING PROGRAM**

When the maximal knee-joint torque provided by FES exceeded 30 to 50 Nm (depending on patient's body weight), a standing training program was started. Continuous FES caused knee extensor muscles to contract, which maintained the knee joints in extension and thus allowed standing. Through the use of two stimulation channels and arm support, the patients stood one hour or more.

If standing is to be a useful functional activity (eg, to get an object out of the reach from the wheelchair), a person must be able to rise from the sitting to the standing position independently. Standing-up can be accomplished by stimulating the extensor muscle groups of both knees. The patient assists FES by lifting himself with his arms. If a patient is not obese or extremely weak in the arms, he can easily accomplish rising from the sitting to the standing position.

The stimulation characteristics for standing-up were the same as for the standing training program. During the motion of standing-up, stimulation voltage up to 100 V was applied and then lessened (for each leg separately) to the minimal value that allowed full knee extension during standing.

**AMBULATION PROGRAM**

**Instrumentation**

A minimum of four channels of FES are required for synthesis of a simple reciprocal gait pattern. A four-channel stimulator* was designed at the Faculty of Electrical Engineering, Ljubljana, Yugoslavia. The stimulation frequency can be internally varied between 5 and 500 Hz, and the duration of rectangular pulses used was rectangular and monophasic.

* Not available commercially.
monophasic pulses between 0.05 to 3 msec. The amplitude of stimulation voltage can be adjusted from 0 to 150 V (measured on a load of 1.5 kΩ connected in parallel with a 0.1 µF condenser). The stimulator is shown in Figure 1.

The four knobs in the upper row belong to four potentiometers and allow adjusting the stimulation amplitude of particular channels. The stimulation must be controlled through three different phases of walking: double stance, right swing, and left swing. This is achieved by two hand switches. When neither of the switches is pressed, both knee extensor muscles are stimulated. When the switch is pressed in the right hand, the right leg is stimulated to flex, and when the switch is pressed in the left hand, the left leg is stimulated to flex. In the very first experiments both switches were held and controlled by the physical therapist. Later, the switches were built into the handles of the walker or the crutches, and the patient controlled them. The duration of the swing phase is equal to the time of pressing the switch. A special electronic circuit takes care of possible erroneous simultaneous pressing of both switches. In this case no change occurs in the stimulator output.

The duration of the swing phase of the right and the left leg can also be preset by two stimulator potentiometers. Thus, the patient has only to trigger the flexion of each lower extremity that is then completed automatically.

Surface electrical stimulation of knee extensor muscles is delivered to the muscles through electrodes like those used for strengthening. The flexion of the swinging lower extremity is elicited through two small (diameter, 2.5 cm) round electrodes made of stainless steel sheet metal and covered by gauze saturated with water (Fig. 1).

Procedures

When the patients were able to stand safely for at least 20 minutes, FES-assisted walking was commenced. A special frame, shown in Figure 2, was designed for the initial walking trials. The frame was similar to parallel bars except that it was on wheels. For safety reasons, the patient was strapped to the frame with leather belts. At the very beginning of the program, a patient usually was able to take only a few steps; after a week he usually was able to walk for several minutes without a rest. A half-hour of cyclic stimulation was applied to the quadriceps femoris muscles before the gait training to reduce muscle spasticity and promote smooth walking.

To achieve the double-stance phase, extensor muscles of both knees were stimulated to provide sufficient support for the body. The extensor muscles of one knee were excited during the single-stance phase. The swing phase of the opposite leg was obtained by eliciting a synergistic flexor muscle response. The flexion response was achieved by stimulating afferent nerves (cutaneous and mixed peripheral nerves) at the sites where they are close to the surface of the skin. In this way, stimulation elicited responses in the cutaneous nerve endings and the largest of the lower threshold fibers in the peripheral nerve itself. Simultaneous flexion of the hip and the knee and dorsiflexion of the ankle were obtained by one-channel stimulation over one of the following nerves: superficial peroneal, common peroneal, sural, or sa-
The approximate stimulation points are shown in Figure 3.

The positioning and the polarity of the electrodes were critical to the effectiveness of the obtained movement. A small change in electrode position resulted in a considerable change of stimulated movement. It was sometimes difficult to correctly position the electrodes to avoid obtaining plantar flexion instead of dorsiflexion. Placement of electrodes with respect to hip and knee flexion usually was not difficult. Initially, the electrodes were placed on the approximate positions, regardless of their polarity, while the patient was sitting in a wheelchair. They were connected to the stimulator, and the stimulator was switched on. One of the electrodes was then slightly shifted to find satisfactory dorsiflexion. If appropriate movement was not achieved, the search was repeated by changing the position of the other electrode. If the dorsiflexion still was not appropriate, the polarity of the electrodes was reversed. We noted a somewhat higher stimulation intensity than the one needed for dorsiflexion resulted in synergistic hip, knee, and ankle movement. When the optimal electrode placement and polarity were found, the stimulation points were marked by water-resistant pencil. We altered the flexion response (ie, hip-, knee-, and ankle-joint angles) by increasing or decreasing the stimulation amplitude.

During standing and walking, rectangular monophasic stimuli of 20 Hz were used to lessen the fatigue of electrically stimulated paralyzed muscles. The same frequency was used to obtain both extension and flexion responses. The single-stimulus duration was 0.3 msec. The stimulation intensity differed from patient to patient. The stimulation amplitude for flexion responses ranged from 30 to 50 V, with an increase of up to 100 V for knee extension responses. For an appropriate flexion response, only a minimal stimulation intensity was required to obtain swinging of the leg without dragging of the foot.

During the stance phase, there was no FES control over the hip and the ankle muscles of the supporting legs. Because paraplegic patients with complete lesions always walk with assistive devices for support (walking frames, walkers, crutches), some hip and trunk stabilization can be achieved through the use of the arms and the active functioning of trunk muscles. Ankle stability cannot be provided by the arms, however. Therefore, for safety reasons, ankle-foot orthoses were used for posterior ankle joint stabilization.

**TREATMENT RESULTS**

Twelve paraplegic patients with complete lesions have so far completed the program of electrically stimulated walking with assistive devices.
stimulated muscle strengthening and were able to stand up unassisted and to stand for at least 20 minutes. Only one patient was able to complete these tasks before the strengthening program. All patients initially were given two-channel stimulators to use at home. They were asked to apply cyclic electrical stimulation to their knee extensor muscles (for at least a half-hour) and to perform the FES-assisted standing every day. Four of these patients were willing to come to the rehabilitation institute for one month for the training program, which was long enough to enable them to walk in parallel bars. Three of the four patients had T5-level spinal cord lesions and one had T10-level lesions.

A four-channel stimulator was given for additional home use to one of the patients with a T-5 level lesion. This patient had started with the FES program one year after the injury. After three months of the FES strengthening program applied to the atrophied knee extensor muscles, he was able to rise from the wheelchair without any external help and to stand continuously for more than 30 minutes. The training program was carried out by the patient himself and his parents at their home. Then the patient came to the rehabilitation institute for two weeks. During this time, he was instructed to walk with the assistance of the four-channel stimulator and the walking frame. Shortly after returning home, the patient started to walk with the help of an ordinary, commercially available walker (Fig. 4a). After five months he was able to walk for three hours each day. Then he started to use crutches. He was controlling the stimulator by two switches that were built into the handles of the walker or the crutches (Fig. 4b). Currently, he is walking with the crutches and the stimulator for three to four hours each day, which corresponds to the distance of one kilometer. For safety reasons, he is always accompanied by his father who also readjusts the intensity of particular stimulation channels as needed. The patient is able to walk outside of his house, and he can step over small obstacles on the floor. The reason for such a success is that the patient (23 years) and his parents decided to devote most of their time to the FES exercising.

Some patients included in the program reported other positive side effects, such as improved bladder control, regular defecations, reduced spasticity, and strengthened trunk muscles. One of the patients, before being included in the program, had to use pharmacological means for reducing high blood pressure. During the FES program, his pressure remained normal without any additional means. No research efforts have been undertaken up to now to document these improvements objectively.

One of the patients, who was able to stand for more than one hour, quit the program and returned the stimulator. He complained that positioning the surface electrodes was time-consuming and that trousers and underwear became wet from the water-soaked electrodes. Another patient refused to use the stimulator because he was living alone and because his vocation took too much of his time.

DISCUSSION

Assisted ambulation of paraplegic patients with complete lesions represents an advanced example of the great effectiveness of FES. Every movement of their completely paralyzed lower extremities results only from stimulation of efferent nerves for contraction of the knee extensor muscles and stimulation of afferent nerves to elicit the preserved flexion reflex pattern.

The FES-assisted walking may require less energy from paraplegic patients with complete lesions than the swing-to or swing-through gaits using knee-ankle-foot orthoses because the patients do not have to lift their whole body weight during the ambulation. Also, FES-assisted walking is much more aesthetic than orthoses-assisted. Further, stimulating electrodes can be mounted on an extremity more easily and faster than mechanical orthoses. Finally, the stimulator is about the same price as orthoses; its production does not depend on the size of the patient's extremity. Therefore FES can be expected to have the potential to become an effective approach to improve the locomotion abilities of paraplegic patients.

REFERENCES