ASSESSMENT OF FUNCTIONAL CHARACTERISTICS RELEVANT TO FES APPLICATION IN INCOMPLETE SCI PATIENTS

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ABSTRACT - Maximal voluntary and stimulated knee and ankle isometric torques were assessed together with fatigue and relaxation indices in ten incomplete spinal cord injured subjects demonstrating relatively stabilized motor disability. Simple biped gait pattern, using knee extensors stimulation during stance phase and flexion reflex triggering through peroneal nerve stimulation during swing phase, is proposed. Based on the results from the study one-, two- and three-channel stimulators applied unilaterally or bilaterally are necessary for gait restoration in incomplete SCI patients.

INTRODUCTION

Incomplete spinal cord injuries (SCI) could be studied in two distinct phases. First is the initial phase when the disability is not yet stablized. Here, two main groups of patients can be distinguished. In the first group there are patients who immediately after the accident display a complete lesion to spinal cord while in the second group there are patients with an incomplete deficit. In a group of 112 randomly chosen spinal cord injured patients 54 cases demonstrated an incomplete disability immediately after the injury /1/. Out of 58 patients showing complete initial deficit, 16 patients recovered with respect to both, motor and sensory functions. Improvement of only proprioceptive and pain sensibility was found in 25 patients from the second group while no changes were observed in 17 patients. It is known that an improvement in motor functions can be to a large extent predicted from preceded improvement in pain sensation.

The division of incomplete lesions with respect to initial deficit does not bring relevant information when using functional electrical stimulation (FES) rehabilitative approach. Namely, all patients with upper motor neuron lesion enter daily therapeutic program of cyclic electrical stimulation. With respect to the outcome of FES restrengthening program of disuse atrophied paralyzed muscles, three different groups were identified /2/: patients where an improvement of both voluntary and stimulated muscle force was observed, patients with an increase of stimulation response only, and patients with whom no effect of electrical stimulation training was recorded.

After this initial phase the incomplete SCI subjects enter into the second phase displaying relatively stabilized motor and sensory disability. Four different patterns of incomplete lesions can be recognized /3/. The first one is acute anterior cervical syndrome where the patient has bilateral motor loss below the lesion, and bilateral impairment of pain and temperature sensibility. Light touch, proprioception, and vibration sense are relatively normal. The second pattern is acute central cervical cord syndrome. Here, greater motor and sensory impairment is observed in the arms than in the legs which sometimes may even be normal. The third type, Brown-Sequard lesion, is due to hemisection of the spinal cord. It results in complete motor loss below the lesion on the same side, and loss of pain and temperature sensation on the opposite side. In the fourth group of the incomplete SCI lesions, there are injuries to the cauda equina resulting in lower motoneuron lesion. Only the subjects from the first and third group seem to be candidates for introducing FES ambulation program. It appears that in the first group FES should be applied bilaterally while unilateral stimulation systems are sufficient with the incomplete SCI patients from the third group.

It was the aim of this study to extend our knowledge on FES in incomplete SCI patients /9/ and to find more detailed division of the incomplete SCI patients with regard to their needs for FES rehabilitative systems restoring walking abilities. According to Dimitrijević /4/, upper motor neurone functions can be studied and examined through four distinct approaches: control of motor activity, posture, equilibrium and gait. The first type of assessment was chosen in the present study. Volitional and FES activated forces of knee extensors and ankle dorsiflexors were isometricaly measured. Fatigue resistance of stimulated muscle group and spasticity were assessed in knee extensors of both lower extremities.

INSTRUMENTATION AND METHODS

The muscle forces were estimated through the joint torque measurements. There are two biomechanical approaches to the assessment of the joint torques: isometric and isokinetic modality. We made use of measuring braces where isometric torques were assessed by the help of strain-gauge transducers. To ensure standardisation of position and fixation of limb during assessment, a special chair was designed for knee and ankle torque testing. The knee joint torques were measured in the direction of extension while ankle joint torques in the direction of dorsiflexion. First, the joint torques resulting from stimulation of knee extensors and ankle dorsiflexors were assessed. The frequency of electrical stimulation was 20 Hz and pulse duration 0.3 ms. The amplitudes were increased from threshold value up to 120 V. Maximal stimulation amplitudes were determined according to patients' sensation of pain and their tolerance and were usually below 100 V. The joint torque was assessed during the train of pulses lasting for one second. After testing the joint torques produced by different electrical stimulation amplitudes, maximal volitional torques were measured. Knee extension and ankle dorsiflexion torques were assessed in both lower extremities.

When testing the fatiguability of the stimulated knee extensors the duration of the train of electrical stimuli was increased up to 30 seconds. The fatigue index was defined as follows:

$$\text{fatigue index} = \frac{\text{initial moment} - \text{moment after 30 s stimulation}}{\text{initial moment}} \cdot 100 \ \%$$

Spasticity of the knee extensor muscles was tested by placing a patient on a tilt table in supine position with both legs bent over the edge hanging free at the knee /5/. The incomplete spinal cord injured patients were asked to relax as much as possible. The examiner grasped the foot and brought one leg to a horizontal position. The limb was allowed to fall freely while recording knee angle with an electrogoniometer. The level of spasticity was estimated from the first drop of the leg. For quantification of spasticity, a relaxation index was proposed:

$$\text{relaxation index} = \frac{\text{magnitude of first drop}}{1{,}6 \cdot \text{magnitude of initial angle}}$$

The relaxation index equal or greater than one would signify a non-spastic limb whereas values lesser than one would quantify various degrees of spasticity.

Ten incomplete paraplegic and quadriplegic patients were chosen for the investigation. They all displayed relatively steady state of their disability. The SCI patients selected were able to stand and walk to a limited extent by the help of crutches, walker of physiotherapist. The general data on ten incomplete SCI patients are listed in Table 1.

TABLE 1

No.	Sex	Age	SCI level	Time post injury	FES orthosis used
1	M	48	C6	23y	left FEPO
2	M	58	C5,6	9m	-
3	M	46	T12	5y7m	left FEPO
4	M	26	T5,6	6y	bilateral FEPO
5	F	18	C5,6	1y8m	right FEPO
6	M	27	C5,6	6m	-
7	M	26	C3	3y3m	left FEPO
8	M	20	T6	1y10m	-
9	M	35	T5,6	3y	left FEPO
10	M	55	C6,7	4m	-

FEPO - functional electric peroneal orthosis

RESULTS

Maximal volitional isometric knee joint torques are presented in Fig. 1. According to our experiences gained with application of FES to completely paralyzed paraplegic subjects, the knee joint torques equal or greater than approximately 50 Nm represent minimal functionality required during standing-up maneuver and biped walking /6/. With regard to this criterium and also taking into account our clinical experineces four patients (No.: 2, 6, 9, 10) were able to stand, stand-up and also walk to a limited extent without any external active or passive knee bracing. The main characteristic property found in the rest of the patients is significant non-symmetry of the responses. In addition, in all patients maximal voluntary knee joint torque appertaining to one extremity is functional, while the knee extension of the other limb is very weak. Non-symmetrical response is evident

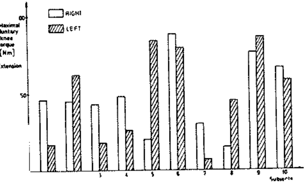
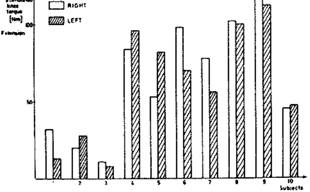


Fig Ma: volitional sometric joint torques

also patient where right and left knee joint torques display rather low values.

Because of pain sensation, the maximal electrical stimulation amplitudes used the measurements ranged most cases from 70 9?%. This the reason why in several cases (Fig.2) stronger



Maximal stimulated isometric knee joint torques responses were obtained volitionally than by the help of FES. In our previous investigation we have found that isometric torques exceeding 100 Nm can be easily obtained with the stimulation amplitudes up to 120V in completely paralyzed subjects /7/. Nevertheless, electrical stimulation of knee extensors was found effective in patients 4,5,7, and 8 where functional joint torques were achieved. No success was recorded in subjects 1 and 3, very likely because of mixed peripheral and central spinal cord lesion.

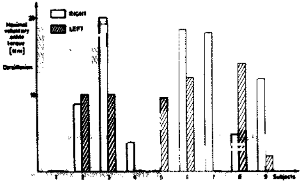


Fig. 3. Maximal voluntary isometric ankle joint torques

In Fig. 3 maximal voluntary isometric ankle joint torques in the direction of dorsiflexion are presented. Assuming 10 Nm as a level of practical functionality,it can be stated that patients 2, 3 and 6 demonstrate satisfactory responses in both extremities. In two patients (1 and 4) both dorsiflexors were found weak. In the rest of patients highly non-symmetrical ankle joint torques were obtained. By comparing Fig.1 and Fig.3 it can be noticed that this non-symmetry is in patients 5,7, and 8 of the same type what means that in these patients one

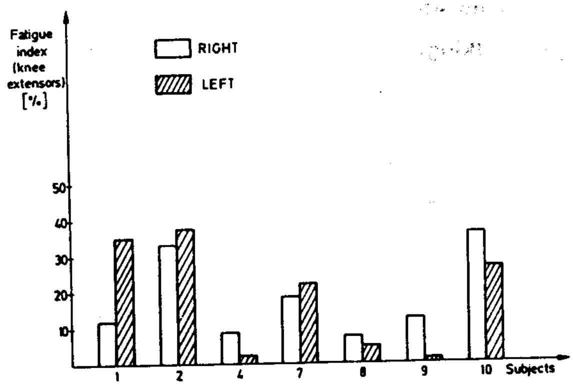


Fig. 5. Fatiguability of stimulated knee extensors

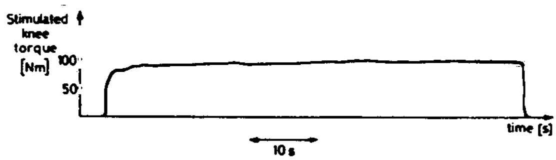


Fig. 6. Increase of knee joint torque during continuous electrical stimulation of knee extensors

In Fig. 7 relaxation indices are shown displaying the degree of spasticity in knee extensors. All patients demonstrated extension pattern of spasticity. Except in two subjects (patients no.: 2 and 5), we can denote the level of spasticity as moderate. This spasticity

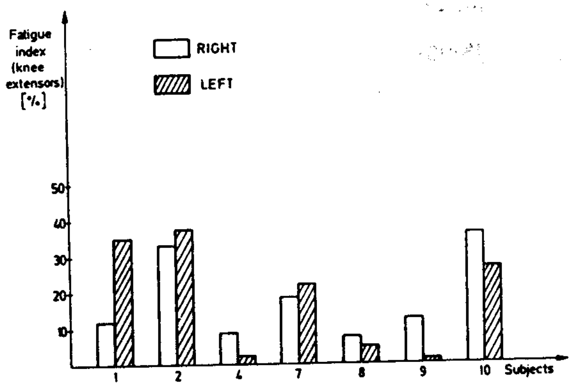
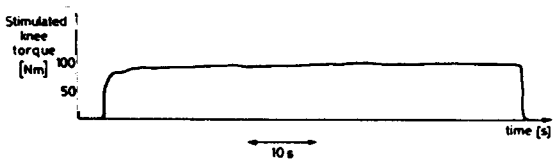


Fig. 5. Fatiguability of stimulated knee extensors



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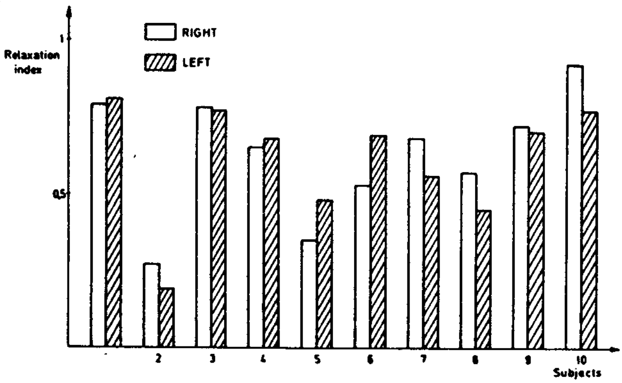

Fig. 7. Knee extensors spasticity

CONCLUSION

In our previous work, it was found that a minimum of four channels of FES is required for synthesis of a simple reciprocal gait pattern in the complete SCI patient /6/. During the stance phase, knee extensor muscles are stimulated, while the swing phase is accomplished by eliciting a synergistic flexor response in hip, knee and ankle joints through electrical stimulation of an afferent, usually peroneal, nerve.

Based on this simple biped gait pattern and taking into account the results from the study described in this paper, the needs of incomplete SCI patients for FES assistive devices can be divided into the following groups:

Unilateral FES application

a) one-channel stimulation
   peroneal stimulation
   knee extensors stimulation

b) two-channel stimulation of peroneal nerve and knee extensors

2. Bilateral FES application

a) two-channel peroneal stimulation

b) three-channel stimulation of both peroneal nerves and one knee extensors muscle group.

From the data gathered in this paper and also from our previous /8/ clinical observations it can be concluded that two-channel unilateral stimulator of peroneal nerve and knee extensors represents the FES orthotic device which can satisfy the largest group of incomplete SCI patients. It can be noticed from the Table 1 that the patients participating in this study were fitted with peroneal stimulators. The reason was in the commercial availability of only this type of stimulator at the time of the investigation.

ACKNOWLEDGEMENTS

The study was supported in part by the Research Communities of Slovenia, Yugoslavia and the National Institute on Disability and Rehabilitation Research, Department of Education, Washington, D.C., USA.

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