Technology and Health Care 7 (1999) 301–308
IOS Press

Problems associated with FES-standing in paraplegia

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Abstract. Prolonged immobilization, such as occurs after the spinal cord injury (SCI), results in several physiological problems. It has been demonstrated that the standing posture can ameliorate many of these problems. Standing exercise can be efficiently performed by the help of functional electrical stimulation (FES). The first application of FES to a paraplegic patient was reported by Kantrowitz in 1963. It was later shown by our group that standing for therapeutic purposes can be achieved by a minimum of two channels of FES delivered to both knee extensors.

The properties of the stimulated knee extensors (maximal isometric joint torque, fatiguing, and spasticity) were not found as sufficient conditions for efficient standing exercise. According to our studies, the ankle joint torque during standing is the only parameter which is well correlated to the duration of FES assisted standing. For good standing low values of the ankle joint torque are required. To minimize the ankle joint torque the lever belonging to the vertical reaction force must be decreased. Adequate alignment of the posture appears to be the prerequisite for efficient FES assisted and arm supported standing exercise.

Some patients are able to assume such posture by themselves, while many must be aided by additional measures. At present, surface stimulation of knee extensors combined with some appropriately “compliant shoes” looks to be adequate choice.

1. Introduction

Prolonged immobilization, such as occurs after the spinal cord injury (SCI), results in several physiological problems. It has been demonstrated that passive standing can ameliorate many of these problems. Bone loss occurs in both healthy and traumatized individuals during prolonged bed-rest immobilization. Disuse of large masses of bone and muscle produces abnormal losses of bone calcium, reduced bone density and hypercalciuria. Passive standing therapy (three hours per day) proved to be sufficient to induce a slow decline of the elevated calcium excretion [1]. Urinary tract infections occur in more than half of persons with SCI. It was shown that bladder pressure is for about three times higher in the standing posture than in the supine position. Urine is drained more completely during micturition in the standing position, reducing in this way the incidence of bladder infections. The limitation of range of motion caused by contractures has serious impact on mobility and independence for the individual with SCI. It was demonstrated that patients can maintain the range of motion solely through passive standing. Passive standing has been shown to produce significant decreases in muscular tone in patients with spasticity [2]. Following 30 min of standing with the feet in dorsiflexed position, there was observed a 30% decrease in resistance to passive stretch. Due to loss of sympathetic vascular tone and the skeletal muscle pump, patients with SCI have problems maintaining blood pressure and cardiac output. It is well accepted that repeated and progressive standing can lead to cardiovascular system adaptation producing functional circulation [3]. Pressure sores are important medical complication after SCI. Regular standing allows sustained periods of relief to the sacral and ischial high-pressure areas of the buttocs.

In addition to stationary standing frames and long-leg braces, standing exercise can be performed also by the help of functional electrical stimulation (FES). An overview of the early applications of FES for the standing exercise can be found in Vodovnik et al. [4] and Kralj and Bajd [5]. The first application of FES to a paraplegic patient was reported by Kantrowitz in 1963. The quadriceps and glutei muscles of a T-3 paraplegic subject were stimulated using surface electrodes. The patient's erect standing was achieved for a few minutes. The next similar trial was performed by implanted FES at Rancho Los Amigos Hospital in California in 1970. They have implanted stimulators to both femoral and gluteal nerves with the aim to obtain contraction of knee and hip extensors. A T-5 female paraplegic patient was able to stand with the aid of FES, crutches, and short leg-ankle braces. The stimulation frequency was set between 20 and 25 Hz, while 0.3 ms pulse duration was chosen. First continuous FES standing exercise program was started in Ljubljana in 1979 [6] and is lasting up to nowadays. It was shown by our group that standing for therapeutic purposes can be achieved by a minimum of two channels of FES delivered to both knee extensors through two pairs of large surface electrodes. The patients must make use also of the arm support usually provided by a walker, parallel bars, or simple standing frame. The stimulation frequency of 20 Hz and the pulse duration of 0.3 ms are used. Through the use of two stimulation channels and the arm support some paraplegic persons can stand for an hour and even more.

When electrical stimulation is used for standing, it is typically applied in open-loop manner. Few clinical applications of FES made use of closed loop control because of numerous difficulties involved in its application, particularly the need for sensors and advanced control algorithms with the ability to cope with spasms, spasticity, and fatigue. Controllers for standing are of two types: those for supported and those for unsupported standing. In supported standing, the essential purpose of stimulation is to cause sufficient knee extension to maintain the knee near hyperextension [7]. Feedback of the knee angle modulates the stimulation so that just sufficient knee extension is produced, and this minimizes the rate of fatigue and prolongs the duration of standing [8,9]. Jaeger [10] simulated a controller for unsupported standing using the stimulated ankle plantar flexors. With only ankle angle fed back, he demonstrated that, following small disturbances, the standing person represented by the inverted pendulum was stable with the parameters he was using. However, if the gain of the muscle fell to half its initial value due to muscle fatigue, the system became unstable. Hunt et al. [11] have also studied the behavior of a single link model of a standing person controlled by an ankle controller. They proposed a cascade controller where the outer loop stabilizes the inverted pendulum while the inner loop enhances the ankle loop tracking. The authors have shown in controlled laboratory conditions that the approach proposed can be accomplished with a paraplegic subject.

The following are the advantages of FES assisted standing training as compared to passive standing accomplished by the supporting frames and mechanical orthoses [12]:

- patient's own muscles are used together with his/her own metabolic energy,
- atrophied paralyzed muscle restrengthening is achieved,
- improved reduction in spasticity and increase in muscle and skin blood flow are achieved,
- FES orthosis has a favorable appearance, is quickly and easily applied to the extremity, has no attachments to cause pressure spots or decubiti, does not depend on extremity size to fit, and costs less than mechanical orthosis.

2. Biomechanics of FES assisted standing

It was our aim to study which parameters are important for efficient standing exercise. A standing paraplegic person was assumed to be a rigid structure with the hip joints fixed in the hyperextension,

Table 1
Paraplegic patients general data

Subject	Sex	Age	SCI level	Time past injury	Accident
1	M	20	T – 11	11m	fall
2	M	50	T – 5	3y 3m	GSW
3	M	26	T – 8	5y 5m	MVA
4	M	20	T – 5	1y 7m	MVA
5	M	26	T – 5, 6	2y 5m	MVA

knees locked by FES of knee extensors and ankle joint movement constrained through the arm support. Five completely paralyzed SCI subjects were randomly chosen for the study. Their general data are given in Table 1. All had thoracic spinal cord lesion and were several years (1–5) after the accident, which was in most cases motor vehicle accident (MVA). In one case the spinal cord lesion was a consequence of gun shot wound (GSW). All of them completed the FES restrengthening program (lasting for several months) of the atrophied paralyzed knee extensors. This introductory exercise program consists of daily application of cyclic electrical stimulation delivered to the knee extensors through surface electrodes. The stimulation periods of 4 s are followed by a pause of 4 s. The stimulation frequency of 20 Hz, the pulse duration of 0.3 ms and the stimulation amplitude to bring the legs to full extension are used. During the isotonic training exercise, the patients are positioned supine with both lower extremities semiflexed over a pillow under the knees. Each FES session lasts for 30 min.

The selected paraplegic subjects were, however, not equally successful in performing FES assisted standing. From the uppermost diagram in Fig. 1 it can be observed that the first three SCI subjects were able to stand for about 15 min, while the subjects 4 and 5 could stand for over one and even two hours ($T_{\max}$).

In the first part of the investigation the properties of the stimulated knee extensors were tested. The isometric knee joint torque was assessed with the patients in sitting position and the leg flexed in the knee for 30 degrees. The isometric knee joint torque $M_{\mathrm{K\ iso}}$ describes the average maximal knee joint torque measured in the right and left extremity. All the persons tested were able to produce the knee joint torque above 50 N m, what was in accordance to our observations sufficient for FES assisted standing. Fatiguing of the stimulated knee extensors was measured over 30 s of delivering continuous train of electrical stimuli. The difference between the initial isometric knee joint torque and the torque assessed after 30 s of stimulation was normalized by the initial value and expressed in percents. The parameter was denoted as F. The zero value of F represents no fatiguing of the electrically stimulated muscle, while $F = 100\%$ means that no response was observed after 30 s. Considerable fatiguing of the electrically stimulated knee extensors was found in one of the patients who was considered as moderately successful in standing (no. 3) and, surprisingly, also in the best standing SCI patient (no. 5). The spasticity of the knee extensors was assessed by the use of a pendulum test (eliciting the abnormal stretch reflex during passive swing maneuvers of the limb) and expressed through the relaxation index R [5]. $R > 1$ signifies a nonspastic limb, whereas $R < 1$ quantifies various degrees of spasticity. A relaxation index zero signifies no motion of the knee from an extended horizontal initial position, and therefore, extreme spasticity. A relaxation index of one signifies a normal limb swing, and therefore, no spasticity. The average over ten pendulum tests performed within one minute interval was calculated and denoted as R_{10}. Insignificantly lower spasticity was observed in the two patients who were successful in prolonged standing exercise.

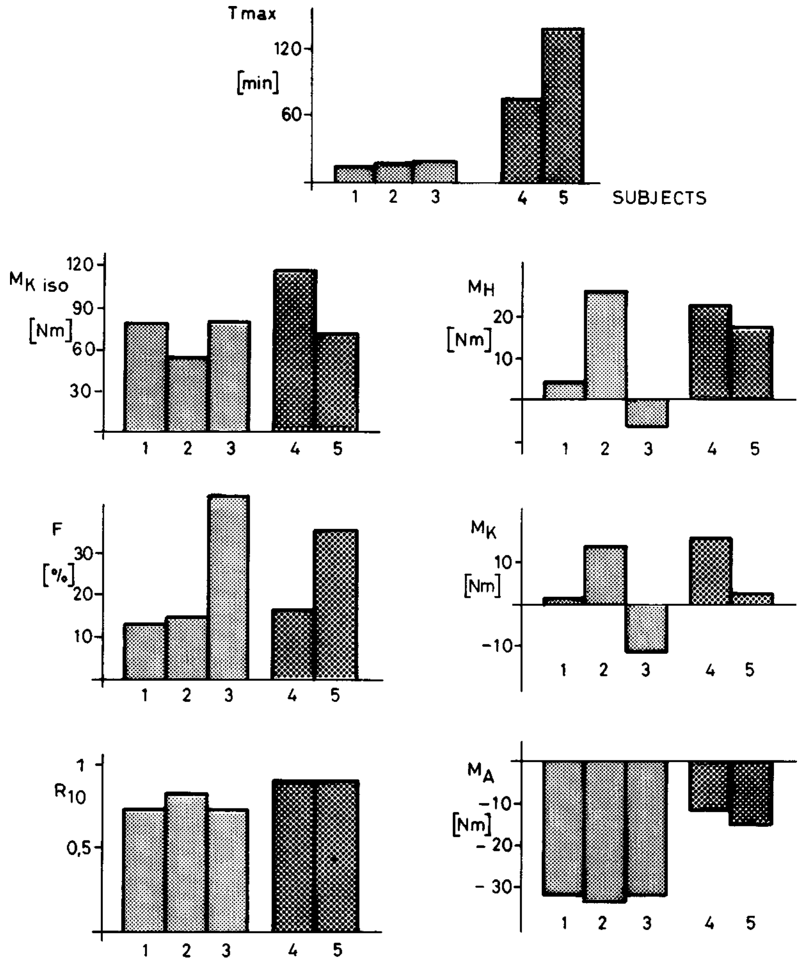

Fig. 1. Characteristic muscle and biomechanical parameters assessed in five paraplegic subjects standing assisted by FES: maximal time of FES standing T_{max}, maximal isometric knee joint torque $M_{K\ iso}$, stimulated muscle fatigue index F, relaxation index denoting spasticity level R_{10}, and the hip M_H, knee M_K, and ankle M_A joint torques measured during standing.

In the second part of the investigation the five patients were standing with the left leg on the force plate. The balance was provided by the help of arm support, while FES was delivered to both knee extensors. The markers were attached to the approximate centers of hip, knee, and ankle joint rotation of the left lower extremity. The torques were calculated in the three joints from the force plate data and photographic presentation of the lower extremity during FES assisted standing. They are presented in the right column of Fig. 1. Rather inconclusive results were obtained in the hip joint (M_H). The values of the knee joint torques (M_K) are low in all five subjects. It is a necessary condition for efficient standing as FES of the knee extensors cannot counteract large external joint moments. The highest correlation with the maximal standing time T_{max} can be found from the last diagram describing the ankle joint moments. Large values (over 30 N m) were found in the first three subjects, while rather low ankle torques were assessed in the two subjects who were able to perform long lasting standing exercise.

According to our study, the ankle joint torque is the only parameter which is well correlated to the duration of FES assisted standing. The static ankle joint torque is the sum of two components, the first

Table 2
Ankle joint torques during standing

Subject	F_z (N)	y (cm)	$+$	F_y (N)	z (cm)	$=$	M_{A} (N m)
1	276.2	−12.5		26.8	7.5		−32.5
2	434.7	−8.1		12.5	10.5		−33.9
3	397.1	−8.5		13.5	8.5		−32.6
4	323	−4.1		10.1	10.4		−12.2
5	290	−5.1		− 5.1	10.2		−15.3

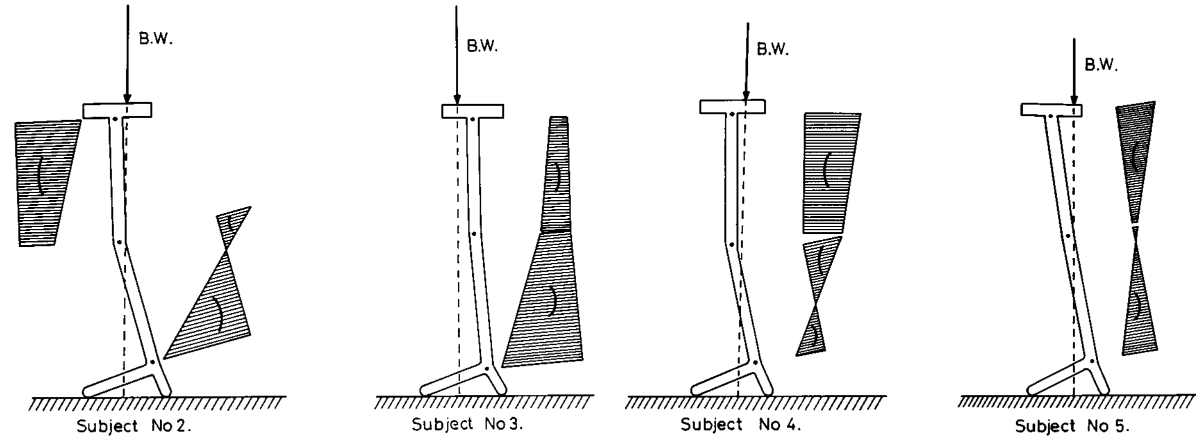

Fig. 2. The gravitational bending stressing profiles along the long bones of the lower extremities as assessed in two average (nos. 2 and 3) and two successfully (nos. 4 and 5) standing paraplegic subjects.

is produced by the vertical component F_z and the second by the horizontal component F_y of the ground reaction force. The static ankle joint torque was calculated according to the formula which is presented in the first row of Table 2. In Table 2 both force components are presented together with the corresponding levers y and z resulting in the ankle joint torque M_{A}. In all five cases considered, the part of the ankle joint torque appertaining to the horizontal ground reaction force represents less than 10% of the total ankle joint moment. Apparently, the component belonging to the vertical reaction force is crucial for the efficiency of FES assisted standing. It is a product of the vertical reaction force F_z and the lever y represented by the horizontal distance between the ground reaction vector and the center of the ankle joint. For an adequate standing exercise we wish that as much as possible of the body weight is carried by the legs. To minimize the ankle joint torque, the lever belonging to the vertical reaction force should be decreased. The length of this lever was around 10 cm in the first three subjects and around 5 cm in the two patients who were performing standing efficiently.

The gravitational bending stressing profiles along the long bones of the lower extremities as assessed in two average (nos. 2 and 3) and two successfully (nos. 4 and 5) standing subjects are presented in Fig. 2. The calculation of the gravitational bending moments is explained in details in [13]. Trapezoidal shape of the external (gravity) bending stressing profile was found in the femoral part of the lower extremity. The direction of the bending stressing in the femur has almost in all cases the same direction. Double triangular shape of bending stressing profile is characteristic for the tibial part of the lower extremity. The difference in the magnitude of the bending stressing at the ankle joint between the subjects nos. 2 and 3 and the successfully standing subjects nos. 4 and 5 is obvious.

Fig. 3. FES assisted standing exercise in two paraplegic persons shown soon after the accident (right) and ten years after (left). The SCI patient in the upper photographs omitted use of FES, while the second patient is training regularly.

3. Discussion

Approximately 500 SCI patients were admitted to the Rehabilitation Institute in Ljubljana in the ten years period from 1983 to 1993. According to our criteria 94 were recognized as candidates for functional application of electrical stimulation. The applied indications for FES standing were the following:

- upper motor neuron lesion,
- no joint contractures,
- no major skin problems,
- adequate upper extremity function,
- adequate physiological status,
- motivated and cooperative.

The 94 paraplegic patients selected were trained to use FES and 83 were capable of performing the standing exercise when leaving the rehabilitation center. At the end of the ten years period some of our first patients were visited at their homes. Two of such cases are presented in Fig. 3. The upper two photographs show our first patient [6] who was after being trained able to stand for 45 min. The patient is living alone and was not motivated enough to exercise standing regularly. Strong contractures, which are specially evident in his hip joints, are preventing standing posture ten years after (right upper photograph). In contrary, the second patient, shown in the lower two photographs, has strong moral support from the side of his family. It can be observed that he is capable of the same well aligned posture after ten years of daily use of FES.

Good alignment of the posture, not only in the knees but also in the ankle joints, appears to be the prerequisite for efficient FES assisted and arm supported standing exercise. Some patients are able to assume such posture by themselves, while many must be aided by additional measures. They can be helped by the use of special stabilizing orthotic shoes such as Vannini-Rizzoli Stabilizing Limb Orthosis [9]. A rather rigid polypropylene orthosis is inserted into a specially designed leather boots which were well accepted by the patients.

By incorporating the ankle stiffness of approximately 10 N m/deg into a compliant ankle-foot orthosis functional standing can be achieved [15,16]. Here, functional standing is considered as upright posture that frees at least one upper extremity to manipulate objects [17]. The strategy of arm-free paraplegic standing is based on voluntary activity of the paraplegic person’s upper body and artificially controlled stiffness in the ankles. An apparatus named mechanical rotating frame was developed which braces the knee and hip joints in extended position. The only degree of freedom of the apparatus is an artificial ankle joint. A hydraulic actuator provided the torque required for stiffness control in the artificial ankle joint. It was demonstrated that intact subject and paraplegic person were able to stand without arm support and also recover from the disturbances when the ankle stiffness was set around 10 N m/deg.

FES assisted standing is not the only exercise available to complete paraplegic subjects. Two other possibilities are FES cycling and simple stepping. It remains to be demonstrated which from these three training modalities brings most therapeutic benefits to the SCI patient. Nevertheless, it appears that from the point of view of cost, simplicity, and safety the standing exercise might be advantageous. At present, surface stimulation of knee extensors combined with appropriately “compliant shoes” looks to be adequate choice.

Acknowledgement

This study was supported in part by the European Commission (BIOMED 2, SENSATIONS-PL 950897) and the Ministry of Science and Technology, Ljubljana, Slovenia.

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