Spinal Cord (2010) 48, 881–885

www.nature.com/sc

ORIGINAL ARTICLE

Effects of quadriceps and anterior tibial muscles electrical stimulation on the feet and ankles of patients with spinal cord injuries

CK Bittar[1] and A Cliquet Jr[1,2]

[1]Orthopaedics Department, Faculty of Medical Sciences, State University of Campinas (UNICAMP), Campinas, Brazil and [2]Department of Electrical Engineering, University of São Paulo (USP), São Carlos, Brazil

Study design: Controlled clinical test.
Objectives: The purpose of this study was to assess the effects of quadriceps and anterior tibial muscles electrical stimulation on the feet and ankles of patients with spinal cord injuries and to compare them with able-bodied individuals and a group of patients who did not undergo neuromuscular electrical stimulation (NMES).
Setting: This study was conducted at the Hospital das Clínicas of Unicamp, Campinas, São Paulo, Brazil.
Methods: Between January and April 2008, 30 patients at the spinal cord injury ambulatory clinic who underwent NMES (group A) were submitted to a clinical and radiographic assessment of their feet and ankles and compared with a spinal cord injury group (group B) who did not undergo NMES and a group of able-bodied individuals (group C). The Kruskal–Wallis test was used to compare all the three groups, and between-group differences ($P<0.05$) were investigated with the Mann–Whitney test.
Results: The mean mobility of the midfoot and ankle subtalar joint was significantly higher in group C than in groups A and B. Differences in the mean measurements of the profiles of the talocalcaneal and the talus–first metatarsal angles were statistically significant for group A vs the other groups ($P=0.0020$, 0.0024, respectively). Foot deformities were found in groups including claw toes and flat feet (group A) and grade I ulcers on the lateral malleolus and calcaneus (group B).
Conclusion: Partial-load NMES maintains the feet and ankles in a planted and adequate walking position in patients with spinal cord injuries, a favorable result of new technologies that allows these patients to reacquire independent walking capacity.
Spinal Cord (2010) **48,** 881–885; doi:10.1038/sc.2010.50; published online 18 May 2010

Keywords: electrical stimulation therapy; spinal cord injuries; quadriplegia; paraplegia; foot; ankle

Introduction

Annually, about 11 000 new cases of spinal cord injury occur in the US population,[1] of which automobile accidents are the most common cause (50%),[1,2] and the majority of victims are young (20–40 years). Spinal cord injuries are classified according to the degree of neurological compromise, which is defined by the sensory and motor evaluation in accordance with the American Spinal Injury Association.[3]

Spasticity, contractures and osteoporosis appear because of neurological lesions and disuse, increasing the risk for deformities, especially of the feet, and making it difficult for the patient to recover a walking condition.

A strategy to diminish these spinal cord injury complications is neuromuscular electrical stimulation (NMES) associated with a partial body weight support system.[4] Such a system allows individuals to maintain an orthostatic position and to be able to move, which diminishes contractures, spasticity, osteoporosis and lower limb deformities. The patient's energy efficiency also improves, facilitating a patient's ability to perform daily activities.[5]

Few studies have described how the feet and ankles of patients with spinal cord injuries behave when subjected to NMES. The aim of this study was to assess the effects of NMES on the feet and ankles of patients with spinal cord injuries and compare them with able-bodied individuals and groups of injured patients who did not undergo NMES.

Materials and methods

From January to April 2008, 30 patients at the spinal cord injury ambulatory clinic at the Hospital das Clínicas da Unicamp (group A) were submitted to a clinical and

Correspondence: Dr CK Bittar and Professor Dr A Cliquet Jr, Department of Orthopaedics, Faculty of Medical Sciences, State University of Campinas (UNICAMP), Campinas, São Paulo 13020-081, Brazil.
E-mails: ckbit@uol.com.br or cliquet@fcm.unicamp.br
Received 24 February 2010; revised and accepted 8 April 2010; published online 18 May 2010

Table 1 Group A epidemiological characteristics

Patient	*Age (years)*	*Gender*	*Paraplegic or Tetraplegic*	*Mechanism*	*Level*	*Lesion time (years)*	*Laboratory start (years)*	*Profession*
1	61	M	Paraplegic	Bone tuberculosis	T4	15	4	Truck driver
2	37	M	Paraplegic	Gunshot wound	T10	9	7	Fire fighter
3	32	M	Paraplegic	Gunshot wound	T6	8	8	Mechanic
4	40	F	Paraplegic	Run over	T6	19	9	Teacher
5	21	M	Paraplegic	Bike accident	T3	2	1	Student
6	25	M	Paraplegic	Gunshot wound	T9	8	4	Billing clerk
7	26	F	Paraplegic	Car accident	T2	2	1	Stylist
8	27	M	Paraplegic	Gunshot wound	T1	6	3	Administrative clerk
9	31	M	Tetraplegic	Diving accident	C5	13	13	Economist
10	41	M	Paraplegic	Car accident	T5	11	5	Office worker
11	43	M	Tetraplegic	Car accident	C5	5	2	Philosopher
12	33	M	Paraplegic	Car accident	T7	13	1	Economist
13	35	M	Paraplegic	Bike accident	T5	2	2	Assistant—dismissed
14	40	M	Paraplegic	Car accident	T6	9	7	Banker
15	33	M	Tetraplegic	Diving accident	C6	11	3	Web designer
16	45	M	Tetraplegic	Car accident	C4	8	2	Machine operator
17	51	F	Paraplegic	Iatrogenic surgery	T9	2	1	Lawyer
18	44	M	Paraplegic	Run over	T10	10	1	Salesperson
19	29	M	Tetraplegic	Car accident	C7	9	1	Laid off work
20	25	M	Tetraplegic	Car accident	C5	10	1	Biologist
21	29	M	Paraplegic	Car accident	T5	9	2	Barman
22	40	M	Tetraplegic	Gunshot wound	C6	7	3	Retired
23	57	M	Paraplegic	Car accident	T5	1	1	Ex-police officer—restaurant
24	22	F	Tetraplegic	Diving accident	C5	2	1	Teacher—laid off work
25	64	M	Paraplegic	Gunshot wound	T3	8	2	Teacher
26	30	M	Tetraplegic	Diving accident	C5	7	6	Student
27	25	M	Paraplegic	Bike accident	T5	7	1	Retired
28	12	M	Paraplegic	Car accident	T2	10	9	Student
29	30	F	Paraplegic	Run over	T5	13	2	Lawyer
30	10	F	Paraplegic	Car accident	T8	10	1	Student

Abbreviations: F, female; M, male.
Patients from the University Hospital ambulatory clinic.

Table 2 Group B epidemiological characteristics

Patient	*Age (years)*	*Gender*	*Paraplegic or Tetraplegic*	*Mechanism*	*Level*	*Lesion time (years)*	*Profession*
1	20	M	Paraplegic	Gunshot wound	T11	2	Student
2	39	M	Tetraplegic	Diving accident	C5	11	Retired
3	30	M	Tetraplegic	Bike accident	T1	2	Retired
4	25	M	Paraplegic	Car accident	T4	5	Retired
5	27	M	Paraplegic	Gunshot wound	T7	5	Computer technician
6	23	M	Tetraplegic	Car accident	C4	2	Student
7	20	M	Tetraplegic	Diving accident	C6	1	Retired
8	59	M	Tetraplegic	Bike accident	C4	1	Businessman
9	25	M	Paraplegic	Car accident	T7	2	Administrator
10	32	F	Tetraplegic	Car accident	C7	7	Mathematician

Abbreviations: F, female; M, male.
Patients from the University Hospital ambulatory clinic.

radiographic assessment of their feet and ankles and compared with a spinal cord injury group that did not undergo NMES (group B) and with a group of able-bodied individuals (group C). The epidemiological characteristics of groups A and B are shown in Tables 1 and 2, respectively.

Group A included complete spinal cord injury patients with intact inferior motor neurons, an absence of cardiopulmonary diseases, absence of a history of foot and ankle fractures and a minimum 1-year follow-up in the rehabilitation program. Patients with incomplete spinal cord injury and patients with previous clinical and orthopedic pathologies were excluded from this study.

The group A treatment consisted of maintaining the individual in the erect position with a walker (paraplegics) or a support and suspension equipment (tetraplegics) to allow free hip and knee movement. The feet and ankles were protected in a neutral position with the aid of a rigid orthosis. The quadriceps and anterior tibial muscles were stimulated for walking with a four-channel electrical stimulator, which emits a 25 Hz signal with monophasic

Figure 1 Anteroposterior radiography: (1) hallux–valgus angle, (2) intermetatarsal angle, (3) talocalcaneal angle hallux–valgus angle. The hallux–valgus angle is formed by the intersection of the long axis of the proximal phalanx and the long axis of the first metatarsal. Normal is $<20°$. The intermetatarsal angle is formed by the intersection of the long axis of the second metatarsal and the long axis of the first metatarsal. Normal is $<9°$. The anteroposterior talocalcaneal angle is formed by the intersection of the long axis of the calcaneus and the long axis of the talus. Normal is $<30°$.

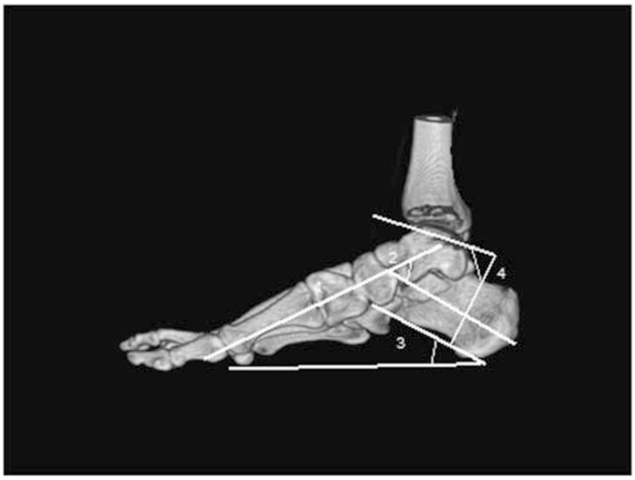

Figure 2 Latera radiography: (1) talar-first metatarsal angle, (2) talocalcaneal angle, (3) calcaneal-ground angle; 4-tibiocalcaneal angle. Talar-first metatarsal angle formed by the intersection of the long axis of the talus and the long axis of the firt metatarsal. Normal is $<4°$. Talocalcaneal angle lateral: formed by the intersection of the long axis of the calcaneus and the long axis of the talus. Normal is $<30°$. Calcaneal-ground angle: formed by the intersection of the long axis of the calcaneus and the axis of the ground. Normal is $<30°$. Tibiocalcaneal angle: formed by the intersection of the perpendicular to long axis of the calcaneus and the long axis of the surface articular of the tibia. Normal is 90°.

rectangular pulses at 30 ms duration and a maximum intensity of 200 V. Each session lasted 20–30 min, and NMES was performed twice per week for a minimum of 1 year.

The clinical assessment of feet and ankle involved documentation of alignment and possible deformities and callosities, joint mobility, detection of posterior tibial and pedis pulses, skin conditions, ulcers, mycosis and onychocryptosis.

Joint mobility of the ankle, subtalar region, and midfoot and the radiographic assessment were evaluated by a physiotherapist and an orthopedist specializing in foot and ankle surgery. The results corresponded to the mean of six measurements carried out by two professionals. A manual goniometer was used to measure mobility following the American Orthopaedic Foot and Ankle Society criteria.[6]

Standard radiographs were used for the radiographic assessment, with dorsoplantar and profile incidences of support. We measured the hallux–valgus angle, intermetatarsal angle, talocalcaneal angle, calcaneal–ground angle, talus–first metatarsal angle, and the tibial–calcaneal angle with a manual goniometer, based on Smith's criteria[7] (Figures 1 and 2).

The results of the clinical and radiographic assessment of the feet and ankles of group A were compared with those of groups B and C using the same measurement criteria established for group A.

Group A consisted of 30 patients with spinal cord injury, who underwent NMES as a rehabilitation method; 24 patients were men and 6 were women, and the mean age was 34.6 years (range, 10–64 years). In all, 21 patients were paraplegic and 9 were tetraplegic; causes included automobile accident (12), run over (3), diving (4), bicycle accident (1), motorcycle accident (3), gunshot wound (6), thoracic tuberculosis (1) and lumbar surgery (1). The mean lesion time was 8.2 years (range, 1–15 years), with a mean NMES rehabilitation time of 3.4 years (range, 1–13 years).

Group B consisted of 10 patients with spinal cord injuries, who did not undergo NMES as a rehabilitation method. This group consisted of nine men and one woman, and the mean age of 30 years (range, 20–59 years). Four patients were paraplegic and six were tetraplegic; four had suffered a motorcycle accident, two a diving accident, one a bicycle accident, one a motorcycle accident and two were wounded by gunshot. The mean lesion time was 3.8 years (range, 1–11 years).

Group C consisted of 11 able-bodied patients (without spinal cord injury), 5 men and 6 women, with a mean age of 29.5 years (range, 18–40 years).

The three groups were compared using the Kruskal–Wallis test. In cases in which a significant difference was found ($P<0.05$), the between-group comparisons were investigated using the Mann–Whitney test.

We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research. This study was approved by the local ethics committee under Project No. 879/2007.

Results

The mean joint mobility in the subtalar mobility comparison was 23.4° in group A, 13.5° in group B and 28.9° in group C. Significant differences were found between groups A and B, and between groups B and C ($P=0.0092$ and 0.0034, respectively). In the midfoot joint, mean mobility was

Table 3 Descriptive statistics for groups A and B

Measurement	*Injured not undergoing electro*			*Normal patients*			*Injured undergoing electro*			*Comparison of the three groups*	*Injured undergoing × not undergoing electro*	*Injured undergoing electro × normal*	*Injured not undergoing electro × normal*
	Mean	*Standard deviation*	*Median*	*Mean*	*Standard deviation*	*Median*	*Mean*	*Standard deviation*	*Median*	P-*value*	P-*value*	P-*value*	P-*value*
Subtalar joint	13.5	5.8	10.0	28.9	9.0	30.0	23.4	6.4	23.8	0.0007*	0.0092*	0.1603	0.0034*
Midfoot joint	15.3	3.0	15.0	24.1	6.6	20.0	22.5	6.2	21.9	0.0018	0.0184*	0.8538	0.0022*
Ankle joint	34.3	10.7	35.0	63.6	3.9	65.0	41.4	7.4	43.8	<0.0001*	0.1527	0.0009*	0.0008*
Hallux–valgus angle	14.8	5.1	14.0	15.6	7.0	12.0	17.5	9.0	17.0	0.9180			
Intermetatarsal angle	8.1	2.6	9.5	10.1	2.0	10.0	9.1	4.6	8.0	0.1405			
Talocalcaneal angle anteroposterior	18.9	2.8	20.0	24.0	5.5	24.0	23.5	6.7	23.0	0.1728			
Calcaneal–ground angle	25.3	6.0	26.3	26.8	6.0	26.0	25.0	5.1	24.0	0.7310			
Talocalcaneal angle lateral	31.1	6.4	31.3	44.7	5.0	44.5	36.8	7.7	38.0	0.0020*	0.1238	0.0184*	0.0040*
Talus–first metarasal	19.3	9.7	20.0	4.0	4.7	5.0	13.8	9.3	14.5	0.0024*	0.2313	0.0089*	0.0075*
Tibial–calcaneal angle	80.6	14.1	85.0	81.8	12.8	90.0	81.0	12.1	90.0	0.9975			

*Statistically significant measurements.

22.5° in group A, 15.3° in group B and 24.1° in group C. Significant differences were found between groups A and B, and between groups B and C when midfoot mobility was compared ($P = 0.0184$ and 0.0022, respectively). The mean ankle joint mobility was 41.4° in group A, 34.3° in group B and 63.6° in group C. Significant differences were found when this mobility was compared between groups A and C, and between groups B and C ($P = 0.0009$ and 0.0008, respectively; Table 3).

The mean hallux–valgus angle was 17.5° for group A, 14.8° for group B and 15.6° for group C. The mean intermetatarsal angle was 9.1° for group A, 8.1° for group B and 10.1° for group C. The mean talocalcaneal angle in the anterior–posterior position was 23.5° for group A, 18.9° for group B and 24° for group C. The mean calcaneal–ground angle was 25° for group A, 25.3° for group B and 26.8° for group C. The lateral talocalcaneal angle showed the following means: 44.7° for group A, 36.8° for group B and 31.1° for group C. Significant differences were found when this angle was compared between groups A and C, and between groups B and C ($P = 0.0184$ and 0.0040, respectively; Table 3).

The mean talus–first metatarsal angle was 13.8° for group A, 19.3° for group B and 4.0° for group C. Significant differences were found when this angle was compared between groups A and C, and between groups B and C ($P = 0.0089$ and 0.0075, respectively; Table 3).

The mean tibial–calcaneal angle was 81° in group A, 80.6° in group C and 81.8° in group C. Deformities in group A included claw toes and flat feet, whereas those in group B were grade I ulcers on the lateral malleolus and calcaneus (Table 3).

Discussion

The group A and B populations were predominantly young (mean age, 34 and 30 years, respectively) and the lesions resulted from traffic accidents, which agreed with Levi *et al.*[8]

In accordance with the Spinal Cord Injury Data Center criteria, the group A (claw toes and flat feet) and group B (grade I ulcer[9,10] on the lateral malleolus and calcaneus) foot deformities suggested that adequate shoes are needed to avoid future lesions when patients with spinal cord injury are submitted to partial load training. The absence of ulcers, mycosis and onychocryptosis may have been due to the high level of education of the studied population, which is highly interested on a different treatment. These people are part of an unusual group of Brazilian spinal cord injury patients because they have a better access to this kind of treatment.

With regard to the mobility of subtalar joints, the mean midfoot and ankle joint results for group A and B patients were lower than the values found in able-bodied individuals (group C). The mobility in group A (NMES) was higher than that in group B (no NMES). This diminished mobility occurred mainly because of disuse, rigidity and shortening of the muscle and capsular tissues, causing loss of sarcomeres and muscle fibers.[11]

Radiographic assessments for groups A and C showed normal mean hallux–valgus angles, intermetatarsal angles, talocalcaneal angles in the anterior–posterior position, calcaneal–ground angles and tibial–calcaneal angles. The talocalcaneal angle and the talus–first metatarsal angle, in profile position, in both groups A and B showed a significant increase in mean angular values compared with the pattern of a able-bodied individual (group C). These angular alterations suggest that in a support position and without axial load, the feet assume a supinated position, but this position was not evident clinically.

The radiographic alterations and diminished mobility observed in group A were statistically significant when compared with able-bodied patients (group C), but group A did not show clinical repercussions in the feet, which remained planted and in an adequate position for walking with a load, suggesting that treatment with electrical stimulation and partial load maintains the feet and ankles in an adequate walking position in patients with spinal cord injuries, which is a favorable aspect of the new technologies allowing these patients to reacquire their independent walking capacity. The clinical and radiographic assessment of group B patients, when compared with group C, suggested that the group B patients' feet were more rigid than those in group A patients. The clinical and radiographic assessment of group B patients, when compared with group C, suggested that the group B patients' feet were more rigid than those in group A patients. This rigidity must be considered because group A patients realize NMES, which can lead to a better mobility.

Some limitations of this study must be considered. The angular and mobility measurements were carried out by two independent examiners according to a manual method. Each examiner conducted three measurements, and the mean was obtained by combining the repeated measurements for each radiographic angulation and each mobility value. This method was used because of the lack of a digital goniometer.[12]

No studies were found in the literature regarding the foot and ankle patterns of patients with spinal cord injuries. The absence of such research suggests that more studies are needed to define standards and to compare different treatments for this group of patients attempting to regain walking.

It is possible to conclude that the partial-load NMES maintained the feet and ankles of patients with spinal cord injuries in an adequate walking position. This finding indicates a favorable aspect of new technologies that may allow these patients to regain independent walking capacity.

Conflict of interest

The authors declare no conflict of interest.

References

1 DeVivo MJ. Causes and costs of spinal cord injury in the United States. *Spinal Cord* 1997; **35**: 809–813.
2 Bracken MB, Freeman Jr DH, Hellenbrand K. Incidence of acute traumatic hospitalized spinal cord injury in the United States, 1970–1977. *Am J Epidemiol* 1981; **113**: 615–622.
3 El Masry WS, Tsubo M, Katoh S, El Miligui YH, Khan A. Validation of the American Spinal Injury Association (ASIA) motor score and the National Acute Spinal Cord Injury Study (NASCIS) motor score. *Spine* 1996; **21**: 614–619.
4 Kim CM, Eng JJ, Whittaker MW. Effects of a simple functional electric system and/or a hinged ankle-foot orthosis on walking in persons with incomplete spinal cord injury. *Arch Phys Med Rehabil* 2004; **85**: 1718–1723.
5 Hidler JM, Harvey RL, Rymer WZ. Frequency response characteristics of ankle plantar flexors in humans following spinal cord injury: relation to degree of spasticity. *Ann Biomed Eng* 2002; **30**: 969–981.
6 Kitaoka HB, Alexander IJ, Adelaar RS, Nunley JA, Myerson MS, Sanders M. Clinical rating systems for the ankle-hind foot, midfoot, hallux, and lesser toes. *Foot Ankle Int* 1994; **15**: 349–353.
7 Coughlin MJ, Saltzman CL, Nunley 2nd JA. Angular measurements in the evaluation of hallux valgus deformities: a report of the *ad hoc* committee of the American Orthopaedic Foot & Ankle Society on angular measurements. *Foot Ankle Int* 2002; **23**: 68–74.
8 Levi R, Hultling C, Nash MS, Seiger A. The Stockholm spinal cord injury study: 1. Medical problems in a regional SCI population. *Paraplegia* 1995; **33**: 308–315.
9 Pownel PH. Pressure sore. Selected readings in plastic surgery. *Plast Surg* 1995; **7**: 1–27.
10 National Pressure Ulcer Advisory Panel. Pressure ulcers: incidence, economics, risk assessment. *Consensus Development Conference Statement*. S-N Publications Incorporated: West Dundee, IL, 1989.
11 McDonald MF, Kevin Garrison M, Schmit BD. Length-tension properties of ankle muscles in chronic human spinal cord injury. *J Biomech* 2005; **38**: 2344–2353.
12 Schneider W, Csepan R, Knahr K. Reproducibility of the radiographic metatarsophalangeal angle in hallux surgery. *J Bone Joint Surg Am* 2003; **85**: 494–499.