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Original Article

Effects of dorsiflexor functional electrical stimulation compared to an ankle/foot orthosis on stroke-related genu recurvatum gait

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Abstract. [Purpose] We evaluated the effects of functional electrical stimulation (FES) and an ankle/foot orthosis (AFO) in hemiplegic patients exhibiting excessive plantar flexion during the stance phase, associated with genu recurvatum. [Participants and Methods] In total, 12 stroke patients were recruited. We measured changes in knee and ankle joint angles, gait speed, and step and stride length during the gait cycle during barefoot walking, walking while wearing an AFO, and walking after FES application; we used a three dimensional gait analysis system. [Results] In terms of kinematic variables, FES walking was associated with significant increases in peak ankle dorsiflexion during swing, dorsiflexion angle at initial contact, peak ankle dorsiflexion during stance, knee angle at initial contact, and peak knee flexion in the loading response compared to AFO and barefoot walking. AFO walking was associated with a significant difference in peak ankle dorsiflexion during swing compared to barefoot walking. [Conclusion] FES afforded kinematic advantages to the ankle and knee joints compared to AFO in hemiplegic patients with a genu recurvatum gait.

Key words: Functional electrical stimulation, Ankle/foot orthosis, Genu recurvatum

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INTRODUCTION

Genu recurvatum (GR), a gait pattern commonly seen in hemiplegic patients, is defined as full extension or hyperextension of the knee in the stance phase. GR is observed in 40 to 68% of patients with post-stroke hemiplegia[1)]. GR can be caused by a variety of mechanisms, including weakness of the quadriceps, hamstring, and hip muscles; spasticity of the quadriceps; excessive plantar flexion; and a proprioceptive disorder[2)]. Excessive plantar flexion is usually caused by weakness of the dorsiflexor or by spasticity or contracture of the plantar flexor per se, which causes the foot to drop during the swing phase[2)].

To solve the problem, ankle/foot orthoses (AFOs) and functional electric stimulation (FES) have been evaluated[3)]. AFOs passively prevent foot drop during the swing phase and thus exert a correctional effect by maintaining ankle dorsiflexion (DF) and improving initial contact[4, 5)]. In addition, when an AFO is worn by hemiplegic patients, the peak angle of knee flexion is significantly increased, and the stride and walking speed also increase[6, 7)].

FES of the peroneal nerve has been proposed as an alternative to AFO when ankle DF is impaired. Unlike AFOs, FES preserves ankle joint mobility and muscle activity. Van Swigchem et al.[8)] showed that application of FES in patients with hemiplegia improved ankle DF and hip and knee joints angles, and also increased the ankle push off force during walking, enhancing gait symmetry more than did an AFO. Kottink et al.[9)] reported that FES increased the knee flexion angle by an average of 3° at initial contact.

Many attempts have been made to analyze the gait of patients with hemiplegia. However, although clinical studies have explored the effects of AFOs and FES on the ankle joint, few have evaluated their effects on the knee joint. Also, few studies

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Table 1. Demographic characteristics of the stroke participants (n=12)

Gender (M/F)	Age (years)	Height (cm)	Weight (kg)	Etiology (ISC/HAE)	Affected limb (R/L)	MMSE-K	MAS	Post stroke (months)
8:4	54.41 ± 19.29	164.70 ± 7.87	66.74 ± 12.88	6:6	6:6	27.41 ± 2.39	0.25 ± 0.45	13.16 ± 9.73

M: male; F: female; ISC: ischemic; HAE: hemorrhagic; R: right; L: left; MMSE-K: Mini Mental State Examination-Korea version; MAS: Modified Ashworth Scale.

have compared the effects of AFO and FES on GR during walking. Therefore, we explored the effects of FES and an AFO in hemiplegic patients exhibiting excessive plantar flexion during the stance phase associated with GR; we used a three dimensional gait analysis system.

PARTICIPANTS AND METHODS

We enrolled 12 adult hemiplegic patients diagnosed with stroke via computed tomography and magnetic resonance imaging at Pusan National University Yangsan Hospital, Korea. The inclusion criteria were 1) MMSE-K score ≥24 points; 2) ability to walk independently for ≥10 m; 3) MAS scores of 0–2; 4) neurological injury creating a requirement for a AFO; 5) excessive plantar flexion during the stance phase associated with genu recurvatum; and 6) a diagnosis of hemiplegia caused by a stroke at least 6 months prior. The exclusion criteria were 1) severe ankle joint contracture (>5° of ankle plantar flexion) and/or 2) a neurological or orthopedic disease causing other motor disabilities. The study was approved by the Institutional Review Board (IRB) of Pusan National University Yangsan Hospital (approval no. 03-2018-005) and written informed consent was obtained from each participant. The general characteristics of all patients are listed in Table 1.

The AFOs used had been physician-prescribed for gait training; all were UD FLEX AFOs featuring 5° of ankle DF. FES was delivered using an XFT-2001D machine (Shenzhen XFT Electronics Co., Shenzhen, China); this is a foot-drop stimulator. The machine features a functional stimulation cuff with an integrated stimulation unit and electrodes, a control unit, and 5 × 5 cm adhesive electrodes, which are attached to the peroneal nerve (at the back of the fibular head) and the anterior tibial muscle (5 cm below the fibular head), and then adjusted to create ankle DF during the swing phase. The FES waveform was asymmetrically balanced and biphasic, and was delivered at an intensity that induced maximum DF without inflicting severe pain. The time to attain peak intensity (the ramp up time) was 2 s, the pulse frequency 35 Hz, and the pulse width 250 µs. We used a Human Motion device (Motion Analysis Corp., Seoul, Korea) to measure gait characteristics when patients walked barefoot, wearing a AFO, and after FES application. To facilitate recording of leg movements, markers were placed on all patients in locations dictated by their physical examinations. Markers were placed on the L5-sacrum interface, the anterior superior iliac spine, the lateral and medial femoral condyles, the lateral and medial malleoli, the second and third metatarsals, and the posterior calcaneus. With the exception of the sacrum, two markers were attached to all regions (one each on the right and left sides), for a total of 15 markers (the Helen Hayes Full Body Static Marker set). Marker data were collected at 100 Hz by six cameras and analyzed using dedicated CORTEX ver. 3.6.1 software.

Before starting measurements, all participants were instructed to walk barefoot on a 6 m board at their most comfortable speed. Next, each participant walked while wearing an AFO and after receiving FES. Each walking modality was repeated three times (nine gait cycles in all). A 10 minutes break was mandatory between evaluation of gait conditions, as was a 3 minutes break between gait cycles. In addition, to exclude any correctional effects of shoes, participants were instructed to walk without shoes both when wearing the AFO and after FES. The outcome measures used to evaluate the effectiveness of AFO and FES were the knee flexion angle, the ankle DF angle in the sagittal plane during gait in the paretic leg, and spatiotemporal parameters (gait speed, and step and stride lengths). Data are presented as means ± standard deviations. Significant differences among the three types of walking (barefoot, wearing an AFO, and after FES) were evaluated using repeated-measures analysis of variance. If any significant interaction between exercise type and side was apparent, a post hoc analysis using the Kolmogorov-Smirnov test and a paired t-test were conducted to identify differences in the paired comparisons. All analyses were performed with the aid of SPSS ver. 18.0 software (SPSS, Chicago, IL, USA). The level of significance was set to $p<0.05$.

RESULTS

FES walking was associated with significant increases in the peak ankle DF during the swing phase, the DF angle at initial contact, the peak ankle DF during the stance phase, the knee angle at initial contact, and the peak knee flexion on loading compared to barefoot and AFO walking ($p<0.05$). AFO walking was associated with a significant difference in the peak ankle DF during swing compared to barefoot walking ($p<0.05$). No differences in gait speed or in step or stride length were noted among walking modalities (Table 2).

Table 2. Mean spatiotemporal and kinematic parameters by device group (N=12)

	No device (ND)	FES	AFO
Spatiotemporal parameters			
Gait speed (cm/sec)	41.06 ± 22.77	39.89 ± 18.30	41.06 ± 20.30
Step length (cm)	32.95 ± 11.10	32.07 ± 8.75	32.80 ± 9.90
Stride length (cm)	65.50 ± 21.38	64.31 ± 16.96	65.66 ± 21.14
Kinematic parameters			
Peak ankle DF in swing (deg)	0.56 ± 6.40	6.15 ± 7.24[a,b]	3.14 ± 6.77[a]
Peak ankle DF on stance (deg)	10.14 ± 7.07	12.49 ± 7.04[a,b]	10.64 ± 6.87
DF angle at initial contact (deg)	−5.65 ± 5.40	0.23 ± 5.80[a,b]	−3.65 ± 4.48
Peak knee flexion in swing (deg)	53.60 ± 12.09	56.93 ± 15.07	53.46 ± 11.08
Knee angle at initial contact (deg)	12.09 ± 11.19	16.59 ± 9.06[a,b]	12.67 ± 9.18
Peak knee flexion in loading response (deg)	20.96 ± 13.62	26.88 ± 12.48[a,b]	23.05 ± 12.08
Knee angle at mid-stance (deg)	8.40 ± 11.22	9.53 ± 11.66	8.20 ± 11.25

a; significant difference from ND ($p<0.05$). b: significant difference from AFO ($p<0.05$).
FES: functional electric stimulation; AFO: ankle/foot orthoses.

DISCUSSION

Improving the gait of hemiplegic patients is a key goal of rehabilitation; this allows patients to regain functional independence and enhances their quality of life. Gait training seeks to reduce gait abnormalities and enhance gait symmetry, lower limb joint movements, and the efficiency of the gait pattern[10]. We enrolled hemiplegic patients with GR exhibiting excessive plantar flexion in the stance phase; they walked with an AFO or after FES, and we performed kinematic and spatiotemporal analyses exploring changes in gait variables.

FES walking was associated with significant increases in the peak ankle DF during swing, in the DF angle at initial contact, and in the peak ankle DF during stance compared to barefoot and AFO walking. The increase in the DF angle after FES indicated that FES corrected excessive plantar flexion by artificially inducing DF via electric stimulation of the weak tibialis anterior muscle during the swing phase. This is consistent with the report by Kottink et al.[9]; participants with foot drop exhibited increased ankle joint DF at initial contact and in the swing phase when they wore a peroneal nerve stimulator compared with DF using an AFO or walking barefoot. Our results are also consistent with those of other studies showing that FES improved foot positioning prior to initial contact by increasing ankle DF in the swing phase. The AFO increased maximum DF only in the swing phase compared to the control (barefoot walking), but it had no effect in the stance phase, indicating that the AFO improved excessive plantar flexion to some extent during the swing phase but that the effect disappeared when the entire sole, rather than only the heel, touched the floor after initial contact.

Reduced knee flexion in the stance phase of gait is a characteristic of hemiplegic patients. We found significant increases in knee flexion (both the knee angle at initial contact and the peak knee flexion on loading) during FES walking compared to AFO and barefoot walking, indicating that the angle of knee flexion increased as the heel was rocked by the FES at initial contact[11]. Kottink et al.[9] reported that stimulation of the peroneal nerve to reduce foot drop in hemiplegic patients increased knee flexion at initial contact during gait by an average of 3°, consistent with our results, but it did not correct GR during mid-stance. Here, knee flexion was increased via FES of the peroneal nerve when the heel touched the floor at initial contact; the center of the knee joint then moved forward via tibial advancement, but knee hyperextension could not be avoided in mid-stance because of the considerable passive momentum of the knee, which might be attributable to the fact that we focused only on correcting excessive plantar flexion in the swing phase. Springer et al.[12] suggested that FES should be applied not only to the peroneal nerve but also to the proximal quadriceps femoris muscle or the hamstring (proximal muscles) when seeking to correct GR in the stance phase. This would correct any weakness of the proximal muscles so the focus would not be exclusively on the distal muscles. We found that GR was not efficiently corrected in the stance phase, perhaps because the devices used did not stimulate the proximal muscles.

We found no significant difference in gait speed or in step or stride length among the walking conditions, perhaps because all participants had been hemiplegic for at least 6 months and had become accustomed to walking barefoot.

The limit of this study is that the number of patients participated in the experiment was small (n=12). Also, we did not explore the association between the trunk and the pelvis; we focused on only the ankle and knee joints. In addition, the long term effects of AFO and FES therapy were not explored. We compared the effects of FES and an AFO on gait in hemiplegic patients with GR associated with excessive plantar flexion. FES increased knee flexion from the time of initial contact to loading by inducing maximum DF during the swing phase via peroneal nerve stimulation; FES was thus useful for gait training. Further studies are needed.

Conflict of interest

None.

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