The effects of dual-channel functional electrical stimulation on stance phase sagittal kinematics in patients with hemiparesis

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ABSTRACT

Sixteen subjects (aged 54.2 ± 14.1 years) with hemiparesis (7.9 ± 7.1 years since diagnosis) demonstrating a foot-drop and hamstrings muscle weakness were fitted with a dual-channel functional electrical stimulation (FES) system activating the dorsiflexors and hamstrings muscles. Measurements of gait performance were collected after a conditioning period of 6 weeks, during which the subjects used the system throughout the day. Gait was assessed with and without the dual-channel FES system, as well as with peroneal stimulation alone. Outcomes included lower limb kinematics and the step length taken with the non-paretic leg. Results with the dual-channel FES indicate that in the subgroup of subjects who demonstrated reduced hip extension but no knee hyperextension ($n = 9$), hamstrings FES increased hip extension during terminal stance without affecting the knee. Similarly, in the subgroup of subjects who demonstrated knee hyperextension but no limitation in hip extension ($n = 7$), FES restrained knee hyperextension without having an impact on hip movement. Additionally, step length was increased in all subjects. The peroneal FES had a positive effect only on the ankle. The results suggest that dual-channel FES for the dorsiflexors and hamstrings muscles may affect lower limb control beyond that which can be attributed to peroneal stimulation alone.

1. Introduction

The pathologic gait pattern of patients with hemiplegia is typically characterized by slow speed, asymmetrical pattern of movement, shorter step length, and altered control over the hip, knee and ankle. This impaired gait pattern severely impacts the functional performance and quality of life of these patients (Bethoux et al., 1999; Olney and Richards, 1996; Woolley, 2001). While different types of abnormalities can be identified in the stance phase of the hemiplegic gait, reduced hip extension at terminal stance and knee hyperextension at mid- to terminal stance are two of the most frequent deficits affecting gait (Kerrigan et al., 1996; Moseley et al., 1993; Olney and Richards, 1996).

Hip extension is important for forward progression at mid-stance, with a reduction in the range of hip extension at terminal stance limiting the ability to take longer steps (Shumway-Cook and Woollacott, 2007). Indeed, maximal hip extension of the affected limb in patients with hemiparesis has been shown to strongly correlate with gait speed (Olney et al., 1994). Furthermore, reduced peak hip extension is related to instability and higher risk for falls (Kerrigan et al., 2001).

Knee hyperextension during the stance phase may influence the entire gait pattern, rendering it both spatially and temporally asymmetrical. As knee flexion is initiated during the pre-swing phase, knee hyperextension makes it difficult to achieve the knee flexion necessary for foot clearance during the swing phase (Perry, 1992). Genu-recurvatum also increases the external mechanical work connected to elevation of the body's center of mass, consequently raising the energy cost of gait. Moreover, genu-recurvatum may be painful as a result of stress to the ligaments and tendons at the back of the knee. While knee hyperextension is frequently encountered in patients with hemiparesis, not much is suggested in the literature in terms of management strategies (Bleyenheuft et al., 2010). Weakness and uncoordinated activation of the hamstrings muscles has been mentioned as a cause for knee hyperextension, especially if the quadriceps muscle is spastic (Bleyenheuft et al., 2010).

Hip and particularly knee control depend primarily on the interdependent activation of the quadriceps and hamstrings muscles. In normal gait, the hamstrings muscles are active from late swing

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phase when they act to decelerate hip flexion and knee extension, with their activity continuing into the mid-stance phase (Perry, 1992). Being a two-joint muscle, the hamstrings action during the stance phase is complex, as it can participate both in active hip extension and in restraining knee hyperextension (Perry, 1992; Stewart et al., 2008). Hamstrings activation at the onset of stance is vital to stabilize the knee joint (Wall-Scheffler et al., 2010). Furthermore, studies suggest that the hamstrings may contribute to the hip extensor power at mid to terminal stance and may serve to compensate for reduced soleus power output (McGibbon, 2003; Schmitz et al., 2009). In individuals with hemiparesis, the hamstrings muscles have been shown to be more impaired than the quadriceps muscles (Sharp and Brouwer, 1997; Thijs et al., 1998), with a recent study suggesting that hamstrings weakness in this population is related to functional incapacity and gait impairments (Prado-Medeiros et al., 2012).

Functional electrical stimulation (FES) has been used for many years to assist patients who present with gait difficulties resulting from hemiplegia. An estimated 20% of all patients post-stroke exhibit impaired control of the ankle musculature, resulting in a foot-drop that limits the ability to clear the foot during the swing phase of gait (Wade et al., 1987). Peroneal FES for foot-drop correction is becoming an accepted and effective orthotic device due to technological advances and commercially available systems (van Swigchem et al., 2011). However, FES of the dorsiflexors does not improve all gait deficits associated with hemiplegic gait.

Several studies have reported the contribution of multi-channel FES, including hamstrings muscles stimulation, as a therapeutic modality for gait rehabilitation in patients with acute hemiplegia (Bogataj et al., 1995; Daly et al., 2006; Yan et al., 2005). Although feasibility and some benefits of multi-channel FES have been demonstrated, the research involving multi-channel stimulation has focused mainly on evaluating the therapeutic effects of FES in patients at the initial stages of rehabilitation (acute phase) or in patients with severe motor disability, who are unable to walk independently.

However, many patients with chronic hemiplegia already living in the community still demonstrate gait disorders. Multi-channel FES used as an active orthotic device to assist in controlling the ankle, knee, and hip during gait, may be beneficial to this population.

Moreover, kinematic studies may be useful in understanding the underlying mechanism of the effects of dual-channel FES.

The objective of this study was to investigate the effects of daily peroneal and hamstrings muscles FES on the kinematic aspects of gait performance during the stance phase in individuals with hemiparesis. In particular, we tested the hypothesis that the studied dual-channel FES application would enhance walking performance by improving hip extension and restraining knee hyperextension in patients with hemiparesis.

2. Methods

2.1. Participants

Participants were 16 patients suffering from foot-drop and deficits in knee and/or hip control due to upper motor neuron lesions. Inclusion criteria for subject selection were: (1) diagnosis of an upper motor neuron lesion; (2) hamstrings muscles strength of less than 4/5, as determined by manual muscle testing; (3) foot-drop – toe drag during walking; (4) lower limb spasticity, as defined by a score of 0–3 on the modified Ashworth scale; (5) ability to walk independently or with an assistive device (e.g., cane, walker, etc.)/spot guarding for at least 10 m; (6) ability to follow multiple-step directions, with a score greater than 21 on the Mini

Mental State Exam (Folstein et al., 1975); and (7) sufficient response to electrical stimulation, meaning visible muscle contractions of each designated muscle tested in a seated or standing position. Exclusion criteria were a cardiac pacemaker; a skin lesion at the site of the stimulation electrodes; severe neglect (Star cancellation test <30); or major depression.

2.2. The FES system

The dual-channel FES system used in this study (NESS L300Plus) consists of lower leg and thigh cuffs, a gait sensor, and a control unit that communicates by radio frequency signals. Each cuff integrates two electrodes and a stimulation unit. The electrodes of the lower leg cuff (two round 45 mm-diameter cloth electrodes) were positioned over the common peroneal nerve and the tibialis anterior muscle. The electrodes of the thigh cuff (two oval cloth electrodes, proximal: 130×75 mm, distal: 120×63 mm) were positioned over the hamstrings muscle.

The gait sensor detects the force under the foot using a force-sensitive resistor. It uses a dynamic gait tracking algorithm to detect whether the foot is on the ground or in the air and transmits radio signals to synchronize the stimulation according to the timing of gait events. A miniature control unit enables the user to activate the system and receive information regarding its status. A hand-held computer (PDA) is used by a clinician during the fitting process to set the stimulation parameters (e.g., intensity, pulse frequency) and the timing of the stimulation. To adjust the stimulation timing, stance and swing phases are represented to the clinician by the PDA's screen in a 5% resolution. The peroneal stimulation always starts when heel off is recognized and terminates with heel contact. In some patients the clinician may extend the stimulation beyond heel contact to increase ankle stability. The duration of this "extended" period is defined by percentage of the stance period. The hamstrings stimulation can start and end at any segment in the gait cycle, as defined by the clinician. The NESS L300Plus is based on the NESS L300 module (leg cuff, stimulation unit, and gait sensor), which has proven to be effective for correcting foot-drop (Hausdorff and Ring, 2008; Laufer et al., 2009a, 2009b; Ring et al., 2009).

2.3. Procedures

The study was approved by the Institutional Review Board of the Reuth Medical Center, Israel. All subjects signed an informed consent form prior to participation. At the initial examination demographic and medical history data were obtained. (e.g., diagnosis, age, gender, and affected side) and each patient's gait was assessed during a 2 min walk test (2MWT). In the 2MWT, the subjects were instructed to walk as far as they could, at their self-selected normal walking speed, back and forth along a 50-m hallway, turning around each time they reached the end of the walkway. Average gait speed was determined by dividing the distance covered in 2 min by seconds. Then the subjects were fitted with the L300Plus, providing peroneal and hamstrings muscles FES.

Stimulation parameters were initially set in a seated position and were readjusted during standing and walking to ensure optimal movement, as determined by visual inspection (i.e., no under- or over-correction). The peroneal stimulation (symmetrical biphasic, phase duration 200 μs, pulse rate 30 Hz) was configured to stimulate throughout the swing to early stance so as to ameliorate foot-drop and assist with ankle stability at initial contact, while the hamstrings stimulation (symmetrical biphasic, phase duration 300 μs, pulse rate 40 Hz) was delivered during the stance phase in order to assist with active hip extension and/or to restrain knee hyperextension. In order to determine the appropriate timing of the hamstrings stimulation, two physical therapists independently
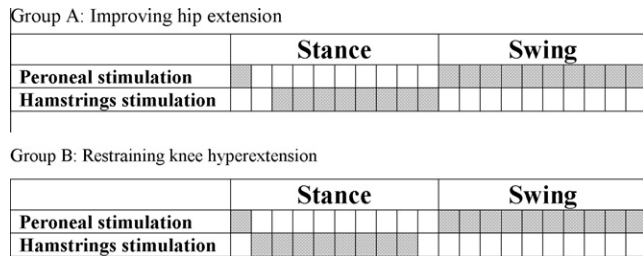
Fig. 1. The timing of the stimulation sequences in the two groups. Stance and swing phases are each divided into ten equal time segments, which are represented by squares. Black squares represent stimulation on, and white squares represent stimulation off.

assessed each patient's gait during a 10-m walk at a comfortable pace, which was repeated twice. The hamstrings FES was applied from 10% to 90% of the stance in patients who demonstrated knee hyperextension during stance; and from 20% to 100% of stance in patients who demonstrated reduced hip extension (see Fig. 1).

This initial fitting was followed by a 6-week adaptation period, during which participants increased their daily use of the system according to a fixed protocol, so that by the end of the fourth week, all subjects were able to use the system for the entire day. During the adaptation period, the subjects could use the system's control unit to fine-tune the stimulation intensity as needed. However, they could not change the timing of the stimulation.

After 6 weeks of conditioning, lower limb kinematics were collected using the Vicon® motion analysis system. Motion analysis was applied according to the biomechanical model PlugInGait, developed by Vicon® (Kadaba et al., 1990), with three markers spatially defining each segment (i.e., pelvis, thigh, shank and foot). Changes in the lower extremity alignment were captured and processed by six computerized cameras at a 120 Hz acquisition rate.

Gait was assessed with and without the dual-channel FES system, and with peroneal stimulation alone, while the patients walked on a treadmill at their self-selected walking speed. The subjects were instructed to walk as naturally as possible and were allowed to hold onto the treadmill handrails. An emergency stop switch was available to both the subject and the clinician. The first assessment was always performed without FES, and the self-selected walking speed in this condition was used for both subsequent FES conditions (i.e., peroneal FES alone and dual-channel peroneal and hamstring FES). At least seven strides were recorded and analyzed to represent the gait pattern under each condition.

The outcomes included the peak knee and hip extension angles determined during the stance phase and the degree of ankle dorsiflexion at initial contact (IC). Also assessed was the step length taken with the non-paretic leg, since the ability to generate sufficient step length with the non-paretic leg is related to the performance of the paretic leg during stance (Allen et al., 2011). In subjects who demonstrated knee hyperextension, an additional calculation was done for the percentage of the gait cycle during which the knee was hyperextended.

2.4. Statistical analysis

Descriptive statistics were used to summarize patient background data. Two subgroups were defined: (1) subjects who did not demonstrate knee hyperextension, where hamstrings

Table 1
Demographic and clinical data on the 16 subjects.

Subject	Gender (M/F)	Age (years)	Diagnosis	Onset (years)	Paretic side (Rt/Lt)	Gait speed (m/s)	FES logic for hamstrings stimulation
1	F	38	Brain tumor resection	2.3	Rt	0.73	Reduced hip extension
2	M	67	CVA	4.6	Rt	0.66	Knee hyperextension
3	F	40	CVA	1.5	Lt	0.66	Knee hyperextension
4	F	46	CVA	16.8	Lt	1.07	Knee hyperextension
5	M	54	CVA	11.5	Rt	0.60	Reduced hip extension
6	M	64	CVA	2.0	Rt	0.40	Knee hyperextension
7	F	34	TBI	10.0	Rt	0.78	Knee hyperextension
8	M	61	CVA	2.7	Rt	0.60	Knee hyperextension
9	F	27	TBI	10.4	Lt	0.85	Reduced hip extension
10	F	66	CVA	7.6	Rt	0.80	Reduced hip extension
11	M	44	CVA	6.8	Rt	1.02	Reduced hip extension
12	F	68	CVA	9.0	Rt	0.28	Reduced hip extension
13	M	57	CVA	0.4	Lt	0.55	Knee hyperextension
14	F	64	CVA	4.2	Rt	0.70	Reduced hip extension
15	F	73	CVA	28.5	Rt	0.84	Reduced hip extension
16	M	64	CVA	7.6	Rt	0.74	Reduced hip extension
Count	F = 9 M = 6		CVA = 13 TBI = 2 Tumor = 1		Rt = 14 Lt = 2		Reduced hip extension = 9 Knee hyperextension = 7
Mean (SD)		54.2 (14.1)		7.9 (7.1)		0.70 (0.2)	

Table 2
Kinematic measures and step length in the three conditions (mean and standard deviation in brackets).

Group	Outcome measure	No stim.	Peroneal stim.	Peroneal and hams. stim.
Group A: Reduced hip extension (n = 9)	Peak hip extension during stance (°)	11.6 (9.9)	11.0 (8.7)	9.1 (8.9)
	Peak knee extension during stance (°)	11.4 (5.3)	10.3 (5.5)	11.5 (5.8)
Group B: Knee hyperextension (n = 7)	Peak knee extension during stance (°)	−4.1 (4.9)	−3.5 (4.9)	−2.5 (4.7)
	Stride duration in knee hyperextension (%)	29.1 (21.4)	27.4 (21.1)	25.8 (21.0)
	Peak hip extension during stance (°)	−7.3 (8.7)	−6.9 (8.1)	−7.3 (8.3)
Group A + B (n = 16)	Ankle dorsiflexion at initial contact (°)	−6.2 (11.8)	7.2 (4.2)	7.0 (3.7)
	Step length non-paretic leg (cm)	41.3 (8.4)	41.7 (9.0)	43.7 (9.8)

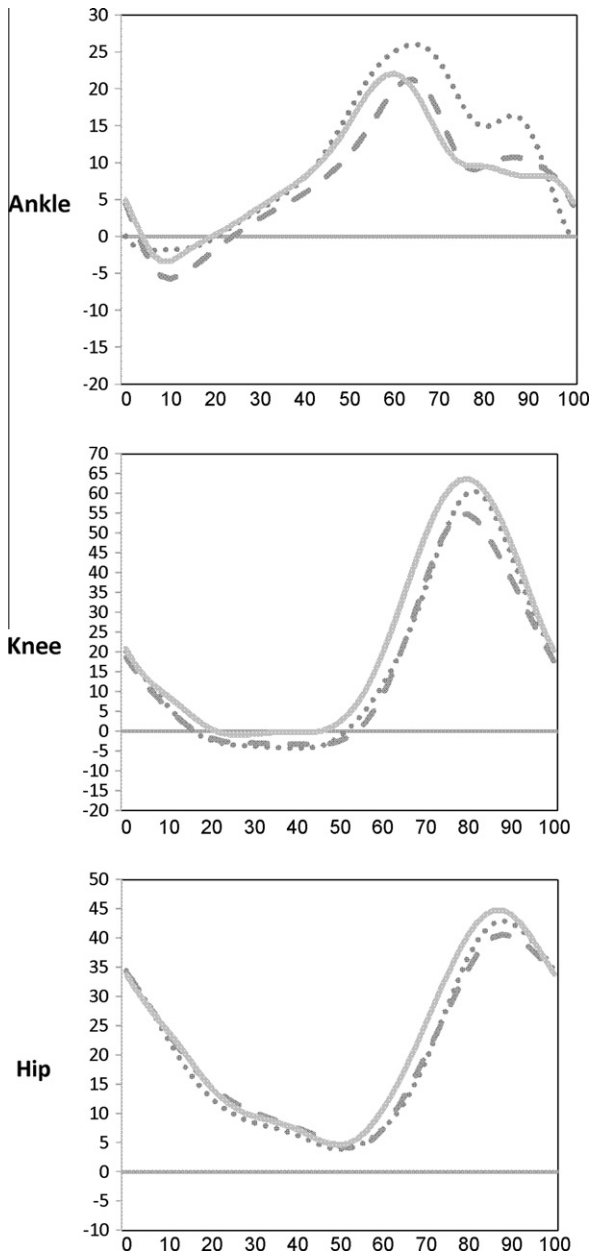Stim. = stimulation; hams. = hamstrings.

Fig. 2. Sagittal plane movement of the ankle, knee and hip one subject (Group B) throughout the gait cycle for the three conditions. Round dot – no stimulation; broken line – peroneal FES; solid line – peroneal and hamstrings FES.

stimulation was aimed primarily at improving hip extension (Group A, $n = 9$); (2) subjects who did demonstrate knee hyperextension, where hamstrings stimulation was mainly intended to restrain knee hyperextension (Group B, $n = 7$).

As the data were not normally distributed, non-parametric statistics were used for analysis. Friedman's test was used to compare the results of the three gait conditions (i.e., no stimulation, peroneal FES alone, and dual-channel peroneal and hamstrings FES). Post hoc analysis comparing all pairs of conditions was performed using Conover's method. Significance was determined at $p < 0.05$.

Separate analyses were conducted for the peak knee and hip extension angles during stance in each subgroup, as well as for the percentage of the gait cycle during which the knee was hyperextended in the subjects who demonstrated knee hyperextension. The degree of ankle dorsiflexion at initial contact and the step length taken with the non-paretic leg were analyzed for all the patients together (Group A + B, $n = 16$).

3. Results

Demographic and clinical data on the 16 subjects is summarized in Table 1. The average age of the patients was 54.2 ± 14.1 years, and 9 patients (56%) were female. Thirteen patients (81%) were post-CVA, while the remaining patients were diagnosed with a brain lesion due to traumatic brain injury ($n = 2$) or resection of a brain tumor ($n = 1$). The average time since diagnosis was 7.87 ± 7.05 years. All the subjects had chronic hemiparesis (i.e., more than 6 months since the insult), with the exception of one subject who was in the sub-acute phase of rehabilitation (i.e., 5 months after the diagnosis). Twelve patients (75%) had right-side hemiparesis. All the subjects were community ambulators, and their average walking speed in the 2-min walk test was 0.70 ± 0.20 m/s.

Table 2 presents the means and SDs of all measured gait variables under all three conditions (i.e., no stimulation, peroneal stimulation alone, and dual-channel peroneal and hamstrings stimulation) per group. Fig. 2 presents the sagittal plane movement of the ankle, knee and hip of one subject from Group B during the three conditions.

Table 3 presents the Freidman's test analysis results comparing the overall effect of the three conditions per group, as well as the Conover's post hoc analysis of multiple comparisons.

In the group where hamstrings stimulation was aimed primarily at improving hip extension (Group A), the Friedman's analysis indicated a significant stimulation effect only on hip extension and not on peak knee extension. The post hoc analysis comparing the dual-channel stimulation condition with no stimulation and with peroneal stimulation alone demonstrated that the effect on hip extension was achieved only with dual-channel stimulation.

In the group where hamstrings stimulation was aimed mainly at restraining knee hyperextension (Group B), the Friedman's analysis indicated a significant stimulation effect only on knee hyperextension and not on the percentage of the gait cycle during which the knee was hyperextended or on peak hip extension. Parallel to the post hoc analysis of Group A, the results indicate that in comparison to no stimulation, peroneal stimulation alone did not affect knee hyperextension, while dual-channel stimulation did have an effect. However, only a trend ($p = 0.07$) was observed when comparing dual-channel stimulation with peroneal stimulation alone.

Finally, a significant condition effect was determined for the two parameters analyzed for the entire group together, namely the ankle dorsiflexion angle at initial contact and the step length taken with the non-paretic leg. The post hoc analysis indicated that both FES conditions demonstrated a positive effect on ankle dorsiflexion angle at initial contact, with no significant difference between them. In contrast, step length improved significantly only with dual-channel stimulation.

4. Discussion

This study aimed to examine the effects of peroneal and hamstrings muscles FES on the kinematic aspects of gait performance in individuals with hemiparesis. The results support the hypothesis that the studied dual-channel FES system improves gait performance in this group of patients. While peroneal stimulation alone eliminated foot drop during the swing phase, but had no effect on hip or knee kinematics, the addition of hamstring muscle stimulation resulted in increased hip extension and decreased knee hyperextension during stance. These findings indicate that such dual-channel FES can serve as an orthotic device, decreasing the deficits at the hip, knee, and ankle which affect the gait of individuals with chronic hemiparesis. It should also be noted that the obtained kinematic changes at the hip and knee are beyond the range

Table 3
Results of Friedman's test and post hoc analysis comparing all pairs of conditions (Conover's test).

Group	Outcome measure	Friedman's test	No stim. vs. peroneal stim.	No stim. vs. peroneal and hams. stim.	Peroneal stim. vs. peroneal and hams. stim.
Group A: Reduced hip extension ($n = 9$)	Peak hip extension during stance	**<0.001**	NS (1.00)	**<0.001**	**<0.001**
	Peak knee extension during stance	NS (0.74)	NS (0.51)	NS (1.00)	NS (0.51)
Group B: Knee hyperextension ($n = 7$)	Peak knee extension during stance	**0.03**	NS (0.35)	**0.01**	NS (0.07)
	Stride duration in knee hyperextension	NS (0.11)	NS (0.06)	NS (0.10)	NS (0.75)
	Peak hip extension during stance	NS (0.40)	NS (0.31)	NS (0.21)	NS (0.79)
Group A + B ($n = 16$)	Ankle dorsiflexion at initial contact	**<0.001**	**<0.001**	**<0.001**	NS (0.29)
	Step length non-paretic leg	**0.04**	NS (0.19)	**0.01**	NS (0.19)

Stim. = stimulation; hams. = hamstrings.

reported as a minimal detectable change (MDC), as determined by changes in joint kinematics in patients with similar pathologies (Kesar et al., 2011).

The positive effect on knee control of combining peroneal and hamstrings stimulation was previously demonstrated in a single case of a patient using dual-channel FES for a prolonged period of 10 months (Springer et al., 2012). Our findings extend the results of this case study by showing a statistically significant effect on knee hyperextension in a group of seven patients using the dual-channel FES for 6 weeks. Furthermore, to the best of our knowledge, the present study is the first to also document improved peak hip extension and increased step length as the result of dual-channel stimulation.

Hip extension is essential for the generation of appropriate step length, allowing the trunk to progress forward while the contralateral leg is in the swing phase (Allen et al., 2011). Thus, it may be surmised that the enhanced non-paretic step length found with dual-channel FES probably resulted from the improved hip function in the paretic leg during stance period. Increased step length (rather than increased cadence) is associated with increased walking speed in people post-stroke (Ada et al., 2003). It should be noted that similar to the effects on knee and hip kinematics, the 2.4 cm change in step length found with dual-channel stimulation is larger than the MDC for this variable, reported as 2.1 cm (Kesar et al., 2011).

Hamstrings muscles have the potential to participate in active hip extension and in restraining knee hyperextension (Perry, 1992; Stewart et al., 2008). Intriguingly, our results showed that in the subgroup of subjects who did not demonstrate knee hyperextension, hamstrings stimulation improved hip extension without affecting the knee. Similarly, in the subgroup of subjects who did demonstrate knee hyperextension, hamstrings stimulation restrained knee hyperextension without having an impact on hip movement. A possible explanation for this selective activation pattern of the hamstrings may be related to the different gait impairments between these two subgroups. Thus, in the subgroup of patients who demonstrated knee hyperextension, the average decrease in hip extension was negligible (i.e., −7.3 without stimulation), while in the subgroup of patients who demonstrated reduced hip extension, none of the subjects presented with knee hyperextension. Another potential mechanism for the obtained results may be the difference in the timing of the hamstring FES between the two subgroups. For example, in the subgroup of subjects who demonstrated knee hyperextension, the hamstrings stimulation started at an earlier stage of the stance phase when the hamstrings normally acts as a knee stabilizer (Perry, 1992; Stewart et al., 2008; Wall-Scheffler et al., 2010). Furthermore, previous studies have highlighted the difficulty of using an intuitive approach when assessing muscle action, particularly for two joint muscles during weight bearing (Kimmel and Schwartz, 2006; Neptune et al., 2004). Thus, for example, it has been demonstrated that the effect of hamstrings contraction on hip and knee joint motion depends on whether the proximal or the distal segment offer the greater resistance to movement (Frigo et al., 2010). Bi-articular muscle activation with FES has yet to be fully investigated.

FES is an accepted treatment method for paresis or paralysis after stroke, as well as for other neurological upper motor neuron disorders. Generally, the implementation of FES as an orthotic device has focused primarily on the stimulation of ankle musculature to improve ankle dorsiflexion during the swing phase of the gait cycle (van Swigchem et al., 2011). Thus, the recommendations made by various clinical practice guidelines point out the benefits of using peroneal FES for patients post-stroke (Bates et al., 2005; Royal College of Physicians Clinical and Evaluation, 2004). The results of this study suggest that these recommendations may be broadened to include dual-channel FES addressing hip and knee impairments as well.

The present study has several limitations. Only one kinematic assessment was carried out, following 6 weeks of daily usage, which allowed the subjects to adapt to the stimulation. As no baseline assessment was conducted prior to FES initiation, it is possible that the 6 weeks of stimulation had a therapeutic effect, resulting in improved gait without stimulation as well. Future studies should address the possibility of such a carryover effect (therapeutic effect) in their design. Additionally, kinematic data collection was performed only during treadmill walking. Assessment during over ground walking, which was in fact the training condition, and is the goal of rehabilitation, may shed further light on the effectiveness of dual channel stimulation.

Furthermore, the kinematic assessment at 6 weeks was always initiated with gait evaluation without FES, and the self-selected walking speed in this condition was used for both subsequent FES conditions. Given the finding of many studies that FES improves gait speed (Hausdorff and Ring, 2008; Laufer et al., 2009a, 2009b; van Swigchem et al., 2011), future investigations should also examine the kinematic effects of dual-channel FES while adjusting gait velocity in each condition respectively.

An additional limitation of the present study is the small sample size and the lack of a control group. However, the participants in this study were subjects with chronic hemiparesis. Since the performance of individuals with chronic hemiparesis is generally expected to either remain steady or deteriorate over time (Bethoux et al., 1999), it is unlikely that the results could have been achieved without the use of FES.

Individuals with hemiplegia often exhibit exaggerated frontal plane movements, such as hip circumduction and hip hiking (Kerrigan et al., 2000). Thus, future studies should examine the effects of FES on frontal plane kinematics. Future research should also evaluate the effects of such FES application on wider variety of patients such as patients in the acute phase of rehabilitation or patients with other relevant pathologies such as multiple sclerosis.

5. Conclusions

Six weeks of daily peroneal and hamstrings muscle FES improved lower limb kinematics and the step length taken with the non-paretic leg of patients with hemiparesis. These enhancements go beyond those observed with peroneal FES alone. The findings suggest that appropriate patients who suffer from hemiparesis can gain meaningful benefits by using dual-channel FES as an orthotic device.

Disclosures

S. Springer is employed by Bioness Neuromodulation, the manufacturer of the L300Plus.

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