Gait kinematics improvement as the result of using multi-pad electrode stimulation for treating foot drop

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Abstract
Recovery after stroke is commonly followed by the gait therapy to regain some independence in daily living. Motor weakness, poor motor control and spasticity result in an altered gait pattern and increased energy expenditure during walking. In more than 30% patients some of the gait impairments remain chronic. Ineffective ankle dorsiflexion during swing (foot drop) and failure to achieve heel strike at initial contact are common problems that disturb gait pattern after stroke.

1 Introduction

Foot drop is inability or difficulty of voluntary foot movement and is a major disability which often remains after a stroke [1]. Also, it is caused by multiple sclerosis, cerebral palsy, spinal cord trauma and neurological trauma from accident or surgical complication [2]. Walking is notably derange at people with foot drop, because of insufficient dorsiflexion in swing phase of the human gait. Decreased speed, longer stance phases and increases the risk of falls are some of the consequences [1].
Ankle foot orthosis (AFO) is commonly used for improving insufficient ankle dorsiflexion during the swing phase. An AFO passively holds the foot in a fixed position during walking [3]. Although AFOs provide safe toe clearance and fetch some biomechanical benefits, there are many disadvantages that remain [3, 4].
An active approach to the treatment of foot drop is functional electrical stimulation (FES). FES was first applied in stroke rehabilitation in 1961 by Liberson and his colleagues [5]. It operates by delivering short bursts of electrical pulses to the tibialis anterior during the swing phase of gait to allow proper foot clearance and prevent gait compensator methods. While numerous studies have shown that FES systems have proved to be successful in improving walking ability in stroke [6, 7], there are some problems associated with their application. The aforementioned issues are reliability and robust in stimulation triggering. Different sensors and its combinations were proposed for automatic stimulation triggering during walking [6, 8].
Multi-pad electrodes provide easier and faster donning and doffing, decrease muscle fatigue and improve selectivity of the stimulation based on multi, relatively small, stimulation pads [9].
In this paper we are presenting effects of using multi-pad stimulation system for correcting foot drop of hemiplegic patients. Presented system focuses on fast donning, fast optimization of stimulation patterns for achieving strong dorsiflexion/plantar flexion and automatic real-time control of ankle joint during FES assisted walking. The presented study involved 3 hemiplegic patient during 20 gait therapies. The functional improvement of the patient was assessed using kinematic measures during 10 m gait test: gait velocity, gait symmetries and kinematics of ankle joint during gait cycles measured with inertial measurement unit (IMU) positioned on patient's paretic and healthy foot.

2 Method

2.1 Subjects

3 subjects (2 males/1 female, age 57 ± 10) with hemiplegia were included. Demographic and clinical data of subjects are given in Table 1. All subjects received the conventional stroke rehabilitation program, given 1 session per day, 5 days a week for 4 weeks. No subject had another diseases or conditions which would compromise walking.

Table 1. Demographic and clinical data for 3 patients

Subject ID	Sex/age	Time since stroke (months)	Stroke diagnosis	The degree of disability	Aid
1	F/47	18	Right/hemo	Rankin 3	SC+AFO
2	M/68	16	Right/isch	Rankin 3	AFO
3	M/56	2	Right/hemo	Rankin 3	QC+AFO

With: Stroke diagnosis: ischemic (isch), hemorrhagic (hemo), aid: Ancle Foot Ortosis (AFO), simple cane (SC), quad cane (QC).

2.2 Stimulation

For the stimulation we used newer version of the INTFES stimulator [10] (Tecnalia Research and Innovation) with the same functionalities as well as some additional features. Every stimulation optimization session resulted in a definition of two stimulation patterns, one for dorsiflexion and one for plantar flexion. One stimulation pattern comprise set of pads along with accompanying stimulus parameters (pulse width and amplitude for each active pad). Each pad within multi-pad electrode acted as cathode and PalsPlatinum electrode (Axelgaard Manufacturing Co.) placed under the knee acted as anode. For this purpose was used multi-pad electrode in 8x2 configuration which enabled covering regions of interest for producing dorsiflexion (common peroneal nerve) and plantar flexion (tibial nerve). Wireless inertial sensor was part of the system used for static optimization protocol and gait phases detection during assisted walking (Figure 1). The whole protocol was controlled by PC application running on tablet PC. During walking, system was independent from tablet PC (Figure 2).

Figure 1. Set-up: INTFES stimulator (Tecnalia Research and Innovation), multiplexer, inertial sensor and garment with multi-pad and PalsPlatinum electrode, tablet PC.

Figure 2. INTFES system (Tecnalia Research and Innovation) during walking session.

2.3 Protocol

Each subject had 20 therapy sessions, five times a week during 4 weeks. Therapy sessions were divided into two groups: measurement and standard session. Standard session included set-up of the system, static optimization, testing of the results of optimization and 20 minute of assisted walking. At the beginning of the standard session, the therapist positioned garment around the knee and inertial sensor on the foot of the affected leg. Static optimization was based on the signal from inertial sensor during short twitches protocol. These twitches were produces by short stimulation trials made of 7 pulses every half second. Every trial presented another combination of individual pad and one current from the defined range of currents. The stimulation frequency was set to 40 Hz and the pulse width to 400 μs. After automatic algorithm suggested pads with currents for dorsiflexion, plantar flexion, inversion and eversion, the therapist evaluate quality of the produced movement and, if it is necessary, adjust stimulation pattern. After obtain of the satisfying foot movements, patient started assisted walking. Triggering stimulation during assisted walking is automated, based on signal from the sensor. Measurement sessions were conducted at the beginning, the middle and the end of the therapy. Foot trajectories and gait kinematics with inertial sensors placed both on the affected and on healthy foot during 10 m gait test, with and without aid of FES, were recorded in every measurement session. The gait velocity [m/s] was calculated from recorded trials.

For evaluating the effects of the INTFES foot drop system (Tecnalia Research and Innovation) use, three subjects walked four trials along a 10 m long pathway at a self-determined comfortable speed at the beginning, middle and end of the therapy. Resting period between trials was also self-determined, no longer than 1 minute. Gait kinematics were recorded with inertial sensors placed on both healthy and paretic leg of subjects. Offline analysis was performed to obtain gait velocity, gait symmetries and angular velocities of the feet in sagittal plane. Swing and stance durations are one of the characteristics of gait, where stance phase refers to period while foot has contact with ground and in healthy subjects lasts approximately 60% of the step. While foot doesn't have contact with ground it is defined as the swing phase.

3 Results

Gait velocities, gait symmetries from paretic leg and examples of foot angular velocities from heathy and paretic leg of one patient are shown on figures 3, 4, 5 and 6.

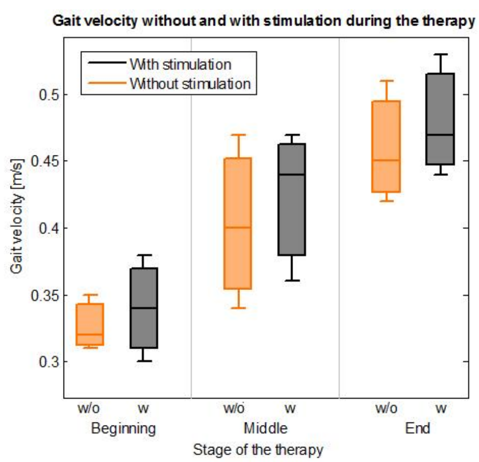

Figure 3. Gait velocities during 10 m test with (grey boxes) and without (orange boxes) aid of the FES at the beginning, middle and end of the therapy.

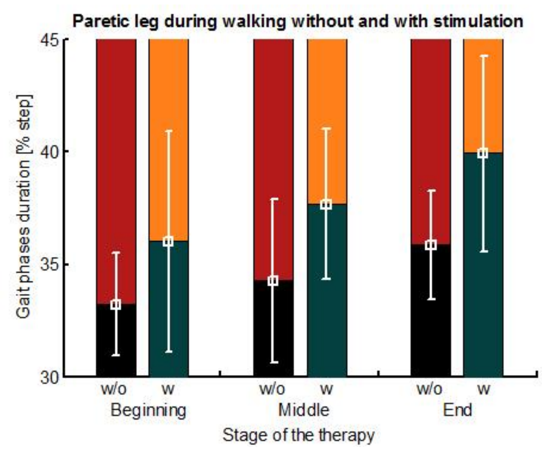

Figure 4. Gait phases duration [% step]. Without stimulation: swing phases (black), stance phases (red); with stimulation: swing phases (green), stance phases (orange).

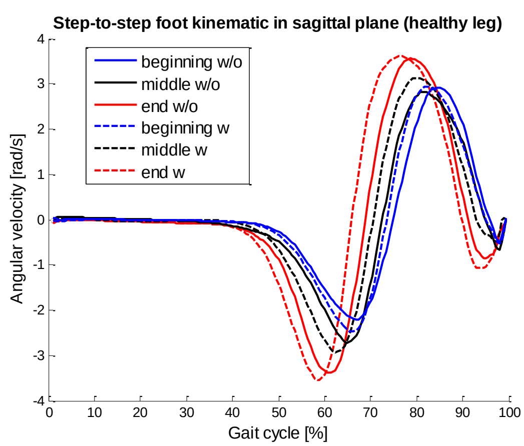

Figure 5. Step-to-step angular velocity in sagittal plane (healthy foot) during therapy, walking without and with stimulation.

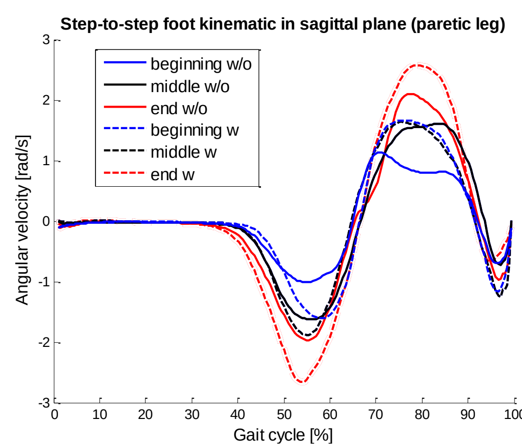

Figure 6. Step-to-step angular velocity in sagittal plane (paretic foot) during the therapy, walking without and with stimulation.

4 Conclusion

In this paper we present results of using the INTFES system (Tecnalia Research and Innovation) for correcting foot drop based on multi-pad electrode. The stimulation protocol was tested on 3 hemiplegic patients who prior to this study had undergone conventional gait therapy procedure. The therapeutic effect was observed in terms of increased gait velocity, not just during FES assisted walking, but also in walking without electrical stimulation in later stages of therapy. Gait phases durations are shown in Figure 4. Durations of the phases were improving during the therapy (swing phase increased and stance phase reduced).

The improvement due the therapy can also be observed on the example foot trajectory during dorsiflexion. At the beginning of the therapy, patients have been showing inability to clear the ground with the foot which results in compensatory movements, in this case, circumduction. That is visible in the angular velocity profile which has two distinctive maximums during swing phase of gait. Patient's foot trajectory in sagittal plane started to reassemble the shape of trajectory of healthy individual's trajectories already with first use of the INTFES foot drop system (Tecnalia Research and Innovation) and retained "normal like" shape for the rest of the therapy when patient was walking with or without aid od stimulation. Also, magnitudes of angular velocity increased on both legs (Figures 5 and 6).

Acknowledgment

This work was partially supported by the Ministry of Education, Science and Technological Development of Serbia (Contract No: 175016), by FIK, and the Spanish Ministry of Science through the Consolider Ingenio project HYPER (HYPER-CSD2009- 00067).

We would like to acknowledge valuable suggestions by Prof Laszlo Schwirtlich and assistance in clinical tests by Anđelka Pjanović P.T. and Ivana Nikodijević P.T., Clinic for Rehabilitation "Dr Miroslav Zotović", Belgrade, Serbia.

We would also like to acknowledge Axelgaard Manufacturing Co. for providing stimulation hydrogel used in this study.

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