Testing FES of Ankle Plantarflexor and Dorsiflexor Muscles to Support Unilateral Gait Disorders

J. Gil[1,2], A. Ortiz[1], A. J. del-Ama[3], J. L. Pons[1], and J. C. Moreno[1](✉)

[1] Neural Rehabilitation Group, Cajal Institute,
Spanish National Research Council (CSIC), Avda Doctor Arce, 37,
28002 Madrid, Spain
`jc.moreno@csic.es`
[2] Tecnun (University of Navarra), Manuel de Lardizábal 13,
20018 San Sebastián, Spain
[3] Hospital Nacional de Parapléjicos, Unidad de Neurorrehabilitación,
Biomecánica Y Función Sensitivo-Motora (HNPSESCAM),
Unidad Asociada al CSIC, Finca La Peraleda S/N, 45071 Toledo, Spain

Abstract. This work presents the evaluation of a new control system of Functional Electrical Stimulation (FES) for applying strategies for artificial activation of the ankle joint muscles. In particular, we present an investigation of the direct effects of event-driven open loop FES assistance of the ankle muscles during walking on the lower limb kinematics in able-bodied individuals ($n = 5$) and one incomplete spinal cord injured (iSCI) patient. We analyzed gait kinematics between walking with and without FES assistance. Effects consistent with normal physiological gait were obtained, but some unexpected alterations also occurred. Therefore, further studies are needed to help adjust the FES strategy.

1 Introduction

FES-driven support at the ankle dorsiflexors and plantarflexors has been shown valid to improve unilateral gait disorders in stroke survivors. In the case of motor impairment after incomplete spinal cord injury, gait can be affected by impairment components related to muscle weakness (paresis) and loss of dexterity. A FES-driven strategy might be useful to facilitate overground walking in iSCI subjects with decreased force generation by the ankle plantarflexors (deficit affecting both the swing and stance phases of gait) and dorsiflexors. Moreover, it has been reported that differences in ankle angles at foot contact and during stance can be mostly due to alterations in knee flexion in the iSCI group [1]. Interestingly, as shown by Kesar et al. [5], delivering FES at both paretic ankle plantar flexors muscles during terminal stance and to the ankle dorsiflexors muscles during swing phase provides the advantage of improving swing phase knee flexion on post-stroke gait. Thus we hypothesize that stimulating both

L. Masia et al. (Eds.): ICNR 2018, BIOSYSROB 21, pp. 434–438, 2019.
https://doi.org/10.1007/978-3-030-01845-0_87

plantar and dorsi flexors muscles can induce beneficial alterations on the iSCI patients. This descriptive case study investigates the direct effects of event-driven open loop FES-assisted of ankle muscles during walking on the ankle and knee in a group of healthy and one iSCI patient with hemiparesis.

2 Materials and Methods

The two main objectives of the experiments are the technical validation of the system in healthy subjects, as well as the verification that there are no significant kinematic alterations in normal physiological gait, and the benefits of using it in an iSCI patient. The Cartesian Optoelectronic Dynamic Anthropometer (CODA) system was used to measure bilateral kinematics and perform gait analysis.

2.1 FES System

Our new software platform is a control Interface developed using the Matlab-Simulink R2016b software to allow the investigation and customization of FES patterns on ankle plantar and dorsiflexors muscles. First aim of it is to compensate drop foot [2–4].

In our FES system, we detect both the contact and takeoff of heel and toe of each foot during gait through 4 FSR sensors to distinguish gait phases. These sensors were placed on the toes and heels of each foot and let to deliver (unilaterally) stimulation to the ankle dorsiflexors muscles and plantarflexors as in Kesar et al. [5].

Pressure thresholds for the FSRs can be adjusted and allow activating the different stimulation logic. Logic 1 assists plantar flexion and is applied to gastrocnemius from of the phase of terminal stance (heel off) of the paretic foot until final of pre-swing phase (toe off) (from 35 to 60% [6] of the gait cycle). Logic 2 assists the dorsiflexion and is applied to tibialis anterior and peroneus during the entire swing phase (from 60 to 100% [6] of gait cycle).

For stimulation we use a current-controlled 8 channel stimulator stimulator (RehaStim I, Hasomed, Germany) with galvanically isolated USB interface, [7]. Most studies using FES for SCI and/stroke employ low stimulation frequencies (30–40 Hz). However, it has been also seen that an enhanced effect on muscle contraction can be obtained through the use of electrical stimuli at higher frequencies up to 100 Hz [8]. Thus, we set the stimulation frequency controlled by the Simulink model and PC to 100 Hz, and bi-phasic pulse duration and amplitude can be adjusted in real-time.

2.2 Subjects

Five healthy subjects (3 female, 2 male) with not known neurological injuries or gait disorders participated in the study (mean age: 28.8 years, mean weight: 65.2 kg and mean height: 173.4 cm). One iSCI subject (17 years old, 66 kg weight and 177 cm height) with the right side affected due to medullary injury syndrome C4 ASIA C 2ºA.

The patient did not require support for walking in the trials. Surface electrodes for FES are applied on the left side in healthy group and on the right side (injured) in the iSCI patient.

2.3 Protocol

The experimental procedure was carried out during a single visit. First, the non-invasive FES system is placed and calibrated to the subject. For this, tests were performed to verify that ankle plantar and dorsiflexion occurs through adequate muscle contraction. Next, active markers of the CODA system were placed to track leg movements.

Once properly instrumented and calibrated, subjects were requested to walk along the gait recording volume in the lab in two conditions, 5 times per condition: without stimulation (No FES) and with stimulation (FES).

2.4 Data Analysis

Collected kinematic data was analyzed with a custom script in Matlab® (The Mathworks Inc., USA).

In particular, we analyzed the following points of interest (PoI): angle at heel-strike of the ankle (A1) and knee (K1), maximum ankle plantarflexion (A2) and knee flexion (K2) at loading response, maximum ankle dorsiflexion (A3) and knee extension (K3) in stance, the ankle (A4) and knee (K4) angles at toe-off, maximum ankle dorsiflexion (A5) and knee flexion (K5) at swing and sagittal ROM of the ankle (A6) and knee (K6).

3 Results

Differences between groups (FES and No FES) were evaluated using the U-Mann Whitney t-test at 5% confidence. The results in the able-bodied group show an increase of dorsiflexion in A1 (p-value = 6.34e−10), A2 (p-value = 1.46e−05) and A5 (p-value = 7.67e−05) related to Logic 2 assistance between FES and no FES condition (as shown in Fig. 1(a) and (b)).

Moreover, an increase of knee flexion in K1 (p-value = 4.45e-04), K2 (p-value = 6.49e-04), K3 (p-value = 0.02) and K6 (p-value = 0.02) between FES and no FES conditions (as shown in Fig. 1(c) and (d)) is observed.

iSCI patient showed an increase in plantar flexion in A4 (p-value = 0.005) related to Logic 1. Furthermore, the results showed a decrease in A5 (p-value = 0.03) and an increment in A6 (p-value = 0.003). Finally, an increment of knee flexion in K5 (p-value = 0.01) was observed probably related to Logic 2. All these alterations can be shown in Table 1.

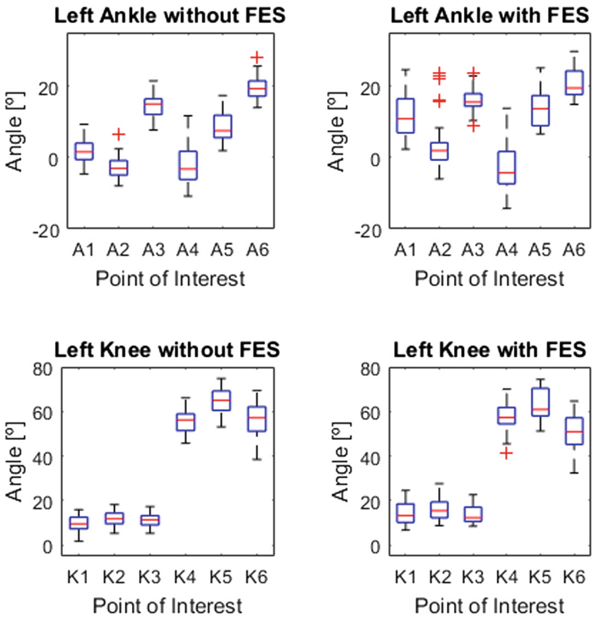

Fig. 1. Ankle and Knee points of interest (PoI) of able-bodied group during gait box plots in FES and no FES conditions.

Table 1. iSCI patient PoI averages (A) and deviations (D)

Joint	Condition	Statistics	PoI1	PoI2	PoI3	PoI4	PoI5
Ankle	FES	A	−9.06	−11.03	12.23	−1.34	3.12
		D	2.53	1.21	1.04	1.16	1.85
	No FES	A	−7.85	−9.09	11.46	1.53	6.01
		D	3.37	2.15	1.74	1.73	1.54
Knee	FES	A	6.59	9.24	−0.03	50.27	63.25
		D	4.40	3.65	0.37	1.30	2.64
	No FES	A	9.56	11.19	1.23	48.44	58.69
		D	1.46	1.04	1.78	3.81	2.15

4 Conclusion

The open-loop stimulation strategy seems to achieve some consistent changes in the ankle of the able-bodied group, but an unexpected increase in knee flexion during the stance phase. With regard to the results with the involved iSCI patient, greater flexion of the knee was obtained during swing, an increase in plantar flexion in pre-swing, and unexpected decrease in dorsiflexion.

Further experiments with able-bodied and iSCI individuals are required to explore both kinematics and kinetic patterns during walking with FES delivered to both plantarflexors and dorsiflexors muscles that allow to better understand the effects that occur and adjust a better strategy.

References

1. Pépin, A., Norman, K.E., Barbeau, H.: Treadmill walking in incomplete spinal-cord-injured subjects: 1. Adaptation to changes in speed. Spinal Cord **41**(5), 257–270 (2003). https://doi.org/10.1038/sj.sc.3101452
2. Seel, T., Werner, C., Raisch, J., Schauer, T.: Iterative learning control of a drop foot neuroprosthesis - generating physiological foot motion in paretic gait by automatic feedback control. Control Eng. Pract. **48**, 87–97 (2016)
3. Malešević, J., Dujović, S.D., Savić, A.M., Konstantinović, L., Vidaković, A., Bijelić, G., Keller, T.: A decision support system for electrode shaping in multi-pad FES foot drop correction. J. NeuroEng. Rehabil. **14**(1), 66 (2017)
4. Kottink, A.I., Hermens, H.J., Nene, A.V., Tenniglo, M.J., van der Aa, H.E., Buschman, H.P., IJzerman, M.J.: A randomized controlled trial of an implantable 2-channel peroneal nerve stimulator on walking speed and activity in poststroke hemiplegia. Arch. Phys. Med. Rehabil. **88**(8), 971–978 (2007)
5. Kesar, T.M., Perumal, R., Reisman, D.S., Rudolph, K.S., Higginson, J.S., Stuart, A.: Functional electrical stimulation of ankle plantar and dorsi-flexor muscles: effects on post-stroke gait. NIH Public Access **40**(12), 3821–3827 (2010)
6. Neumann, D.A.: Kinesiology of the Musculoskeletal System: Foundations for Physical Rehabilitation, 2nd edn. Mosby, St Louis (2010)
7. Schauer, T., Negaard, N., Behling, C.: ScienceMode RehaStim stimulation device description and protocol
8. Crosbie, J., Tanhoffer, A.I., Fornusek, C.: FES assisted standing in people with incomplete spinal cord injury: a single case design series. Spinal Cord. **52**(3), 251–254 (2014). https://doi.org/10.1038/sc.2013.158