

# Ankle Dorsiflexion Assistance Using Adaptive Functional Electrical Stimulation and Actuated Ankle Foot Orthosis



Carlos Canchola-Hernandez, Hala Rifai, Yacine Amirat,  
and Samer Mohammed

**Abstract** This work presents the development of a hybrid control strategy to assist ankle joint dorsiflexion movements during walking. An actuated ankle foot orthosis (AAFO) is used in conjunction with Adaptive Functional Electrical Stimulation (AFES) of the peroneal nerve at the Tibialis Anterior (TA) muscle level. The purpose is to provide sufficient ankle dorsiflexion during the swing phase to compensate for foot-drop in paretic patients. The degree of ankle dorsiflexion is indexed with respect to the knee flexion through an adaptive FES paradigm.

## 1 Introduction

The merging of robotic technology and neuroprosthesis was originally conceived to compensate the individual drawbacks of the use of either Functional Electrical Stimulation (FES) or actuated orthosis separately [1]. The limitations of using FES-based techniques for rehabilitation purposes have been extensively reported in the literature. They include mainly the use of open-loop FES control strategies, inducing premature fatigue and uncertainties in human torque estimation and system modeling [2, 3].

One of the objectives of this research is to study the combination of an adaptive knee-joint based Functional Electrical Stimulation (AFES) system based on a previous work [4] along with an actuated ankle foot orthosis (AAFO). The goal is to reduce the stimulation intensity, compensate muscular induced fatigue and improve

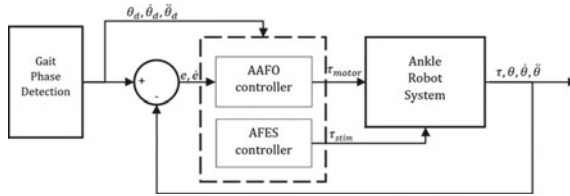
---

C. Canchola-Hernandez (✉) · H. Rifai · Y. Amirat · S. Mohammed  
Univ Paris Est Creteil, LISSI, 94400 Vitry, France  
e-mail: [carlos.canchola-hernandez@u-pec.fr](mailto:carlos.canchola-hernandez@u-pec.fr)

H. Rifai  
e-mail: [hala.rifai@u-pec.fr](mailto:hala.rifai@u-pec.fr)

Y. Amirat  
e-mail: [amirat@u-pec.fr](mailto:amirat@u-pec.fr)

S. Mohammed  
e-mail: [samer.mohammed@u-pec.fr](mailto:samer.mohammed@u-pec.fr)



**Fig. 1** Proposed hybrid controller. A Finite State Machine detects the beginning of the swing phase and enables the AFES and AAFO compensation accordingly. A variable speed reference trajectory is generated for position tracking based on [7]

the repeatably of each gait cycle. The proposed method is validated and compared with respect to the use of only Adaptive Functional Electrical Stimulation. The proposed hybrid control system is conceptually depicted in Fig. 1.

## 2 Method

### 2.1 Adaptive Functional Electrical Stimulation

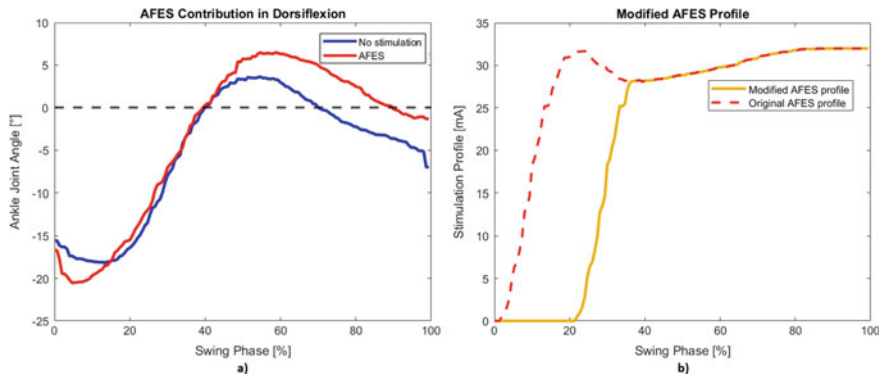
AFES is applied to the peroneal nerve at the TA muscle using transcutaneous electrodes. Clinical tests have shown an increase of the ankle joint dorsiflexion angle during mid and late swing subphases [4]. Regarding the early swing phase, the stimulation of the peroneal nerve has shown minimal effect on the ankle joint dorsiflexion since the knee joint is already flexed during this subphase. A comparison of an ankle joint profile with and without AFES is provided in Fig. 2a. Based on these previous results and with the objective of increasing the range of motion (ROM) of the ankle joint while decreasing the duration of the stimulation during the swing phase, the stimulation has been delayed by 20% of the whole swing phase duration (Fig. 2b). This is an average delay value obtained during several tests performed by healthy subjects.

Additionally, to compensate for the lack of assistance at the beginning of the swing phase, a torque profile is provided by actuating the AAFO to ensure a sufficient foot clearance where no stimulation is provided.

### 2.2 AAFO Controller

Previous studies have focused on identifying the ankle foot model during walking [5]. The ankle orthosis system model has been defined as [8]:

$$J\ddot{\theta} + B\dot{\theta} + K\theta = \tau + d \tag{1}$$



**Fig. 2** **a** Comparison of the average profile of an ankle with and without AFES. An increase in the ankle joint dorsiflexion during the mid and late swing subphases is obtained as a result of the stimulation. **b** Proposed AFES profile. The current stimulation value changes reaching a maximum value ( $I_{\max}$ ) at the last part of the swing phase

where  $J$  is the moment of inertia,  $\theta$  is the angle between the foot and the shank,  $B$  represents the viscous friction coefficient and  $K$  the system's stiffness coefficient. Additionally,  $\tau$  denotes the torque developed by the actuator and  $d$  represents all the non linear disturbances.

According to [6], the error dynamics of the system correspond to:

$$\ddot{e} + K_v \dot{e} + K_p e = 0 \quad (2)$$

where the position error ( $e$ ) is defined as  $e = \theta_d - \theta$ ,  $\theta_d$  represents the desired ankle joint angle,  $K_p$  and  $K_v$  denote the positive design parameters of the desired error dynamics.

From (2), it is possible to obtain  $\ddot{\theta}$  and substitute it in (1), resulting in:

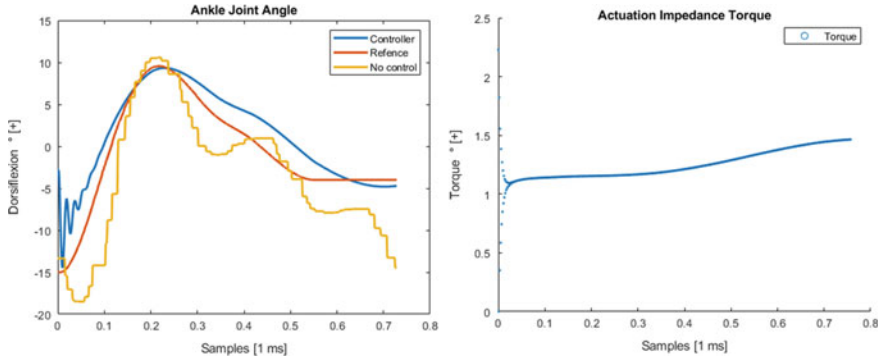
$$\tau = J(\ddot{\theta}_d + K_v \dot{e} + K_p e) + d \quad (3)$$

### 3 Results

The proposed hybrid controller was validated in simulation. The ankle robot system model was identified based on the analysis of previous experimental data obtained from one healthy subject. For the AAFO controller, the positive design parameters were tuned by trial and error. Furthermore, the AFES maximum current intensity ( $I_{\max}$ ) was determined based on the subject sensitivity threshold identified during the tests (Table 1).

**Table 1** AAFO controller and AFES parameters

$J$ (N ms <sup>2</sup> /deg)	$K_v$ (s <sup>-1</sup> )	$K_p$ (s <sup>-2</sup> )	$I_{max}$ (mA)
0.000025	0.01	200	20



**Fig. 3** Ankle joint angular position comparison (left) and torque profile (right). The initial disturbance in the ankle joint angle is caused by the AAFO controller that is enabled only during the swing phase

**Table 2** Mean dorsiflexion values

No stimulation	AFES	Hybrid
1.74° ± 1.44°	6.34° ± 1.74°	11.04° ± 2.37°

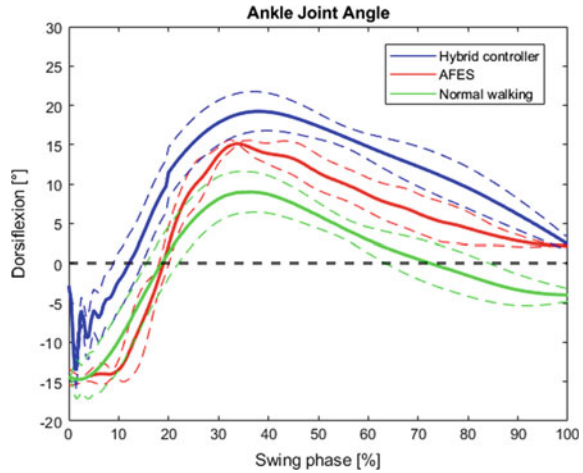
The AAFO controller showed an angular rms error of 0.0526 [rad] and a maximum torque of 1.5 [Nm]. An example of the performance for one swing phase is provided in Fig. 3.

To validate the hybrid control scheme, the motor actuation was applied to ensure a dorsiflexion of the ankle joint for the first 20% of the swing phase, whereas the modified AFES stimulation profile was applied during the swing phase. A total of 15 gait cycles were analyzed. The results were compared with AFES and no stimulation and are reported in Fig. 4 and Table 2. The hybrid approach obtains an increase of 4° compared to AFES stimulation.

## 4 Conclusion

The hybrid approach proved to enhance the ankle dorsiflexion compared to the conventional AFES stimulation. A future extension of this work is the consideration of a closed-loop AFES control and the development of a collaborative strategy to provide assistance as needed.

**Fig. 4** Normalized mean ankle joint profiles. The ankle joint dorsiflexion angle resulting from the hybrid controller is depicted in blue, from the AFES stimulation in red and from the normal gait in green. The dotted lines correspond to the standard deviation



**Acknowledgements** This work was not supported by any organization.

## References

1. A. del-Ama, A. Gil-Agudo, J. Pons, et al. Hybrid FES-robot cooperative control of ambulatory gait rehabilitation exoskeleton. *J. NeuroEngineering Rehabil.* **11**, 27 (2014)
2. A. del-Ama, A. Koutsou, J. Moreno, A. de-los-Reyes, A. Gil-Agudo, J. Pons, Review of hybrid exoskeletons to restore gait following spinal cord injury. *J. Rehabil. Res. Dev.* **49**(4), 497–514 (2012)
3. K. Ha, S. Murray, M. Goldfarb, An approach for the cooperative control of FES with a powered exoskeleton during level walking for persons with paraplegia. *IEEE Trans. Neural Syst. Rehabil. Eng.* **24**(4), 455–466
4. W. Huo, V. Arnez-Paniagua, M. Ghedira, Y. Amirat, J. Gracies, S. Mohammed, Adaptive FES assistance using a novel gait phase detection approach, in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Madrid (2018), pp. 1–9
5. H. Lee, N. Hogan, Time-varying ankle mechanical impedance during human locomotion. *IEEE Trans. Neural Syst. Rehabil. Eng.* **23**(5), 755–764 (2015)
6. J. Kim, J. Kim, An impedance control of human ankle joint using functional electrical stimulation, *2018 7th IEEE International Conference on Biomedical Robotics and Biomechanics (Biorob), Enschede* (2018), pp. 1230–1235
7. V. Arnez-Paniagua, H. Rifai, Y. Amirat, S. Mohammed, M. Ghedira, J.M. Gracies, Modified adaptive control of an actuated ankle foot orthosis to assist paretic patients, *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Madrid (2018), pp. 2311–2317. <https://doi.org/10.1109/IROS.2018.8594046>
8. W. Huo, V. Arnez-Paniagua, G. Ding, Y. Amirat, S. Mohammed, Adaptive proxy-based controller of an active ankle foot orthosis to assist lower limb movements of paretic patients. *Robotica* **37**(12), 2147–2164 (2019)