Assessment of the Suitability of the Motorized Ankle-Foot Orthosis as a Diagnostic and Rehabilitation Tool for Gait

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Abstract: A unilateral powered exoskeleton (Motorized ankle-foot orthosis, MAFO) is presented in this work, with the aim of studying muscle and kinematics short-term adaptations of the ankle during rehabilitation tasks. For this purpose, we conducted this study during gait over a treadmill, measuring surface electromyography activation and biomechanical data, in different conditions of assistance. This pilot study also aims to demonstrate that the tool is suitable for measuring biomechanical data while allowing EMG measurements, proving it as a useful tool during gait assessment and rehabilitation. Gastrocnemius Medialis activation presents slightly higher amplitude with higher assistances, so the subjects performed a higher range of motion gait pattern. Tibialis Anterior EMG activation presents consistent data with previous studies. Ankle angle at lower assistances makes the robot force less the subject to reach the imposed gait pattern, and so the range of motion diminishes. Regarding ankle angular velocity, at higher assistances, higher velocities are reached. The torque between the subjects foot and the robot. For lower assistances, the imposed reference pattern is less restrictive, and so the force the user exerts against the robot is lower.

1 INTRODUCTION

Stroke is the principal neurological disease in the developed world that culminates in physical disability. Most promising interventions for the rehabilitation of locomotor function are based on robotic systems which are focused on the rehabilitation of the function by acting at the periphery of the body (BOTTOM-UP approach). It is unclear how effective these treatments are, and one of the biggest problems they have is the non-adherence of the patient to the therapy.

The opposite approach, which focuses on neurological interventions that are based on the state of the brain after the pathology to alter peripheral behavioural outcomes is known as TOP-DOWN approach(Belda-Lois et al., 2011). Iosa and colleagues applied this approach in the framework of the European Project BETTER with a new tool in which a specifically designed ankle-foot orthosis (AFO) is combined with sEMG (surface electromyography) and kinematics sensors to provide the user a continuous online feedback of his/her performance (Iosa et al., 2012).

Several motorized devices for training during overground gait have been described in the literature. The WalkTrainer is intended for a patient to relearn gait by combining a hybrid orthosis with functional electrical stimulation (Stauffer et al., 2009) with a BWS (body-weight-support) portable mechanism. The IHMC (Institute for Human and Machine Cognition) Mobility Assist Exoskeleton (Kwa et al., 2009), the externally powered lower limb orthosis (Saito et al., 2005), and the Lower Body Exoskeleton (Costa and Caldwell, 2006) are other similar devices that allow over ground and treadmill gait rehabilitation. Focusing on exoskeletons that target single joints like the device used in this work, the literature describe apparatuses such as the powered KAFO (knee-ankle-foot orthosis), a unilateral KAFO that actuates proportionally to surface EMG signals from the patient (Sawicki and Ferris, 2009) by actuating artificial pneumatic muscles. GAIT is a quasi-passive KAFO that was developed as a low-power device (Moreno et al., 2008), where the knee is actively powered, but the ankle relies on a springed passive actuator to avoid foot drop while providing mobility. The variable impedance AFO described by Blaya and Herr (Blaya and Herr, 2004), an ambulatory version

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of the AnkleBot (Krebs and Hogan, 2006; Wheeler et al., 2004), is an AFO that impedes foot drop by regulating the impedance via a series elastic actuator. Galle and colleagues propose an assistive bilateral AFO exoskeleton (Galle et al., 2013) based on an adaptive sEMG controller and pneumatic actuators, to reduce the metabolic cost of walking. Ferris and colleagues in several papers presented the use of an AFO powered by artificial pneumatic muscles for the study of EMG activation of dorsiflexors (Tibialis Anterior) and/or plantar flexors (Soleus, Gastrocnemius) while gait (Ferris et al., 2005; Ferris et al., 2006; Sawicki and Ferris, 2008; Gordon and Ferris, 2007; Kao and Ferris, 2009; Kao et al., 2010a; Kao et al., 2010b); but highlighted the main limitation of this kind of actuators: they make the exoskeleton not readily portable.

A motorized AFO developed in the framework of the BETTER project (MAFO, motorized AFO) (Asín et al., 2012) has been proposed as a controllable orthosis that can alter the ankle joint neuromuscular control and therefore be applied to assist in locomotion training after neurological injury.

Our goal is to study muscle and kinematics short-term adaptations of the ankle with the use of a unilateral powered exoskeleton. For this purpose, we conducted this study during gait over a treadmill, measuring EMG activation and biomechanical data, in different conditions of assistance (ratio between "robot in charge" and "patient in charge" (Van der Kooij et al., 2006) concepts). This pilot study also aims to demonstrate that the tool is suitable for measuring biomechanical data while allowing EMG measurements, proving it as a useful tool during gait rehabilitation.

2 MATERIALS AND METHODS

2.1 Subjects

Three healthy right-handed subjects (2 male, 1 female, age 25 $\pm$ 1.73 years, body mass 75.67 $\pm$ 16 kg) were enrolled in this study. A left MAFO (see Figure 1) weighting 1.1 kg was used. It was adjusted to match each of the subjects lower leg length and malleoli position. The insole is located inside the sports footwear of the subject as a means of tight attachment to the foot, to reliably transmit the movement to the joint. A rubber insole of the same height as the robots insole has been located inside the contralateral shoe to compensate the height difference.

2.2 Procedure

The subjects underwent robot-aided walking on a treadmill (TC-450 by Domyos) at 1 m/s with the MAFO under these conditions:

1. Full Assistance (refer to 2.2.1 for an explanation of this parameter) (FA): robot in charge, i.e. the robot performs all the movement with no need of any contribution from the subject.
2. Medium Assistance (MA): the robot performs 50% of the movement, i.e., the robot is only able to reach 50% of the targeted trajectory. The remaining 50% is accomplished by the subject.
3. Low Assistance (LA): the same as MA condition, being the ratio 10% from the robot and 90% from the subject.

As a partial aim of the study was to study angular position while walking with the orthosis, subjects were asked to walk as if they were not wearing the robot, but forcing the robot if needed in order to try to perform a normal gait pattern. They had no visual reference so they were just focused on walking. They had to walk without resting the hands on the bars of the treadmill, to emulate as close as possible overground walking.

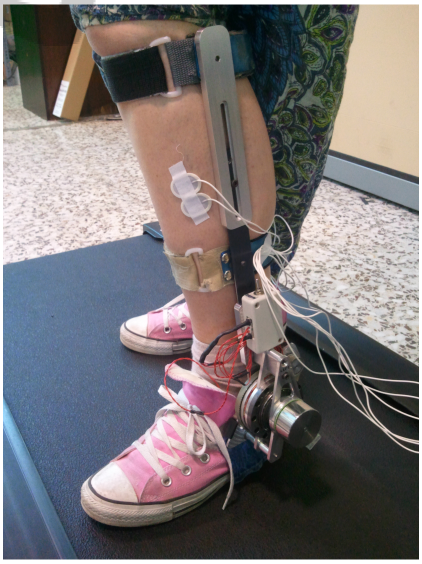


Figure 1: MAFO (motorized ankle foot orthosis), worn by one of the subjects of the study.

The trials (summarized in Table 1) had a duration of 3 minutes and were separated in time by at least half an hour to ensure independence between trials and let muscles rest to eliminate fatigue due to the exercise.

Table 1: Study conditions.

Trial	*Velocity*	*Assistance*
FA	1 m/s	100%
30 minutes rest		
MA	1 m/s	50%
30 minutes rest		
LA	1 m/s	10%

2.2.1 Hybrid Controller

The device is controlled using a hybrid controller where the value of contribution of a position controller and an admittance controller (based on the measured torque) is selected prior to the beginning of the exercise (see Figure 2). A parameter called "assistance", with values from 0 to 100 per cent, modulates the output from the controller. 100 per cent of assistance indicates that the controller output depends only on the position controller; at 0 per cent, the controller output comes from the admittance controller; and so at values in between the controller output is distributed with "assistance" percentage from the position controller, and 100 minus "assistance" percentage from the admittance controller. This parameter was calibrated by measuring the percentage of ankle range of motion the robot was able to reach while performing a dorsi-plantar flexion continuous movement at different velocities.

The gait pattern is pre-recorded from a healthy subject as in (Hitt et al., 2009) and modulated as a function of the stride time as in (Ward et al., 2006). The admittance controller is dependent on the gait phase, with a lower stiffness in the swing phase than in the stance phase, i.e. a higher proportional gain in the swing than in the stance phase, to avoid the effect of the interaction torque against the ground.

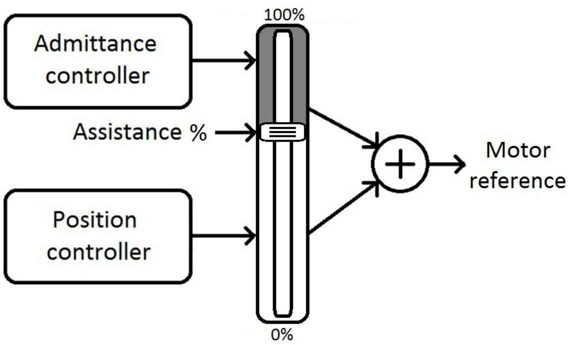


Figure 2: Hybrid controller conceptual scheme.

2.3 Data Acquisition and Analysis

The MAFO records ankle joint angular position, angular velocity, and torque resulting from the interaction between the foot and the orthosis. Two footswitches were located at the heel and the toe to record heel strike and toe-off conditions respectively, for the identification of the gait phase. This allows the robot to synchronize to users gait phase.

Two muscles have been measured in the study: Tibialis Anterior (dorsiflexion) and Gastrocnemius Medialis (plantar flexion). These distal muscles exert the more powerful EMG signals involved in the control of the ankle joint. Furthermore, as the ankle joint produces the majority of the positive mechanical work during stance in human walking (Kao et al., 2010b), further studies with this hardware could lead to mechanical analysis of the whole limb. They have been recorded with the equipment EMG-USB by OT Bioelettronica, in a bipolar configuration according to SENIAM recommendations (Hermens et al., 1999), with both DRL and reference at the subjects left wrist.

Kinematic signals were sampled at 1200 Hz, and EMG signals at 2048 Hz. Raw EMG data were high-pass filtered (3rd order Butterworth digital) at 20 Hz and envelopes for each signal were extracted. Individual stride cycles were separated with gait events determined using the footswitches data, obtaining for the three-minute sessions 90 $\pm$ 5 steps. Kinematic signals were resampled to 2048 Hz sampling frequency to match EMG data sample frequency. The smoothed EMG and kinematic signals were then averaged (stride-by-stride and for all the subjects) to obtain averaged time-normalized gait cycles for all conditions and data for the comparison between conditions.

3 RESULTS

3.1 EMG Activation

The subjects were asked to walk as normally as possible, so the hypothesis was that the activation patterns may remain almost unchanged in such a short exercise. Figure 3 shows the activation of the Tibialis anterior (TA) and Gastrocnemius Medialis (GM) for the three subjects. GM presents slightly higher amplitude with higher assistances (FA), which responds to the fact that at higher assistances, the subjects performed a higher range of motion gait pattern (see section 3.2 for further details on biomechanical signals). TA presents, according to gait phases in Table 2 (Perry, 1992), a less difference between the values of muscle activation at the endpoints in the figure (heel strike moment, i.e. initial loading and terminal-swing moments) and EMG values from mid-stance to mid-

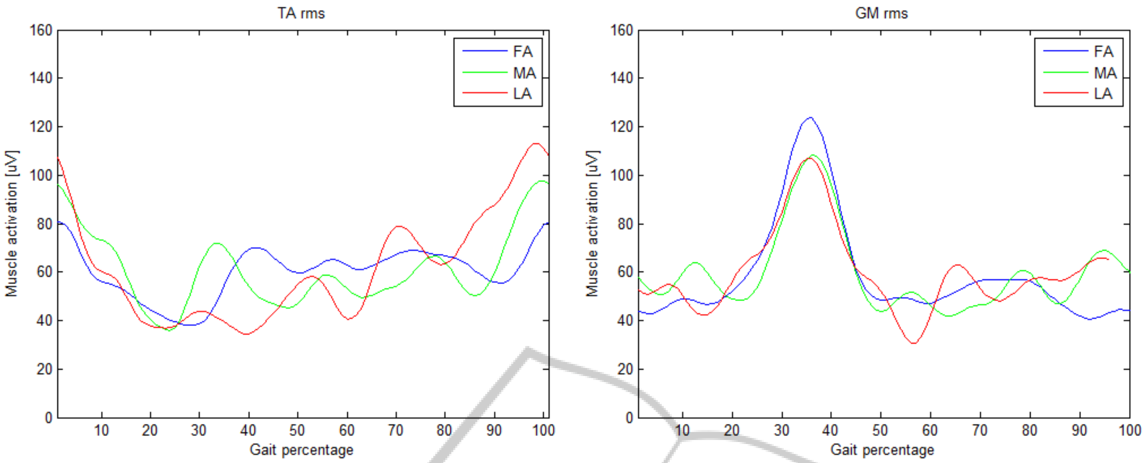


Figure 3: Mean RMS TA and GM activation; per gait phase percentage.

Table 2: Phases of the gait cycle.

Phase	Percent of gait cycle
Initial loading	0 – 12
Mid-stance	12 – 30
Terminal-stance	30 – 50
Pre-swing	50 – 62
Initial-swing	62 – 75
Mid-swing	75 – 87
Terminal-swing	87 – 100

swing. These signals are consistent with data presented by Hidler and Wall (Hidler and Wall, 2005).

3.2 Biomechanical Data

Figure 4(a) presents the ankle angle. These data shows that for lower assistances, the robot forces less the subject to reach the imposed gait pattern, and so the range of motion diminishes. Although the user was told to perform a normal gait, for very low assistances (LA condition) the lack of a gait reference imposition maybe the cause of the lower range of motion.

Figure 4(b) presents the ankle velocity. These data is a direct consequence of the angle, so the data extracted is consistent to the data for the ankle angle: higher assistances lead to higher range of motion and so higher velocities.

Figure 4(c) presents the torque between the subject's foot and the robot. For lower assistances, the imposed reference pattern is less restrictive, and so the force the user exerts against the robot is lower, as the robot tries to follow subject's movements.

Mean values for the range of motion and maximum values for the velocity and torque are presented in Table 3 for the three subjects and the three conditions.

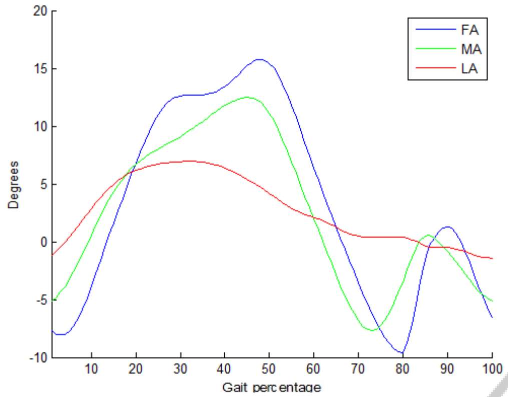
Table 3: Mean range of motion and maximum velocity and torque for the three subjects.

Subject	Trial	ROM [°]	Top speed [°/ s]	Max torque [N· m]
1	FA	24.40	84.84	10.36
	MA	18.29	72.21	6.34
	LA	7.15	31.32	3.68
2	FA	27.40	88.25	7.92
	MA	21.38	89.20	8.25
	LA	6.15	29.62	3.30
3	FA	26.50	87.87	6.61
	MA	22.84	79.80	5.11
	LA	14.31	57.54	4.56

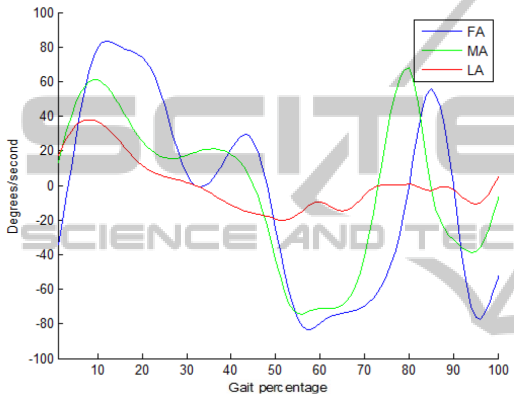
4 DISCUSSION AND FUTURE WORK

This work presented a tool to assist physiotherapists in the rehabilitation tasks, providing not only the movement task, but measurements to assess functional improvements. The tool proved to be suitable for these rehabilitation and assessment tasks, being much more portable than artificial-muscle-powered devices.

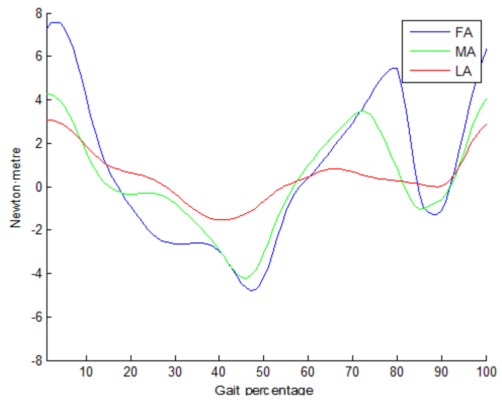
A deeper study is to be carried out enrolling more subjects, and modifying the protocol of the current study to perform a long term experiment, to be able to observe the evolution on the measurements due to the rehabilitation exercises. This will lead to the observation of short-term adaptations in muscle activation and kinematic signals. Due to its portability, another future could be performed overground and not over a treadmill, thus eliminating the reflex to walk when the "ground" moves. This approach makes the presented experiment set-up prone to be combined with elec-



(a)



(b)



(c)

Figure 4: Biomechanical signals: angle (a), velocity (b), and torque (c).

troencephalography to study walking intention, and further combination of EEG and EMG data could lead the device to be an assistive device based on a brain-neural-computer interface.

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