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ANALYZING MOTOR PRIMITIVES OF HEALTHY SUBJECTS WEARING A LOWER LIMB EXOSKELETON

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Abstract. *The present work aims to evaluate the motor primitives of a person wearing an exoskeleton for lower limbs, and compare them with the primitives of the same person not wearing the robotic device. Exoskeletons are being currently developed by the field of engineering to help physiotherapists in the rehabilitation of individuals with some motor impairment of the lower limbs. Surface electromyography (EMG) signals and joint positions, obtained from Inertial Measurement Unit (IMUs), are used to compute the primitives. Motor primitives, combined with different weights, is a minimum set of components capable of reconstructing all possible muscular stimulations or position profiles. The Principal Component Analysis (PCA) is used in this paper to extract the motor primitives and the weights. A set of experiments was carried out to evaluate the influence of the exoskeleton structure on the motor primitives during walking. A healthy subject walked on a treadmill in two conditions: first, not wearing the exoskeleton, and, in the sequence, wearing the device.*

Keywords: *rehabilitation robotics, computer network, serious games, telerehabilitation, distributed system*

1. INTRODUCTION

Due to the growth of the relative participation of elderly people in societies around the world, the number of cases of stroke has increased considerably. Stroke can lead to severe sequelae in the neuromusculoskeletal system that affect about 50% of survivors, including damage to the neural areas that control the movement of both upper and lower limbs. In general, patients who have some sequelae in the neural system, whether by stroke or some injury caused by trauma, require physiotherapeutic treatments for a better quality of life from the point of view of physical and mental health.

Proposing and developing technologies to rehabilitate the neuromusculoskeletal system is what has been done by research groups in the area of rehabilitation robotics (Krebs *et al.*, 2008) (Contreras-Vidal *et al.*, 2016). One of these new technologies are active orthosis or exoskeletons. Exoskeletons for lower limbs are robotic systems specially designed to be coupled to the human body, giving support to the musculoskeletal system and aiding locomotion. In this article, we use the modular exoskeleton for lower limbs presented in dos Santos *et al.* (2017) to evaluate the motor primitives. The modularity is present in both the possibility of working on one or more joints of the patient and in the form of actuation of joints of the robotic system.

It is known that the nervous system simplifies the motor control by grouping the muscles in motor units, and these motor units form modules, which combined, generate the motor behavior (Turvey *et al.*, 1978). This form of module combination is called motor primitives. The motor primitives have been widely studied considering experiments with animals (Bizzi *et al.*, 2008), (Giszter, 2015), (d'Avella *et al.*, 2003), as well as with humans (Li *et al.*, 2013), (Ivanenko *et al.*, 2004). These motor primitives, combined with different weights, form a minimal set of components capable of reconstructing all possible muscle activations or position profiles. To extract the motor primitives in this work, the Principal Component Analysis (PCA), initially proposed by Person (1901), was used.

The present work aims to evaluate the influence of the exoskeleton structure on the motor primitives of a healthy subject

walking on a treadmill. For comparison purposes, two conditions are considered: first, the subject walked not wearing the exoskeleton, and then, wearing the device. Inertial measurement units (IMUs) are used to measure the hip, knee, and ankle joint positions. The muscles' activations during the walking on the treadmill are estimated by surface electromyography (EMG) signals. Electromyography is a technique to evaluate the mechanics involved in the neuromuscular physiology and to diagnose neuromuscular disorders. Based on the EMG signals, it is also possible to identify and evaluate the motor intention and to perform the control of robotic devices as presented in Dollar and Herr (2008).

The purpose of this paper is to find recognizable relations between motor primitives and weights of the wearing and not wearing conditions.

2. EXPERIMENTAL PROCEDURE

A set of experiments were carried out to evaluate the influence of the exoskeleton structure on kinematic and muscular activity profiles during walking. A healthy subject (male, 29 years, 84 kg, 1.77 m) was instructed to walk on the treadmill for 2 minutes at a comfortable speed in two conditions: first, not wearing the EXO-TAO, and, in the sequence, wearing the exoskeleton. The average speeds were 3.3 km/h and 2.5 km/h, respectively. Then, the subject wearing the exoskeleton was instructed to walk for 2 minutes at a velocity of 3.3 km/h. The first and last twenty steps were discarded in the analysis, 40 steps were considered for each condition.

The kinematic profiles for the lower limbs were evaluated by processing the data from 7 IMU sensors (MTx, static RMS-error $< 1^\circ$, dynamic RMS-error $< 2^\circ$) from XSens Technologies, Netherlands. The sensors were fixed at torso (B), thigh (T), shank (S), and foot (F).

We used a Trigno Wireless EMG system (Delsys Inc., Natick, MA, USA) to measure electromyographical (EMG) signals of five lower limb muscles: rectus femoris (RF), vastus medialis (VM), tibialis anterior (TA), biceps femoris (BF), and gastrocnemius lateralis (GL). EMG data were collected at 2 kHz in a separate computer using the Delsys EMGworks Software and later processed using MATLAB (The MathWorks, Inc; Natick, MA, USA). First, the signal's moving average is subtracted to eliminate DC bias. Then, the corrected signal is fully rectified, low-pass filtered and normalized considering the maximal value obtained at the experiments. The low-pass filter corresponds to a second order butterworth with a cut-off frequency of 2 Hz.

Figure 1 shows the subject wearing the exoskeleton and the attached IMU (orange) and EMG (black) sensors. For sake of simplicity, only the data from the right leg are presented in this study. The left leg's data are similar.



Figure 1. Experimental setup, IMU (orange) and EMG (black) sensors.

The reduction of dimensionality of the EMG and joint position profiles was obtained using PCA (Principal Component Analysis). The PCA was proposed in 1901 by Pearson, whose objective is to analyze data aiming at its reduction and elimination of unnecessary characteristics.

3. RESULTS AND DISCUSSION

To evaluate the influence of the exoskeleton structure on the profiles of kinematic and muscle activity during walking, a set of experiments had been realized. A healthy individual (male, 29 years old, 84 kg, 1.77 m) was instructed to walk

on the treadmill for 2 minutes not using the exoskeleton at a comfortable speed of 3.3 km/h and in sequence, wearing the exoskeleton the individual walked at a comfortable speed of 2.5 km/h, and after, at a speed of 3.3 km/h. The first and last steps were discarded from the analysis and 40 steps were considered for each condition.

Figure 2 shows the articular angles of the knee (θ_K), the ankle (θ_A) and the hip (θ_H) in the sagittal plane, in cases where the subject was instructed to walk on the treadmill. Note that the average kinematic profiles are similar, but the variability of the data with the individual using the exoskeleton is higher, mainly at the speed of 3.3 km/h, indicating that the healthy user is always "fighting" against the structure of the exoskeleton to impose your own walking profile.

The primitives of the joint angles are shown in Figure 3 and illustrate this behavior of the user by making a greater effort to maintain their natural gait pattern. When the subject is using the exoskeleton and walking at a speed of 3.3 km/h, the maximum amplitude of the hip flexion is increased, as shown by the higher weight for the Primitive 2 (light red bar). Regarding the ankle joint, there is a greater dorsiflexion in the balance phase, validated by a lower weight for the Primitive 1.

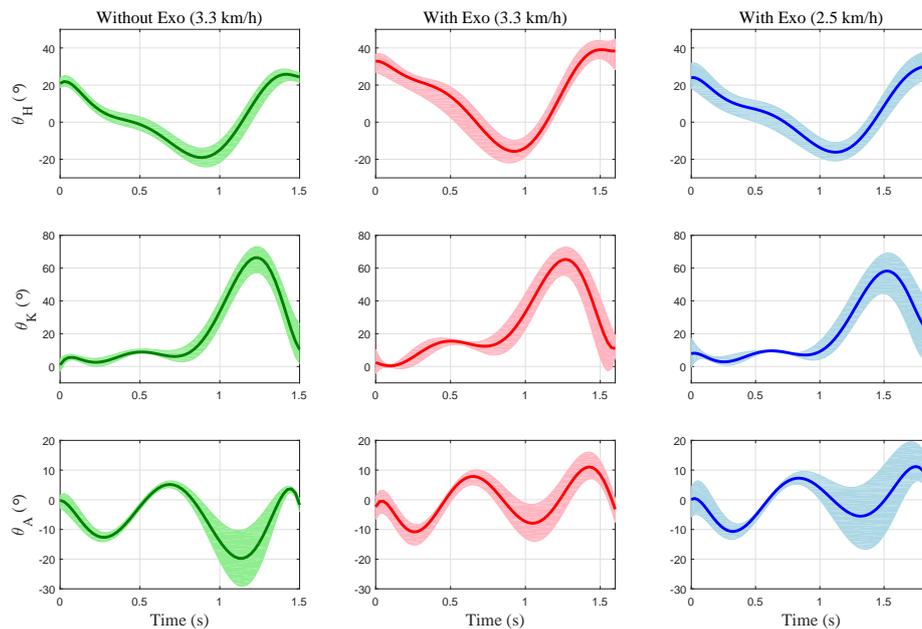


Figure 2. Joint angles at the sagittal plane.

Figure 4 shows the normalized EMG signals, which correspond to the muscle activity of the subject submitted during the experiments. As for kinematic data, the greatest variability is observed for the condition where the user is using the exoskeleton. From the EMG signals, four primitives and their weights were extracted for each of the five muscles during the walking (support and swing) phases, according to Figure 5.

In the support phase, the vastus medialis and the gastrocnemius lateralis present greater activation. Since it is a muscle responsible for the balance, the vastus medialis has a greater activation at the beginning of the support phase (beginning of the step), according to the weights of primitives 3 and 4. On the other hand, the gastrocnemius lateralis, due to its stronger propulsion work, being less important in for balance and stabilization, present greater activation in the final support phase and beginning of the balance, according to the weight of primitive 3.

The maximum flexion amplitude of the hip, shown in Figure 3, is confirmed by analyzing the weights of primitives 2 and 4 of the rectus femoris, in Figure 5, and the weight of primitive 4 of the biceps femoris. The rectus femoris showed a greater activation at the beginning of the balance phase, since it initiates the movement of hip flexion and extension of the knee in the preparation for the contact with the ground and the absorption of the impact.

Whereas the biceps femoris, responsible for balance and to stabilize the knee joint immediately after the heel strike (beginning of the step), presented a more lasting activation at the beginning of the support phase. In the balance phase, the anterior tibial presented greater activation, being a muscle responsible for keeping the foot dorsiflexed, avoiding that the toes drag on the ground, according to the weights of primitive 2 with exoskeleton at 3,3 km/h.

The results indicate clear advantages in computational efficiency for the PCA-based approach. Note that the algorithm reconstructed responses with a high degree of fidelity, where the variance in all sets was greater than 98%. Thus, the results suggest that, from a minimal set of components (two EMG primitives and four IMUs), it is possible to reconstruct all possible muscle stimulations or position profiles.

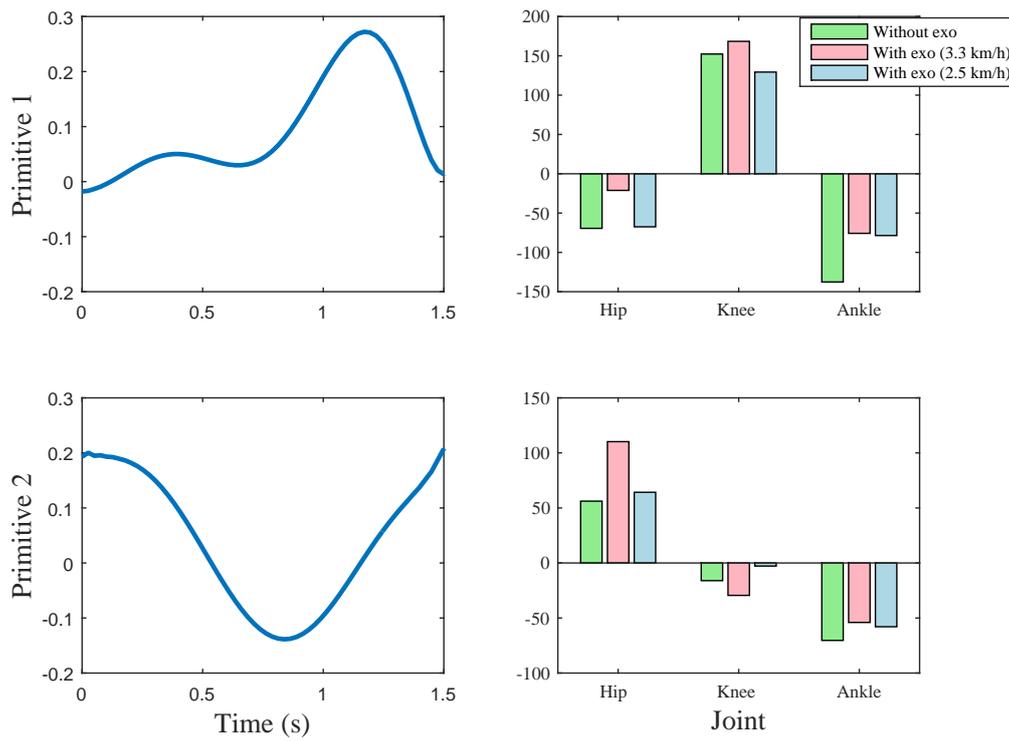


Figure 3. Position primitives.

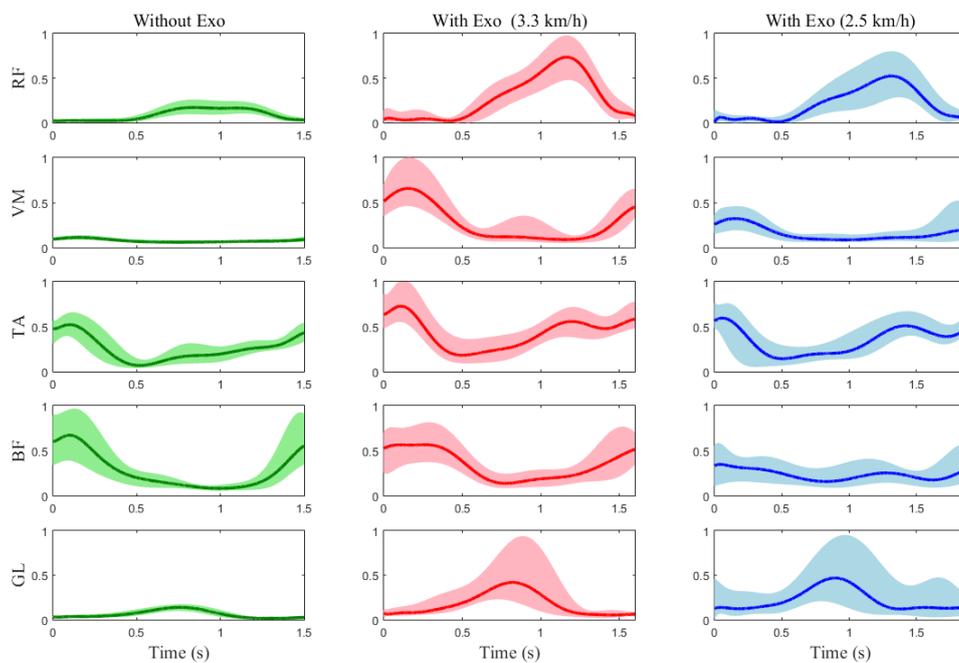


Figure 4. Normalized EMG signals.

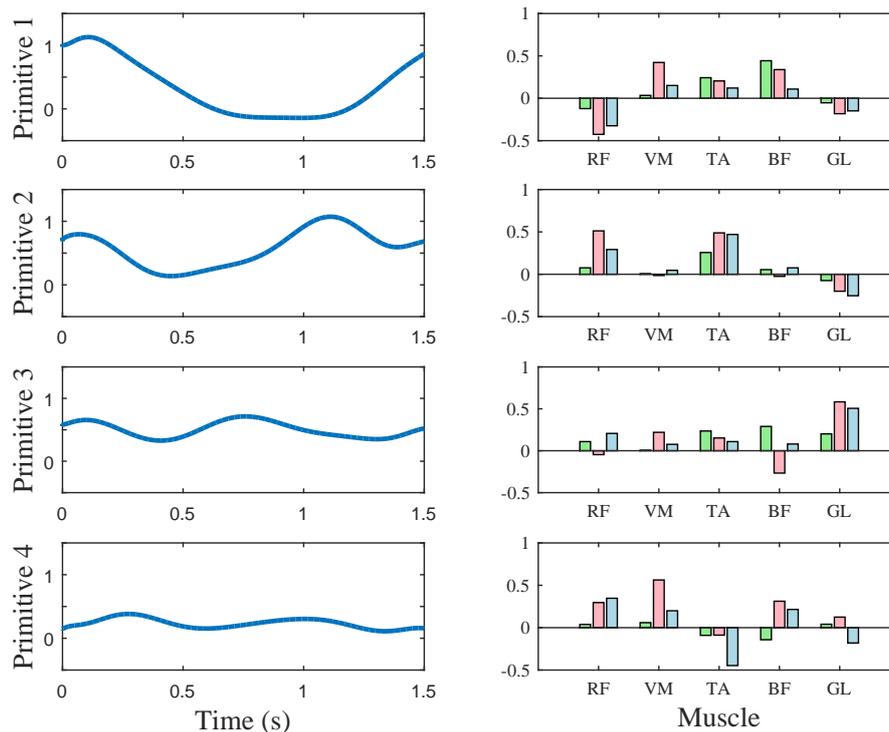


Figure 5. EMG primitives.

4. CONCLUSIONS

In this work, we propose to evaluate the influence of the exoskeleton structure on the motor primitives during the walk. A healthy subject walked on a treadmill in two conditions: first, not wearing the exoskeleton, and then using the device. Surface electromyographic (EMG) was used to obtain muscle signals and the Inertial Measurement Unit (IMUs) for joint positions (IMUs). From the EMG signals and the IMUs, the motion motor primitives were calculated, which combined with different weights formed a minimal set of components that were able to reconstruct all possible muscle stimulation or position profiles. For the extraction of Primitives, the component analysis (PCA) was used. The algorithm was able to reconstruct the responses with a high degree of fidelity, where the variance in all sets of signals was greater than 98%. The muscle activation (EMG) and joint positioning patterns (IMUs) obtained by treadmill walking by the subject can be explained as the combination of four muscle primitives and only two primitives derived from positions combined with different weights. The experimental results also showed that the kinematic profiles are minimally modified when a comfortable velocity is selected. However, an increase in ankle dorsiflexion and greater hip flexion could be observed at higher speeds, in the case of 3.3 km/h wearing the exoskeleton. In both cases of cadence wearing the exoskeleton, the muscle activity increased, which characterizes a greater effort to maintain the walking pattern, however, wearing the exoskeleton at a comfortable speed of 2.5 km/h would be enough for a muscle stimulation. In future work, to validate the technique, a robot control strategy will be developed, capable of improving the recovery of patients with compromised lower limb movements, analyzing their movement primitives. This work was approved by the Ethics Committee of the Federal University of São Carlos (Number 26054813.1.0000.5504).

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7. RESPONSIBILITY NOTICE

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