Control Design Inspired by Primitive Motors to Coordinate the Functioning of an Active Knee Orthosis for Robotic Rehabilitation

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Abstract
In order to assist physiotherapists during the rehabilitation process of individuals, after abnormalities in the neuromusculoskeletal system, different types of lower limb orthoses were developed. This work aims to develop a robotic control strategy based on kinetic motor primitives capable of assisting in the recovery of patients with compromised movements. The primitives are calculated from the torques obtained by OpenSim's Inverse Dynamics tool, which uses as input the scaled model of the subject and the knee joint positions provided by the orthosis encoders during extension/flexion movements. The objective is for the control strategy to work transparently, inducing the user to perform the same torque with and without the orthosis. The proposed strategy was evaluated using a simulator, where new knee joint position data were obtained.

Keywords: Rehabilitation Robotics, Motor Primitives, Exoskeleton for Lower Limbs.

1. Introduction
Anomalies or deficiencies in the neuromusculoskeletal system caused by diseases such as stroke (AVC) have increased significantly in the number of cases due to the growth of the elderly population in the world (OMS, 2015). Therefore, it is important that physically healthy individuals can take care of themselves and perform simple tasks on a daily basis, and this goal has been pursued by many research groups in the field of robotic rehabilitation (Contreras-Vidal et al. 2016).

The improvement in the quality of life of these patients occurs due to neuroplasticity, which is the ability to adapt and learn in an experience-dependent manner, from repetitions using lower limb exoskeletons and active orthoses for care and rehabilitation (Chen et al. 2016).

Figure 1. Position of the orthosis. A user wearing the active knee orthosis used in this work.

The modular exoskeleton for lower limbs presented in (dos Santos et al., 2017), Figure 1, is used, and for the control, the concept of assistance based on primitive motor explored by (Ruiz Garate et al. 2016), in which the primitives are identified and combined by weights to produce the desired robot torque profiles. The torques of the robot obtained by the primitives were tested in the simulator and presented promising results.

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2. Experimental Produce

In order to evaluate the influence of the orthosis on the kinetic activity profiles during knee joint flexion/extension, a set of experiments was performed, as shown in Figure 2.

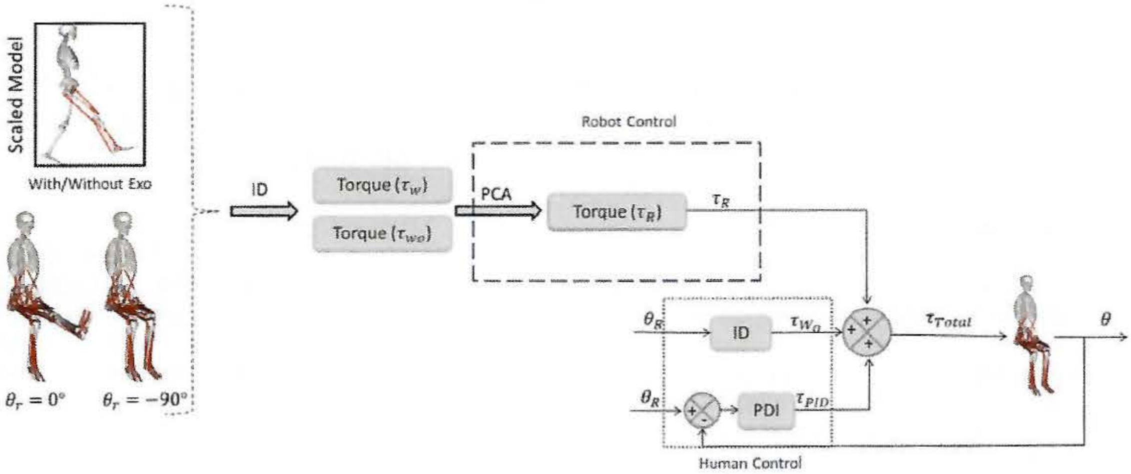

Figure 2. The Gait2392 model was scaled with the measurements of the user who made the sinusoidal trajectory, with amplitude ranging from $\theta_{r=} - 0°$ a $\theta_{r=} - 90°$. Torques with and without the orthosis were calculated by the OpenSim DI and subsequently used to calculate the robot torque (τ_R) from the primitive motors. Human control is a feedforward loop, modeled using DI, and a PID feedback loop. The advance loop provides an estimated torque τ_{Total} by the user to perform the motion and the feedback loop eliminates the effects of disturbances θ is the calculated position expected to be equal to the reference position θ_r.

Firstly, in order to obtain the position data, a subject of 1.80 m in height and with a mass of 80 kg performed a series of movements wearing the knee orthosis. The movements correspond to a sinusoidal trajectory, with a period of 6 seconds and amplitude ranging from $\theta_{r=} - 0°$ a $\theta_{r=} - 90°$. This path is defined as the path desired by the orthosis.

The orthosis position data was sent to the OpenSim Inverse Dynamics (ID) tool. The OpenSim *Gait2392* model was used to input the Inverse Dynamics together with anthropometric data and the subject's mass using the orthosis, the subject's articular positions were also inserted. The mass of 80 kg was considered when the subject was without the orthosis, and the mass of 82.53 kg with the orthosis, resulting in the torque without the orthosis (τ_{wo}) and the torque with the orthosis (τ_w). The robot torque was calculated based on the motor primitive weights for both cases.

The motor primitives consist of the sum over time of the product between primitive curves $p_i(t)$ and their respective active weights w_i, $i = 1, \ldots, N$, where N is the number of primitives. Using Principal Component Analysis (PCA) the motor primitives for the torques of a subject who did not use the orthosis were extracted, according to Equation 1:

$$\tau_{wo}(t) = \sum_{i=1}^{N} p_i^{wo}(t).w_i^{wo}, \tag{1}$$

where $p_i^{wo}(t)$ and w_i^{wo} are the primitives and the torques weights of the subject without the orthosis (wo). The desired robot torque is calculated based on the ratio (p_i) between the weights of both cases, using the orthosis (w^w) and not using the orthosis (w^{wo}) according to Equation 2, and the robot torque (τ_R) is calculated according to Equation 3:

$$\vartheta_i = \frac{w_i^w}{w_i^{wo}} \tag{2}$$

$$\tau_R = \sum_{i=1}^{N} p_i^{wo}(1 - \vartheta_i).w_i^{wo}. \tag{3}$$

The human control consists of a feedforward loop, modeled using the OpenSim Inverse Dynamics Tool, and a PID feedback loop. The feedforward loop provides an estimated torque (equivalent to the τ_{wo}) by the user to perform the motion. The feedback loop seeks to eliminate the effects of disturbances that affect good movement performance; and θ is the calculated position expected to be equal to the reference position θ_r.

The robot torque induces the user to perform the same torque when not using the orthosis, assisting only where the weight of the primitive is lower. This robot torque τ_R was sent to a Forward Dynamics algorithm developed in MATLAB, together with the orthosis position data θ_R for the calculation of new position vectors θ.

The control presented above was simulated using the Forward Dynamics based algorithm, that is able to reproduce the application of the torques to the model, as shown in the Figure 2. To perform the simulation, was used a computer with Intel® Core™ i7-5500 2.40 GHz processor, 8,00 GB of RAM, 2,00 GB dedicated video card, Windows 10 Home Single Language 64 bits. The OpenSim version 3.3 and the MATLAB R2017b were the platforms where the simulations took place.

3. Results and Discussions

A set of experiments were performed to evaluate the influence of orthosis on kinematic and kinetic processes during knee extension/flexion movement. Figure 3 shows the results in which the green line illustrates the user torque (the sum of the feedforward and feedback torques), the red line represents the torque of the robot that was obtained by the motor primitive strategy, and the blue line illustrates the total torque, which is the sum of the robot and user torques.

The goal is to work the transparency of the orthosis so that the torque without (τ_{wo}) is equal to the torque with the orthosis (τ_w). Applying the torque calculated by the primitives (robot torque) in the orthosis, Figure 3 shows that the torque with the orthosis (green line) and without the orthosis (black line) are equal (overlapping), which shows that the control was able to work transparently during the subject's knee flexion and extension.

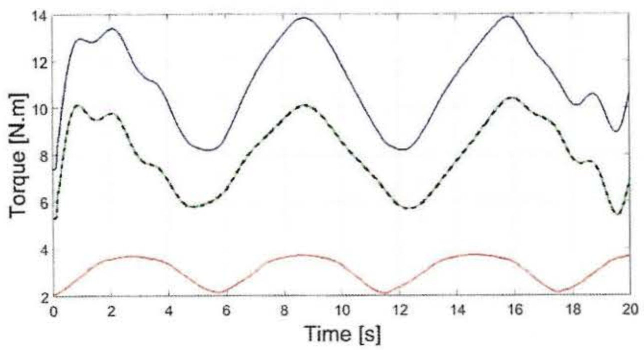

Figure 3. Total torque (blue), robot torque (red), user torque with orthosis (green) and user torque without orthosis (black).

The Figure 4 shows the position reference θ_R (pink) to be followed by the user and the actual position θ (black) followed by the user's knee. Note that the user has followed the desired reference which demonstrates the transparency of the robot during leg flexion/extension.

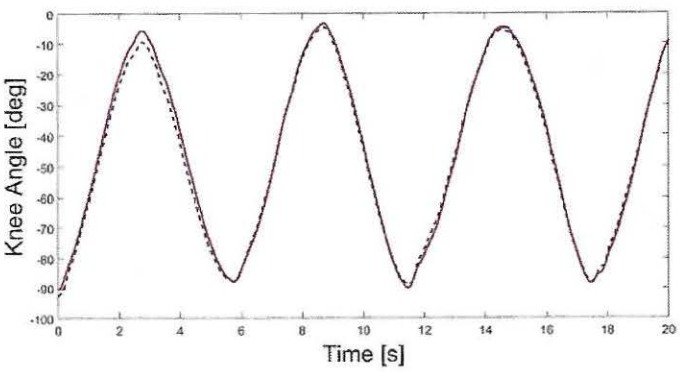

Figure 4. Position reference to follow (pink), and Real knee position (black).

Figure 5 illustrates the position error during the movement of the controlled orthosis movement. The total time to perform the simulation was 3.28 minutes.

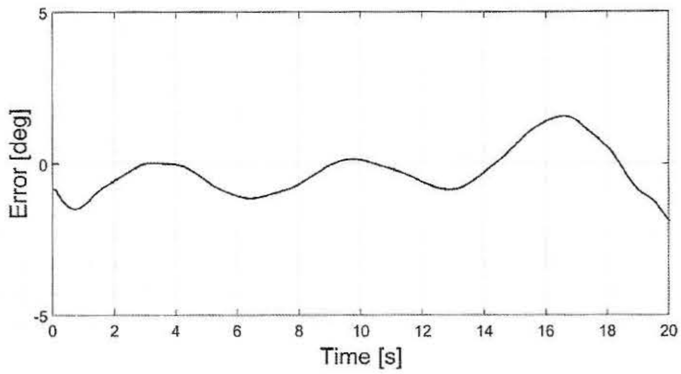

Figure 5. Position error while executing movement with controlled orthosis.

Aiming to improve the quality of life of users with motor problems, a control strategy based on the knowledge of the user's kinetic characteristics, so that the orthosis could work intuitively to the movement intended by the user, providing them with coherent, collaborative and effective assistance, was the purpose of this work. When the user makes use of the exoskeleton, it is important that he is able to assist him in his specific motor impairment individually. Primitives were calculated using Principal Component Analysis (PCA) and simulated results showed that the control was effective in retrieving the knee joint position profile.

4. References

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