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HUMAN-EXOSKELETON INTERACTION MODEL APPLIED TO ROBOTIC NEUROREHABILITATION OF LOWER LIMBS

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Abstract. *The objective of this work was to develop a human-robot interaction model with application in the computational simulation of interaction controls applied in robotic rehabilitation of lower limbs of stroke victims. For the development of the interaction model, a computational model of the knee joint of the rehabilitation robot ExoTao was coupled to the Gait2392 neuromusculoskeletal model from OpenSim. An interaction control based on impedance control was simulated with the interaction model, using experimental data of torque and position as input reference. The obtained results was closely to the experimental one, with the maximum position error reached about 2,5% of the desired motion range, evidencing that the model is effective.*

Keywords: *Human-robot interaction control, robotic assisted therapy, OpenSim*

1. INTRODUCTION

Stroke-cerebral vascular accident is the second leading cause of death in the world and the first cause of lasting disability. The World Health Organization (WHO) defines stroke as a noncommunicable disease of the cardiovascular type, provoked by the interruption of the blood supply to the brain because a bleeding (hemorrhagic stroke) or a clot (ischemic stroke) (WHO, 2011, 2018; Hogan, 2014).

The quality of life of the stroke victim is reduced in face of the disabilities remaining. The patient's capability of perform the *activities of daily life* (ADL) is decreased, and sometimes the patient depends on the willingness of other people to perform simple tasks like walking, eating and dressing. Rehabilitation therapies help to treat injuries and impairments, improving the missed functions (Diaz *et al.*, 2011).

In this context, a promising field that has emerged in recent decades is robotic rehabilitation where the therapy routine is assisted by robots, increasing the effectiveness of the treatment, especially for gait rehabilitation that is very strenuous, both for the patient and for the therapist (Huang and Krakauer, 2009; Diaz *et al.*, 2011; Ibarra, 2014; Androwis *et al.*, 2018).

Human-robot interaction should ensure the effectiveness of robotic assisted therapy without compromising patient safety. In order to satisfy this premise, several studies address the use of computational resources. For example, (de Sousa *et al.*, 2016) used neuromusculoskeletal (NME) models from OpenSim (Delp *et al.*, 2007) integrated to MATLAB to develop and test some human-robot interaction control strategies using Functional Electrical Stimulation. (Durandau *et al.*, 2016) also used NME models from OpenSim to design Electromyographic-driven models of human-machine interaction. (Pena *et al.*, 2019) developed an Adaptive Impedance Controller for human-exoskeleton interaction using NME models from OpenSim to determinate the patient's stiffness. (Nunes *et al.*, 2018) developed an interaction control based on motor primitives using computational models of an subject wearing an exoskeleton to estimate the torques produced by the user.

In this work we present an flexible interaction model able to reproduce computationally interaction controls as well as the experimental results obtained with their applications.

The presented model consists of a NME from OpenSim capable of representing the biomechanics of the human body, coupled to a computational model of a lower-limb exoskeleton that is able to reproduce the torques provided by a rehabilitation robot. The flexibility of the model is related to its ability to reproduce several types of interaction control.

This work seeks to supply the need for a tool that assists in the development and tuning of interaction controls for robotic rehabilitation of lower limbs without excessive consumption of time and money, and ensuring the patient safety. To evaluate the performance of the model, the computational result obtained was compared with the experimental ones.

2. MATERIAL AND METHODS

The human-robot interaction model designed in this work is composed of a computational model of the human neuro-musculoskeletal system, provided by the OpenSim, coupled to a virtual model of a lower-limbs exoskeleton. In this work only the right knee joint of the exoskeleton was applied to the NME model, but the other joints of the sagittal plane of an exoskeleton (e.g. hip, knee and ankle) can be easily added as needed. The description of the materials and methods used is given below.

2.1 OpenSim

OpenSim [1] is an open-source and freely available environment for modeling, simulation and analysis of the human movement developed in 2007 by (Delp *et al.*, 2007).

The OpenSim can provide modeling and simulation of the movement, but not great for controllers (e.g. interaction control of a human-exoskeleton system), then, to fully satisfy the modeling-control-simulation triad, the software must be integrated with MATLAB, which allows to perform the necessary controls.

In this work, the OpenSim was used to matches the anthropometry of neuromusculoskeletal models to a specific subject , calculate the torques necessary to perform a movement and simulate the controllers developed in MATLAB, providing data for analysis.

2.2 Neuromusculoskeletal Model

A three-dimensional, 23 degree-of-freedom, computer model of the human lower-limbs biomechanical system provided by OpenSim, Gait2392 Model, was used in this work to simulate the musculoskeletal system.

The model has 92 musculotendon actuators to represent 76 muscles in the lower extremities and torso (red lines in Fig. 1b), the bones are modeled as rigid bodies. The default version of this model represents a subject with mass of 75.16 kg and a height of 1.8 m.

The anthropometry of the model was adjusted through the *Scale Tool* from OpenSim, in order to match a particular subject with mass of 80 kg.

2.3 Exoskeleton - ExoTao

In this work the modular exoskeleton for lower limbs, ExoTao, introduced by (dos Santos *et al.*, 2017), was used. The exoskeleton is composed of a tubular structure with six free and independent joints that became the system modular and flexible.

For our purposes, only the right knee joint of the exoskeleton (in this text also referred to as *active orthosis*) was used in the experiments, to perform the flexion/extension knee movements. The active orthosis was fixed on a chair, in order to avoid the user feel the weight of the system (Fig. 1a).

2.4 Interaction Model Design

A computational model of the knee active orthosis of the ExoTao exoskeleton was coupled to the NME model in order to provide the human model with the external joint torques generated by a real exoskeleton of lower-limbs (Fig. 1b).

The exoskeleton model was created by editing the NME model and including in the joint of the right knee *coordinate actuators* capable of performing an angular movement in the sagittal plane as the real actuators (motor + reduction set) of the exoskeleton.

A coordinate actuator is a virtual actuator of the OpenSim that applies a generalized force (or torque) to a generalized coordinate. The force applied by the actuator is proportional to its input control signal, as expressed in Eq. (1).

$$\tau = u \cdot \tau_{optm} \tag{1}$$

where τ_{optm} is the maximum torque (optimal torque) that the actuator can apply (in this case, 50 N.m) and u is the control signal that varies between -1 and 1.

In this work, this type of actuator was chosen because of its functional similarity with the exoskeleton actuators: generalized torque application for sagittal plane movements.

Initially some simplifications were considered: the actuator is ideal (no mass, delay or losses), the axes of the joints of the robot and the user are collinear, the torque is applied directly to the joint in question.

[1] http://opensim.stanford.edu

2.5 System Dynamics

Since the exoskeleton and the user perform the same movement, the dynamic of the system can be modeled as:

$$\tau_{user} + \tau_{exo} = M(\theta)\ddot{\theta} + C(\theta, \dot{\theta}) + G(\theta) \quad (2)$$

where $M(\theta)$ is the inertia matrix, $C(\theta, \dot{\theta})$ is the vector of Coriolis and centrifugal forces, $G(\theta)$ is the vector of the gravitational forces.

The torque supplied by the user (τ_{user}) was calculated trough the *Inverse Dynamics Tool* (Section 2.6), and the torque supplied by the robot was determined by the impedance controller (Pena *et al.*, 2019):

$$\tau_{exo} = K_{exo}\theta_e - B_{exo}\dot{\theta} \quad (3)$$

where $\theta_e = \theta_d - \theta$ is the position error, $\dot{\theta}$ is the angular velocity of the joint and K_{exo} and B_{exo} are stiffness and damping parameters.

2.6 Inverse Dynamics

The *Inverse Dynamics Tool* of the OpenSim determines de generalized torques (i.e. the joint torques) necessary to develop a given movement, like to flex the knee. The tool uses the kinematic of the movement (position, velocity and acceleration) and the external forces (e.g. forces applied by the exoskeleton - τ_{exo}) to determine the net torques solving the Eq. (2).

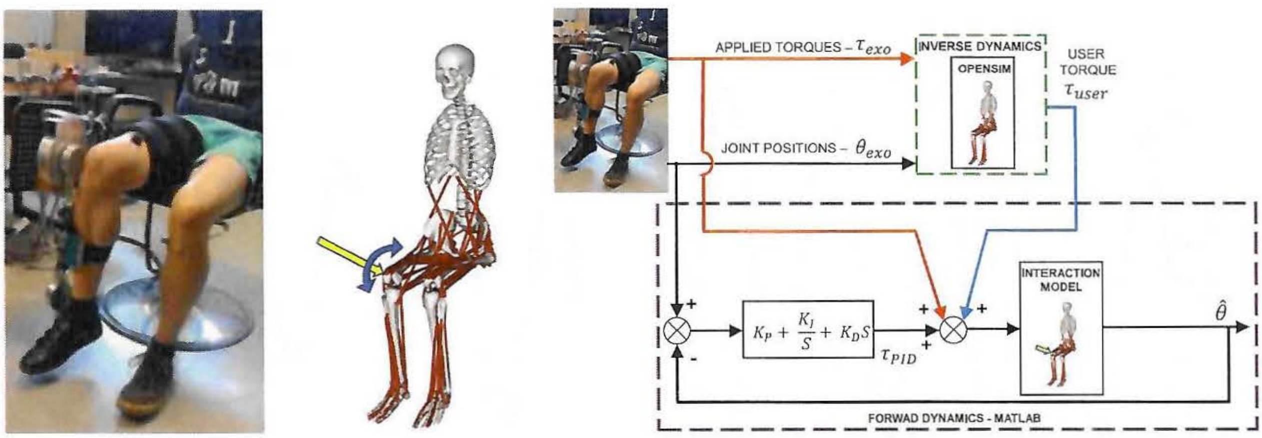
In this work, the inverse dynamics was used to determine the torques developed by the user (τ_{user}) to perform the required movements.

2.7 Experimental Procedure

In order to study and validate the interaction model, an experimental protocol developed by (Pena *et al.*, 2019) was used. The experiment consists of an user wearing the active knee orthosis in a seated position performing active movements (see Fig. 1a). The desired trajectory that the user attempted to execute correspond to a sinusoidal signal with an amplitude of -90 (knee flexed) to 0 (knee extended). The experiment was divided in two phases, according to the variation of the stiffness K_{exo} of the impedance control of the orthosis:

- Phase 1: User is active, robot is active with stiffness $K_{exo} = 60$ Nm/rad;
- Phase 2: User is active, robot is active with stiffness $K_{exo} = 60$ Nm/rad, with a 180 phase shift in the desired trajectory of the robot.

In Phase 1 the orthosis assumes an assistive behavior and in Phase 2 it presents itself resistive to the movement performed by the user.



(a) Right knee active orthosis from the ExoTao. (b) Gait2392 Model. (c) Forward Dynamics.

Figure 1. (a) ExoTao, (b) neuromusculoskeletal model and (c) the Forward Dynamics flowchart routine. In the Gait2392 Model (b), the red lines are the musculotendon actuators, the yellow arrow indicates the location of the coordinate actuator that represents the active orthosis, and the blue arrow represents the movement of the knee.

2.8 Forward Dynamics Based Simulation Algorithm

In order to reproduce computationally the developed controls using the interaction model, a forward dynamics based routine was implemented in MATLAB (Fig. 1c), combining the capabilities of modeling and simulation of the OpenSim with those of control of the MATLAB.

The forward dynamics describes, through a mathematical model of the dynamics of the mechanical system, how the coordinates and velocities of the system changes when a force or torque is applied to its joints.

In the developed routine, the torques from the interaction control are applied to the interaction model through a feedforward loop. A PID feedback loop produces a correction torque in order to compensate for the uncertainties of the model, the scaling, and the errors produced by the numerical integration routine.

In this routine, the input (τ_{exo}, θ_{exo}) variables was experimentally measured through the application of the impedance control law (Eq. (3)) in the robot according to the experimental procedure described in Section 2.7. The users torque (τ_{user}) was obtained through the *Inverse Dynamics Tool*, as stated above. The motion determined by the forward dynamics based algorithm ($\hat{\theta}$), using the Interaction Model was compared with the movement performed by the user during the experiment.

3. RESULTS AND DISCUSSIONS

The simulation algorithm was utilized to reproduce the movement obtained with the experiment proposed by (Pena *et al.*, 2019) (Section 2.7). The intention was to verify if, using the torques applied by the robot which were measured by the sensors of the orthosis, together with the estimated torque of the user through the Inverse Dynamics Tool, the movement performed by the interaction model ($\hat{\theta}$) would be the same measured through the orthosis encoders (θ_{exo}).

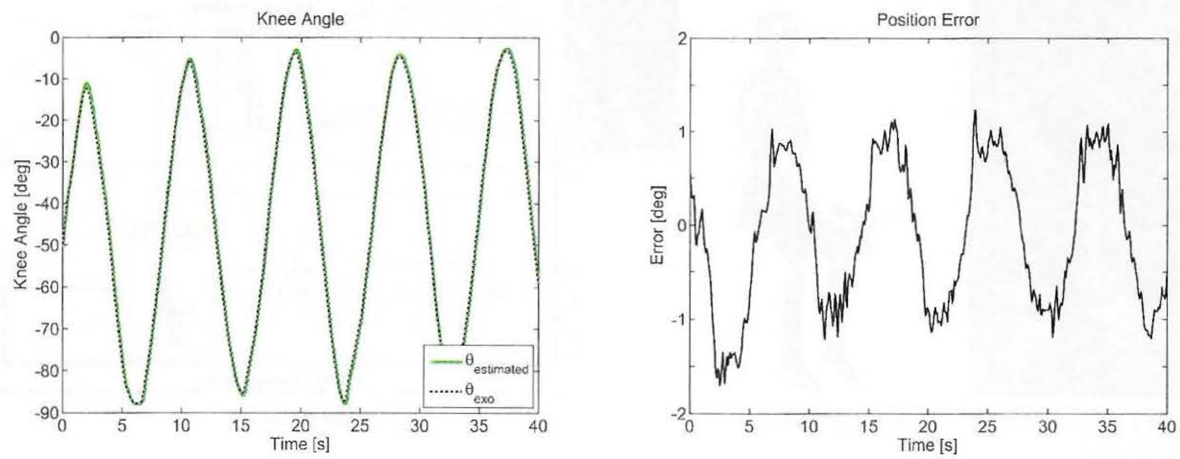
The results obtained from the interaction model were compared with the ones obtained experimentally. They are presented and discussed below.

The angular position measured from the robot was well tracked by the interaction model during the computational simulation (Fig. 2a and Fig. 3a). An analysis of the tracking error is presented in the Table 1. Considering all the uncertainties of modeling, computational integration and experimental data collection, the error obtained is tolerable and the $\hat{\theta}$ is satisfactory.

Table 1. Knee angular position error analysis.

Error [deg]	Phase 1	Phase 2
RMS	0.783	0.755
Maximum positive	1.235	2.281
Maximum negative	-1.694	-1.985

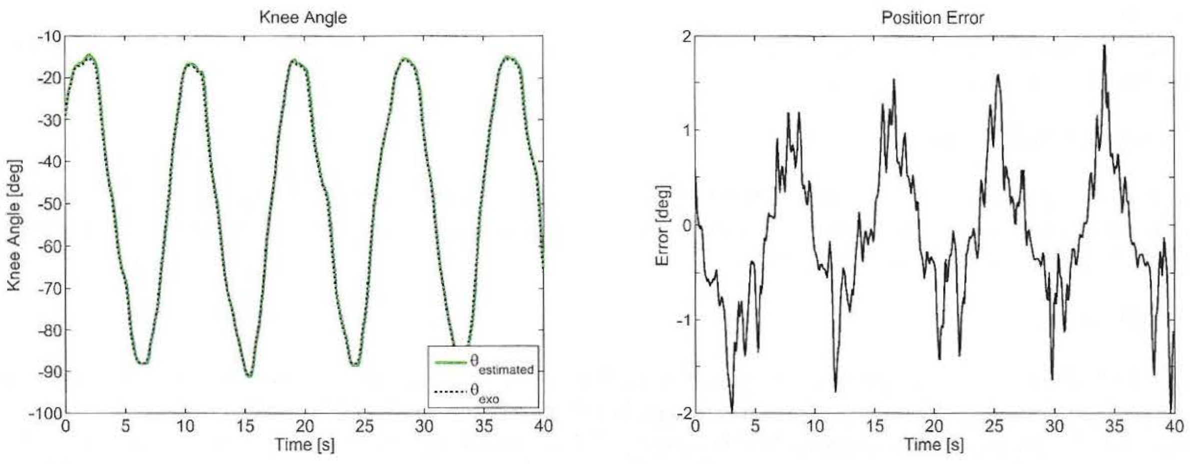
$error = \theta_{exo} - \hat{\theta}$



(a) Angular position.

(b) Tracking position error.

Figure 2. Angular position and tracking error of the phase 1 ($\theta_{estimated} = \hat{\theta}$)



(a) Angular position.

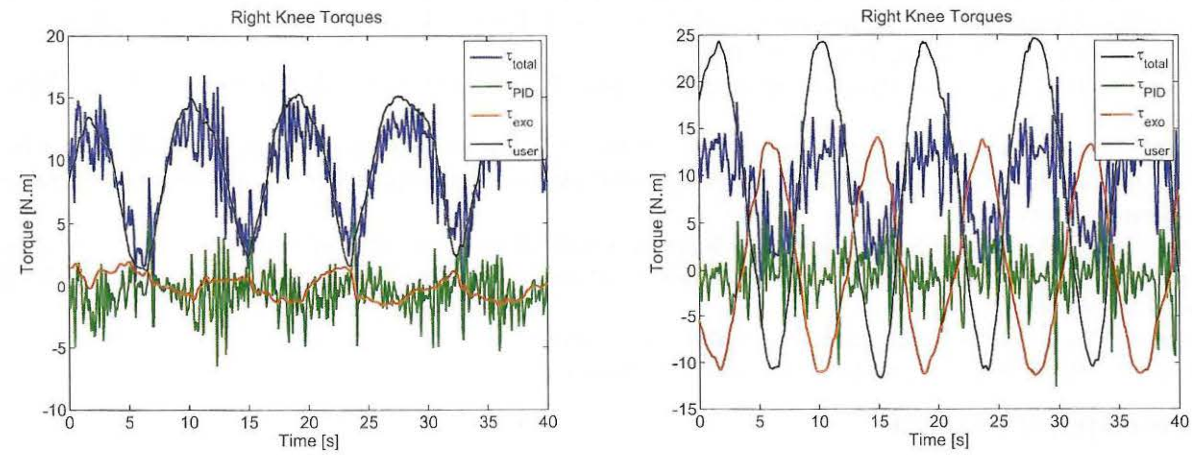
(b) Tracking position error.

Figure 3. Angular position and tracking error of the phase 2 ($\theta_{estimated} = \hat{\theta}$)

The torque produced by the orthosis along with the estimated torque developed by the user are shown in Fig. 4. The feedback PID torque required to compensate for the uncertainties involved is also shown in the figure. The uncertainties come from the interaction model, the anthropomorphic adaptation of the model to the user, the computational numerical integrations and the experimental data collection, in the absence of these uncertainties, such torque would be zero, which is unreachable.

In the phase 1 the torque applied by the robot is assistive and has a small amplitude when compared to the torque developed by the user. In the phase 2, the torque applied by the robot is resistive having a 180 degrees shift in relation to the user torque, what can be seen in the Fig. 4.

The torque applied to the knee joint of the interaction model (τ_{total}) is the sum of the torque applied by the robot (τ_{exo}), the torque of the user (τ_{user}) and the correction torque (τ_{PID}).



(a) Torques of the Phase 1.

(b) Torques of the Phase 2.

Figure 4. Torques involved in the movements of the phases 1 and 2. In the Phase 1 the orthosis torque is assistive and in the Phase 2 the orthosis torque is resistive (see the 180 degrees shift between user torque and orthosis torque.)

4. CONCLUSIONS

In this paper was presented a computational human-exoskeleton interaction model with focus on the sagittal movement of the right knee joint. Although the model was only used to reproduce the knee movement, it can be easily remodeled to receive a complete exoskeleton, performing more types of motion.

The model was simulated using the forward dynamics based algorithm with experimental data as inputs. The obtained results was closely to the experimental one, evidencing that the model is effective. The input data can be generated computationally, making the system independent of the experimental data.

For the next step, is intended to match the model with the actual exoskeleton patterns taken as the basis (mass of the actuators, delay, losses).

It is also intended to apply the interaction model in the simulation of gait movement, which is the main skill to be recovered by the rehabilitation of lower limbs.

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