HUMAN-EXOSKELETON COMPUTATIONAL MODEL: AN APPROACH TO THE HUMAN-MACHINE INTERACTION PROBLEM IN ROBOTIC ASSISTED THERAPY

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Abstract. *The purpose of this work was to develop a human-exoskeleton of lower limbs interaction model and a forward dynamics based algorithm able to simulate and test interaction controls applied to robotic neurorehabilitation. The interaction model was developed using the neuromusculoskeletal model gait2392 provided by the OpenSim, with coordinate actuators coupled to the joints of the hip, knee and ankle, in order to representing the exoskeleton ExoTAO. A fuzzy-based adaptive impedance control was developed and used to test the proposed system. The results proved that the use of interaction models and simulation is a powerful resource to develop and test interaction controls applied to the robotic assisted therapy.*

Keywords: *Human-exoskeleton interaction model, OpenSim, robotic neurorehabilitation.*

1. INTRODUCTION

Stroke is a noncommunicable cardiovascular disease, provoked by the suspension of the blood supply to the brain because a bleeding (hemorrhagic stroke) or a clot (ischemic stroke). In Brazil, stroke is the leading cause of death and permanent motor disability. Every minute 30 people get a stroke for the first time around the world, and one in six individuals in the world will have a stroke throughout their life course. It is predicted that by 2030 there will be 34 million strokes and 200 million people with some motor disability due to the disease (WORLD HEALTH ORGANIZATION, 2011; BRAZIL, 2013).

The stroke victim has its quality of life compromised due to the remaining sequel. The capability of the patient to perform the activities of daily life (ADL) is reduced, and tasks that were simple and common before the stroke, become real challenge or even impossible to be executed without the help of other people, such as dressing, writing, eating and walking. Physical and occupational therapy for rehabilitation help to treat injuries and impairments, improving the lost functions (DIAZ et al., 2011).

The use of robots in rehabilitation therapy has been shown as an efficient alternative to improve the quality of the treatment, providing quantitative data, reliability, repeatability, flexibility and reducing the need for several therapists per patient (which in gait rehabilitation means three per victim).

However, human-robot interaction is still a challenge: it must be performed in such a way as to ensure patient safety, the equipment involved and meet the assist-as-needed paradigm promoting the neuroplasticity. In order to attend these requisites, sundry interaction controls have been developed, most of them based on the impedance control created by Hogan (1985).

Testing, adjusting, and validating these interaction controls often require physical human-robot involvement, which can result in hazards to the user and equipment, and require considerable time and resources to prepare for trials.

The objective of this work was to develop a computational human-exoskeleton interaction model and a simulation algorithm able to be used for reproduction, validation and testing of interaction controls applied in robotic rehabilitation of lower-limbs, promoting agility, flexibility and reducing the need for physical human-robot contact during the tuning and tests of these controls.

The use of computer models has become increasingly common in the field of rehabilitation engineering: Sousa et al (2016) utilized musculoskeletal computational models to test controls strategies for FES, Durandau et al (2016) acquired muscle kinematics information using musculoskeletal model to realize an EMG-driven models of human-machine interaction. Peña (2017) developed an adaptive impedance control were the impedance of the exoskeleton is varied according to the user one, the researcher used musculoskeletal model to determine the impedance of the user. Nunes et al (2018) turned to the computational models to analyze the influence of an exoskeleton on the motor primitives when a subject walking wearing an exoskeleton.

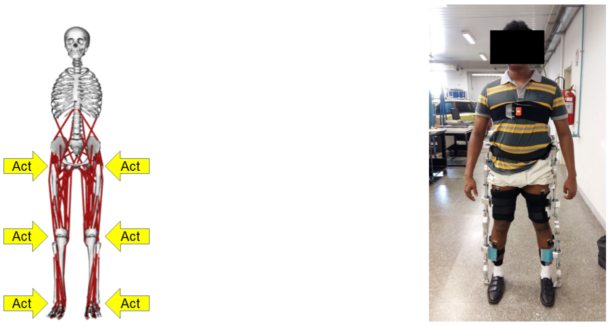
2. METHODOLOGY

This section describes model development as well as the tests performed using an impedance-based interaction control.

2.1 Interaction Model

The interaction model consists of a computational model of the neuromusculoskeletal system (NMS) related to human lower limb biomechanics, with actuators coupled to the joints of the hip, knee and ankle, in order to reproduce computationally the functioning of an exoskeleton (Fig. 1 (a)).

The NMS is the Gait2392: a three-dimensional, 23 degree-of-freedom, computer model of the lower-limbs biomechanical system, provided by the OpenSim[1]. The 76 muscles of the lower extremity of the human body are modeled as 92 musculotendon actuators and the bones are modeled as rigid bodies. The default unscaled model corresponds to an individual that is approximately 1.8 m tall and has a mass of 75.16 kg, this default model was used in this work.



(a) Gait2392 (b) ExoTAO

Figura 1. (a) neuromusculoskeletal Gait2392 model, the red lines are the musculotendon actuators and the yellow arrow indicates the location of the coordinate actuators representing those of the robot, (b) Full ExoTAO being used. The Authors (2019).

The virtual model of the exoskeleton was developed using a set of coordinate actuators that apply generalized torques, representing the ExoTao: an exoskeleton of lower limbs introduced by Santos et al (2017), composed of a tubular structure with six free and independent joints that promote movements in the sagittal plane (Fig. 1 (b)).

For our purposes some simplifications were considered: the actuators are 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 and, to perform the movements tested in this work, only the knee joint was used.

A forward dynamics-based algorithm drives the interaction model allowing the reproduction of the interaction controls. The total torque applied to the interaction model is the sum of the torque developed by the user and the one produced by the exoskeleton (Fig. 2).

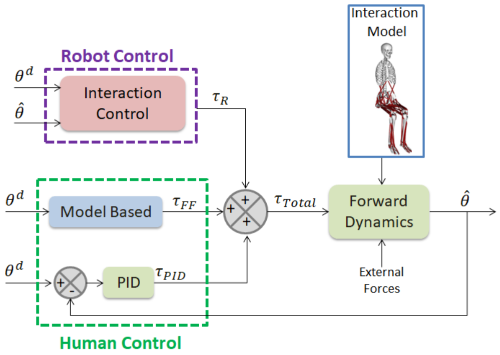


Figura 2. Forward dynamics based algorithm.θ^d is the desired position, $\hat{\theta}$ is the estimated position and the External Forces are the contact forces between the model and the environment (e.g. ground reaction forces). The Authors (2019).

The torques developed by the user comes from human control which consists of a feedforward loop, based on the inverse human internal model concept and a feedback loop whose function is to eliminate the effects of the disturbances that affect the good performance of the motion (LAM et al, 2006). In this work, the feedforward controller was modeled utilizing the *Inverse Dynamics Tool* from the OpenSim and the feedback controller was modeled as a conventional PID controller.

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

The robot control loop consists of the interaction control which in this work is a fuzzy-based adaptive impedance control, presented in the next section.

2.2 Fuzzy-based Adaptive Impedance Control

The control law of the interaction control is given by

$$\tau_{exo} = K_{exo}(\theta^d - \hat{\theta}) - B_{exo}\dot{\theta} \tag{1}$$

where B_{exo} the damp coefficient of the exoskeleton, constant and equal to 0.01 N.s/rad and K_{exo} is the robot stiffness that is variable according to a fuzzy logic inference. The variation of K_{exo} is directly proportional to the level of assistance that the robot provides to the user and seeks to meet the *assist-as-needed* paradigm.

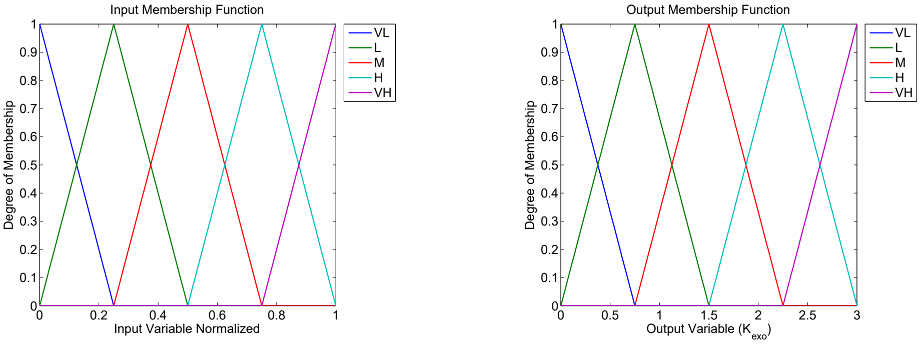
The logical inference assumes that if the position error perceived by the user is large, he tries to apply the maximum force to perform the movement and eliminate such error, and if the applied force is below the necessary, it is understood that it is not the will of the user, but due to weakness, so that the robot must assist him in completing the movement.

For this purpose, the inputs for fuzzy inference are the RMS position error and user torque, normalized to predetermined maximum values according to the Equation (2) and the output is the stiffness K_{exo}.

$$\tilde{x} = \frac{1}{x_{max}}\sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2} \tag{2}$$

where the variable x is the variable of interest (position error or user torque), N is the number of samples to calculate the root mean square, x_{max} is the maximum value to the normalization and $\tilde{x}$ is the variable normalized.

For fuzzification and defuzzification five symmetric triangular membership functions were defined to each input/output, classifying them as Very Low (VL), Low (L), Medium (M), High (H) and Very High (VH).



(a) Input Membership (b) Output Membership

Figura 3. Membership functions for fuzzification and defuzzification. The Authors (2019).

The fuzzy rules for impedance adaptation were formulated in order to meet the assist-as-needed paradigm and are presented in the Table 1. The output inference is determined through the Mamdani fuzzy implication and the Max-Min method. The defuzzification is performed through the center-of-area method and the output surface can be seen in Figure 4.

Tabela 1. Impedance adaptation rules, the Authors (2019).

		τ_{user}				
		VL	**L**	**M**	**H**	**VH**
error	**VL**	L	L	L	VL	VL
	L	M	M	L	L	VL
	M	H	M	M	L	L
	H	VH	H	M	M	L
	VH	VH	VH	H	M	L

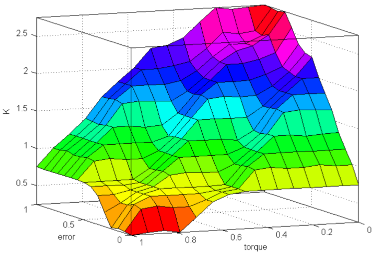


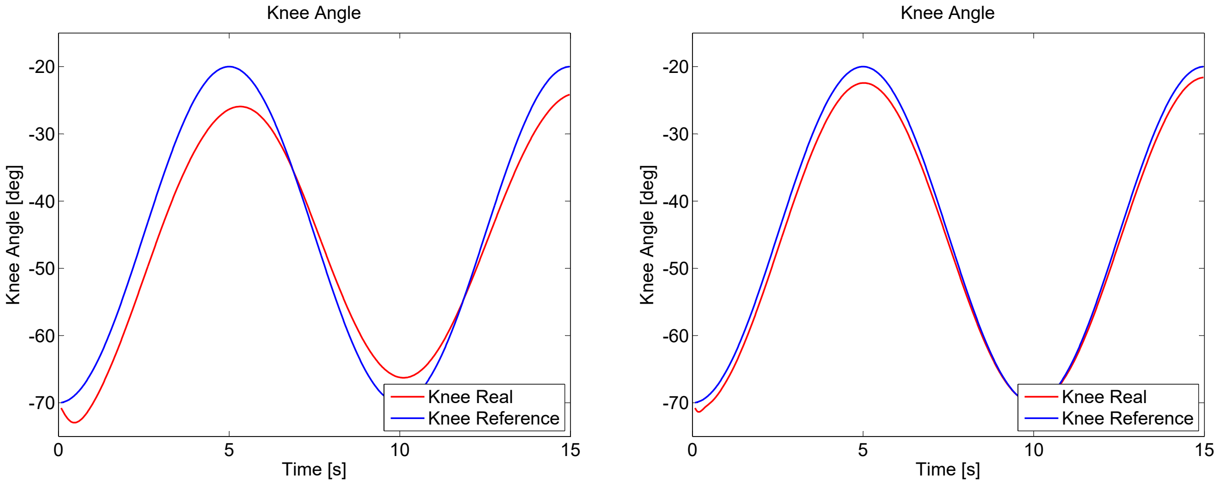
Figura 4. Surface of the fuzzy-based adaptive impedance. The Authors (2019).

3. RESULTS AND DISCUSSION

Two tests were performed considering the model in a sitting position, using only the knee joint of the exoskeleton and performing a movement of flexion and extension of the right knee, following a sinusoidal trajectory. In this condition the model does not suffer action of the ground reaction forces and the external forces were considered null.

In the first test (here referred to as Test 1), was considered only the user, without the exoskeleton, then, all the torque employed to perform the motion was developed by the subject. In the second test (here referred to as Test 2) the robot was utilized with the adaptive impedance control presented in the previous section, in this case the torque involved in the realization of the movement was provided by both the user and the robot.

The user was simulated as a patient with some muscular weakness and unable to develop the necessary torque to perform the movement without tracking errors in relation to the desired positions.



(a) Test 1

(b) Test 2

Figura 5. Knee angular position of the two tests performed. The Authors (2019).

Analyzing the graphs in Figure 5, it is possible to verify that the patient can follow the movement shape determined by the reference trajectory, but cannot perform the movement accurately when doing it alone. Using the robot ensured that the patient could complete the movement with minimal error.

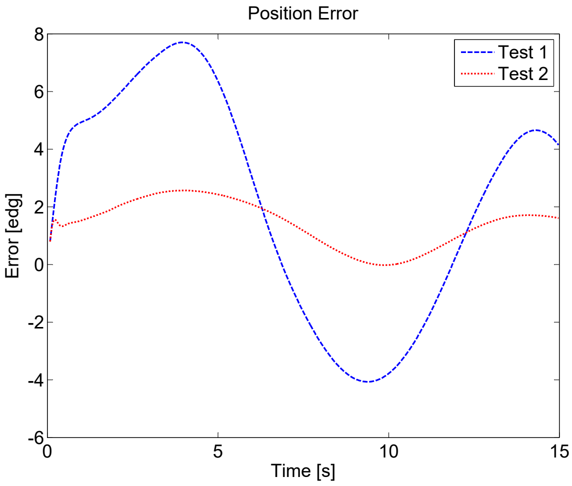
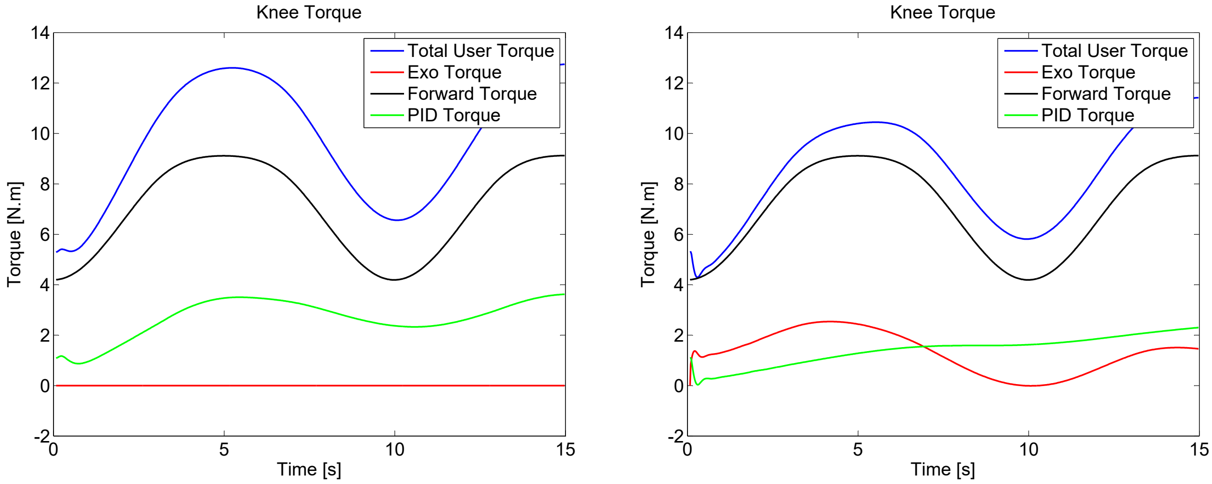


Figura 6. Comparison between the position errors of the both tests. The Authors (2019).

The tracking errors were reduced with the assistance of the robot, as can seen in the Figure 6. The RMS position errors were 4.46° for the first test, and 1.64° for the second one.



(a) Test 1

(b) Test 2

Figura 7. Knee torque. The Authors (2019).

Although the patient performs a larger modulus effort when without the robot (Fig. 7), such effort is not well oriented so that there are tracking errors, as can be seen in Figure 5. The robot assists the patient in guiding the application of force, assisting him to perform the movement correctly and preventing muscle fatigue due to overexertion.

Importantly, treatment seeks to reestablish the patient's movement pattern and motor coordination, so that performing standardized movements is more important than performing high effort.

According to the graph in Figure 7b, it is possible to verify that the robot provides a torque whose sinusoidal shape matches the desired movement.

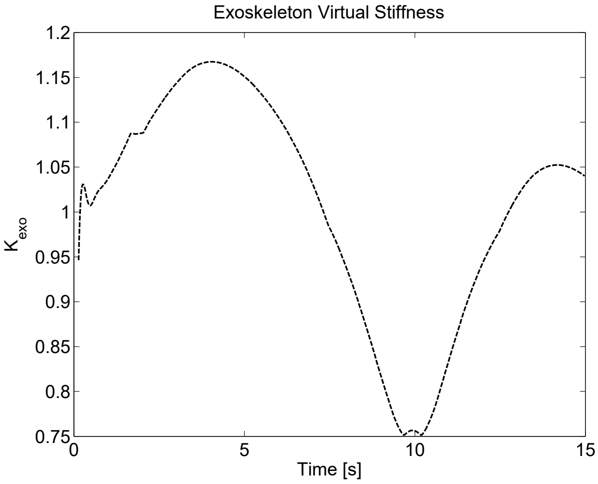


Figura 8. Virtual stiffness of the robot, modulated according to the fuzzy inference. The Authors (2019).

The stiffness of the robot (Fig. 8) depicts the level of user assistance, which decreases along the movement as the error approaches zero. This fact can be proved by checking the torque provided by the robot, which also approaches zero, so that the exoskeleton acts only by assisting the patient to perform the desired motion shape well, without making the movement by the user.

The two tests took 19 minutes each to be computationally simulated, so that in less than one hour the proposed control can be verified and compared with a similar situation, but without robot assistance. Other tests can be performed, such as keeping the stiffness constant or making the robot act in active-resistive mode, these changes only take a few minutes to set up and less than half an hour to test, which is not possible with laboratory tests using the actual exoskeleton and user.

4. CONCLUSION

With this work it is possible to conclude that the use of interaction models and computational simulation is a promising approach for the testing and development of interaction controls applied to robotic neurorehabilitation.

The next steps are to perform gait movements with the model, using external forces and testing other controls present in the literature.

5. Acknowledgments

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7. ACKNOWLEDGMENTS

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