ADAMS/Matlab Co-simulation of an Exoskeleton for Lower Limbs

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Abstract.*This paper deals with modeling, simulation and control of an exoskeleton for lower limbs. First, an ADAMS-based environment simulation was developed considering the main characteristic of a human using the proposed powered orthosis and the interaction forces between the user and the device. Further a co-simulation of the ADAMS software with the Matlab platform was developed. The co-simulation is performed by creating a communication block in the Matlab/Simulink environment which transfers position, velocity and force values from ADAMS processor to Matlab workspace. A predefined trajectory, where the ZMP is considered as stabilization criterion, was used to generate desired values of joint positions and velocities. With the results obtained from simulation, it is possible to estimate the human-exoskeleton interaction forces. This information is useful to design gait-pattern adaptive algorithms which change the desired trajectory according to human behavior.*

Keywords: *Active orthoses, exoskeleton, modeling and simulation, ADAMS/Matlab simulation*

1. INTRODUCTION

Exoskeletons are powered orthosis designed to help physically weak or injured people, increasing their mobility and performing rehabilitation exercises (Ferris, Sawicki & Domingo 2005, Hayashi, Kawamoto & Sankai 2005). In the military area, exoskeletons are designed considering the problem of human power augmentation: allow the soldiers to walk and run while carrying heavy load strapped to a backpack frame. One example of this kind of system is the Bleex (Berkeley Lower Extremity Exoskeleton), an exoskeleton where the links are actuated by hydraulic units driven by a fuel-powered engine. In (Walsh, Paluska, Pasch, Grand, Valiente & Herr 2006), an underactuated and lightweight exoskeleton that considers the passive dynamic of walking is being developed. Two architectures are explored: the first one considers a spring in the hip, a variable impedance device in the knee and a spring in the ankle; the second one substitutes the spring of the hip for a no conservative actuator to examine the effect of power addition during the walking cycle.

In this work deals with the co-simulation of an exoskeleton for lower limbs based on a commercial orthosis. The co-simulation is performed considering the ADAMS software and the Matlab/Simulink toolbox. The ADAMS platform is a simulation software of mechanical systems for testing virtual prototypes, where the designers can improve the performance, security and comfort of the projects without building them. Also, the ADAMS environment allows the user to perform control objectives through the usual PID controllers. However, to implement more sophisticated controllers, alternative procedures must be taking into account. The toolbox Simulink of MATLAB is a powerful tool widely used to develop the control system solutions. The proposed co-simulation joins the qualities of the softwares, the modeling and simulation features of the ADAMS with the computational facilities of the Matlab environment.

Some researchers seek to develop open software for simulation of mechanical systems, (ten DAM; L. Paoli; F. Génot; M. Abadie 2001, Parseghian 2000). However, most models of biped robots used to design and test controllers consider that the point of contact between the robot and the ground is a rotational joint (Plestan, Grizzle & Westervelt 2003). That is, the biped robot is considered as a robot with fixed base. In this case, the constrains in the contact points are not considered in the dynamic equations and the forces resulting from these contacts are not computed.

The human-exoskeleton model proposed in this paper considers the main characteristic of a human using such a kind of device: the interaction forces between them. With the results obtained from simulation, it is possible to estimate these forces, which are useful to design gait pattern adaptive algorithms that change the desired trajectory according to human behavior.

This paper is organized as follows: Section 2 presents the exoskeleton based on a commercial orthosis and its model in the ADAMS software; Section 3 show the user model and the interaction points of contact between the exoskeleton and the user model; in Section 4, the Matlab/Simulink model of the exoskeleton controller is presented; and Section 5 presents the results of co-simulation between ADAMS and MATLAB.

2. EXOSKELETON MODEL

The model was made considering the commercial orthosis shown in Figure1. It corresponds to one Reciprocating Gait Orthosis LSU (Lousiana State University), developed in the Ontario Crippled Children's Centre, at the beginning of 1970. For the final configuration of the exoskeleton, it is considered that all joints in the sagittal plane will be driven by an Series Elastic Actuator (SEA). SEA can performed force and impedance controls, which can be used to generate a variable impedance controller (Walsh et al. 2006).

Figure 1. Commercial orthosis, Solid Edge and ADAMS models of the exoskeleton.

A model of the orthosis was built in Solid Edge, Fig. 1. This representation was useful on the determination of the dynamic parameters of the orthosis, shown in Table 1. It is also presented the parameters of the human considered in the simulation, obtained from (Winter 1990), considering a 85 kg, 1.74 m individual.

Table 1. Orthosis and Human Dynamic Parameters.

Orthosis		**Patient**	
$M_{total,ort}$	4.8	$M_{total,pat}$	85
$L_{total,ort}$	1.0	$L_{total,pat}$	1.74
Limb Mass (kg)			
$M_{tigh,ort}$ 0.95		$M_{tigh,pat}$	8.5
$M_{leg+foot,ort}$	0.72	$M_{leg+foot,pat}$	5.2
$M_{torso,ort}$	1.49	$M_{torso,pat}$	57.6
Limb Length (m) - z direction			
$L_{tigh,ort}$	0.39	$L_{tigh,pat}$	0.39
$L_{leg+foot,ort}$	0.49	$L_{leg+foot,pat}$	0.49
$L_{torso,ort}$	0.12	$L_{torso,pat}$	0.87
Limb Center of Mass (m) - z direction			
$CM_{tigh,ort}$	0.18	$CM_{tigh,pat}$	0.17
$CM_{leg+foot,ort}$	0.17	$CM_{leg+foot,pat}$	0.30
$CM_{torso,ort}$	0.11	$CM_{torso,pat}$	0.33
Limb Inertia Momentum (kgm^2) **- sagital plane**			
$I_{tigh,ort}$	0.03	$I_{tigh,pat}$	0.14
$I_{leg+foot,ort}$	0.02	$I_{leg+foot,pat}$	0.22
$I_{torso,ort}$	0.06	$I_{torso,pat}$	10.73

The ADAMS model of the orthosis is a 7 degree of freedom multi-body system, with the ground represented as a flat and rigid body. This ADAMS orthosis model was created by saving the Solid Edge model as a 'STEP(.*stp) and importing it in the ADAMS environment. This procedure is a little complex because doesn't allow the passage of models with many details, but makes it possible to calculate the inertial properties of the body through the geometry.

The exoskeleton links were joined by revolution joint, which only allows one degree of freedom (DOF). Thus, the six joints connecting the links are numbered as shown in Figure 1. Joints 1 and 2 correspond to the hip joints, joints 3 and 4 correspond to the knee joints and joints 5 and 6 are ankle joints.

In the model impact and friction of the feet with the ground were considered. The normal component of contact force depends on the weight distribution of the members of the model and dynamic variables (velocities and accelerations of the joints). The tangential component is represented in terms of friction. The direction of the force of friction depends on the relative movement between the foot and the ground. The magnitude depends on the static friction coefficient, considered here as 0.9, and dynamic friction coefficient, equal to 0.8. The inertial characteristics of each orthosis part were determined using the tools given by the CAD software and specifying the correct density for the orthosis parts.

3. HUMAN MODEL

According to (Winter 1990), the measures of human segments can be simplified by some relation with the height of the individual. The model of the human also constructed in the Solid Edge software, Figure 2, takes into account the values proposed by (Winter 1990) for a 1.74 m individual as shown in Table 1. The complete human-exoskeleton configuration is shown also in Figure 2.

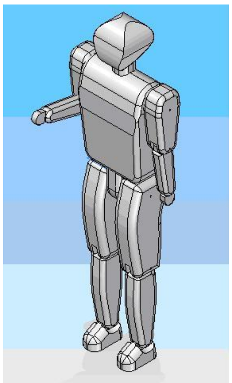


Figure 2. Human model and human-exoskeleton configuration.

3.1 Human-exoskeleton interaction

The interactions between the human and the exoskeleton are modeled as spring-dampers, fixing the user to the orthosis. Five interaction points are considered in the human-exoskeleton model: one at the torso; two at the thigh (one for each leg), between the hip and knee joints; and two at the each leg, between the knee and ankle joints.

These points try to model in the closest way the belts that are used to attach the bracing to humans as seen in Figure 3. The interactions between the leg, thigh and torso are shaped as shown: two springs are placed parallel to the exoskeleton to prevent rotation between the parts of human model for bracing and a spring is placed perpendicularly to the device part to represent the interaction force and make possible the mensure of the interaction forces. Since it is considered the user will use shoes to connect him/her to the exoskeleton foot, the human foot is fixed to the device through a fixed joint.

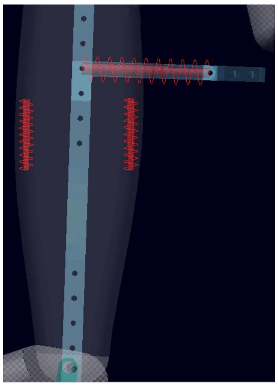


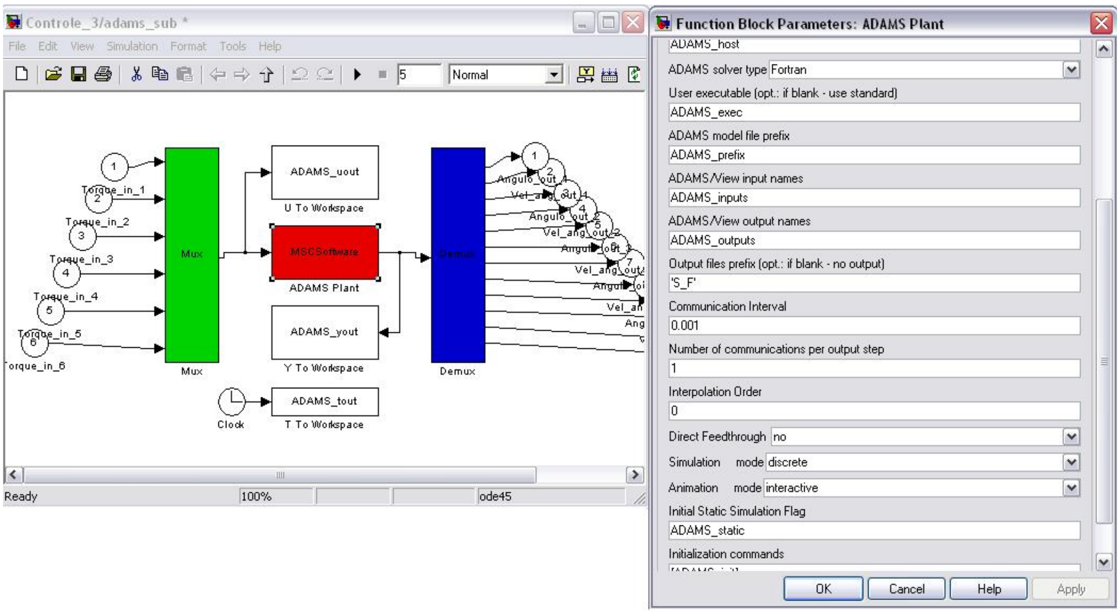
Figure 3. Interaction model for the leg point.

4. MATLAB/SIMULINK MODEL AND CONTROL IMPLEMENTATION

In this section we present the Matlab/Simulink control strategy for the human-exoskeleton model. It is also show the guidelines to implement it in a co-simulation with the ADAMS environment. For controlling purposes, a predefined path, where the ZMP was considered as a stability criterion, is used to generate the desired values of position and velocity of the joints.

According to (Huang, Yokoi, Kajita, Kaneko, Arai, Koyachi & Tanie ,2001), the walking cycle can be separated in two phases, double support and single support. The double support phase starts when the heel of the forward foot touches the ground and finishes when the toe of the backward foot leaves the ground. The second phase is characterized by the fact only one foot is in contact with the ground. In this work, the double support represents 20% of the entire walking cycle.

The foot and hip trajectories can be computed as function of the length and duration of the step and the position of the torso during the step. The ZMP optimization proposed in (Huang et al. ,2001) considers the minimization of a functional that guarantees the ZMP remains most of the time next to the center to the support polygon, configuring a stable trajectory. The minimization of this functional was performed considering as argument the position of the torso during the step. The resulting joint trajectories are set as the desired joint trajectories for the exoskeleton. The human moves according to the interaction forces acting in the interaction points. To implement the Matlab/Simulink control block, the ADAMS model of the human-exoskeleton configuration is exported in block form of the Simulink, Figure 4. In this case the simulation was set as discrete and the animation as interactive.



ADAMS_host
ADAMS solver type: Fortran
User executable (opt.: if blank - use standard): ADAMS_exec
ADAMS model file prefix: ADAMS_prefix
ADAMS/View input names: ADAMS_inputs
ADAMS/View output names: ADAMS_outputs
Output files prefix (opt.: if blank - no output): 'S_F'
Communication Interval: 0.001
Number of communications per output step: 1
Interpolation Order: 0
Direct Feedthrough: no
Simulation mode: discrete
Animation mode: interactive
Initial Static Simulation Flag: ADAMS_static
Initialization commands

Figure 4. ADAMS Block.

The input variables for this ADAMS model block are the torques of each joint and the output are the angular velocities and positions of each joint. Figure 5 shows a block diagram of the control strategy for one joint. It correspond to a PD controller directly acting in the ADAMS block input. Although a more sophisticated controller could be implemented, the main objective of this paper is to show the ADAMS/Matlab co-simulation is suitable for human-exoskeleton models.

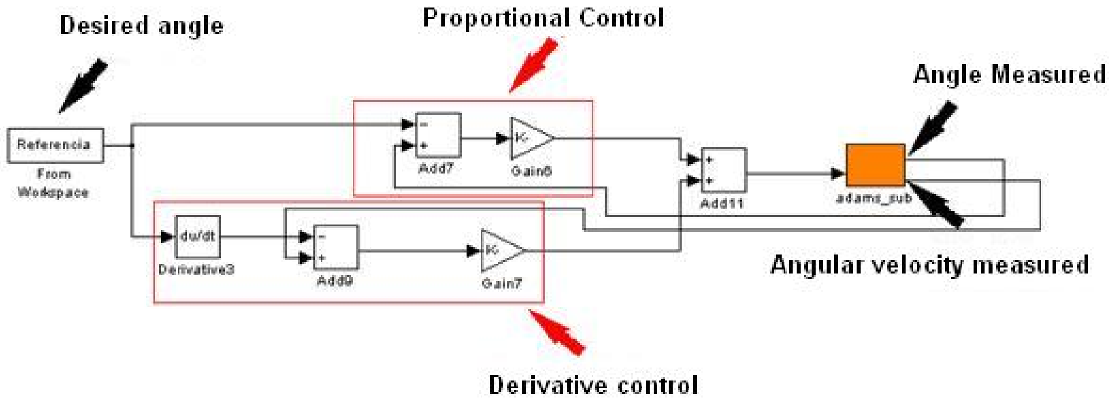


Figure 5. Block diagram of the PD controller for one joint.

Figure 6 shows the complete block diagram of the controller. Basically, there are six controllers, one for each joint following the numerical order shown in Figure 1. The values of the PD gains, shown in Table 2, were selected in such a way that the exoskeleton follows satisfactorily the desired trajectory and the human does not suffer discontinuous or high velocities movements.

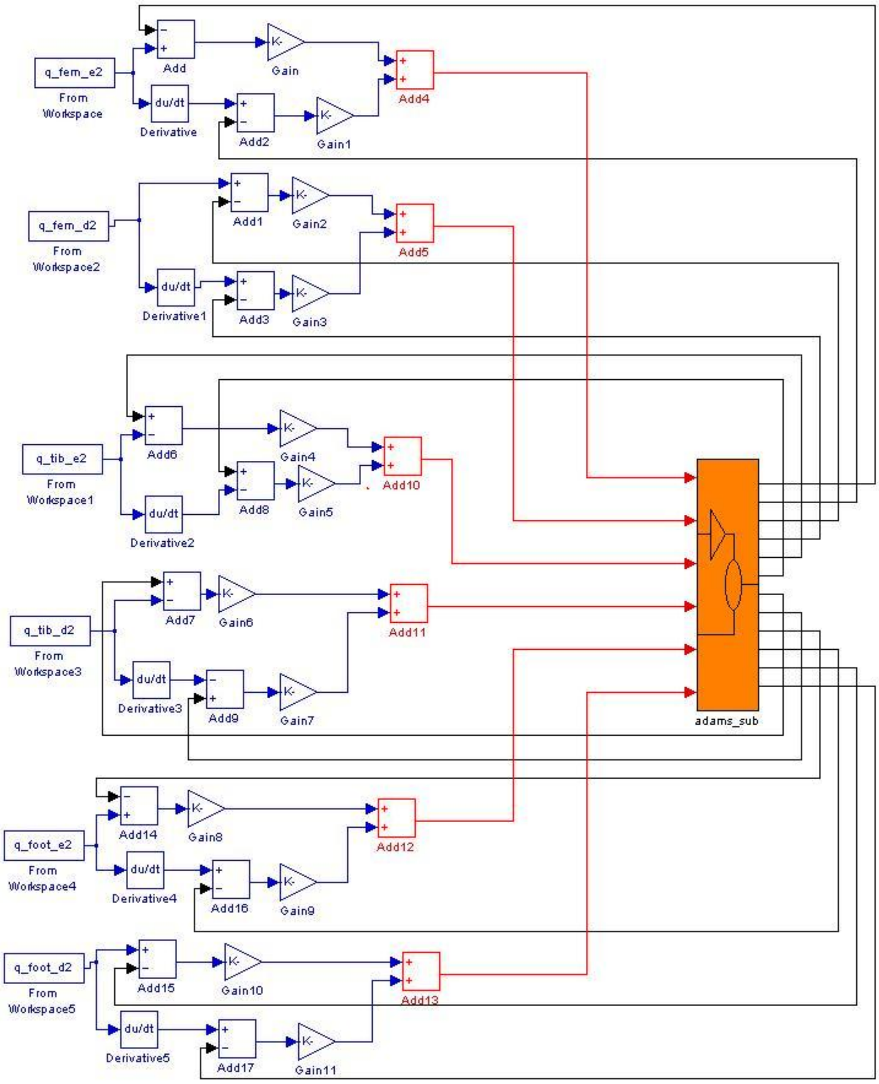


Figure 6. Complete block diagram of the exoskeleton controller.

Table 2. Values of the *PD* gains.

Joints	**Proportional gain**	**Derivative Gain**
1 e 2	2000000	80000
3 e 4	1500000	80000
5 e 6	800000	1000

5. RESULTS

The results obtained from the ADAMS/Matlab co-simulation is presented in this section, considering step length of D_s =0.001s. The overall simulation was performed for 5s, with sampling time of 0.001s. The results presented in the above sections considers the notation shown in Figure 1.

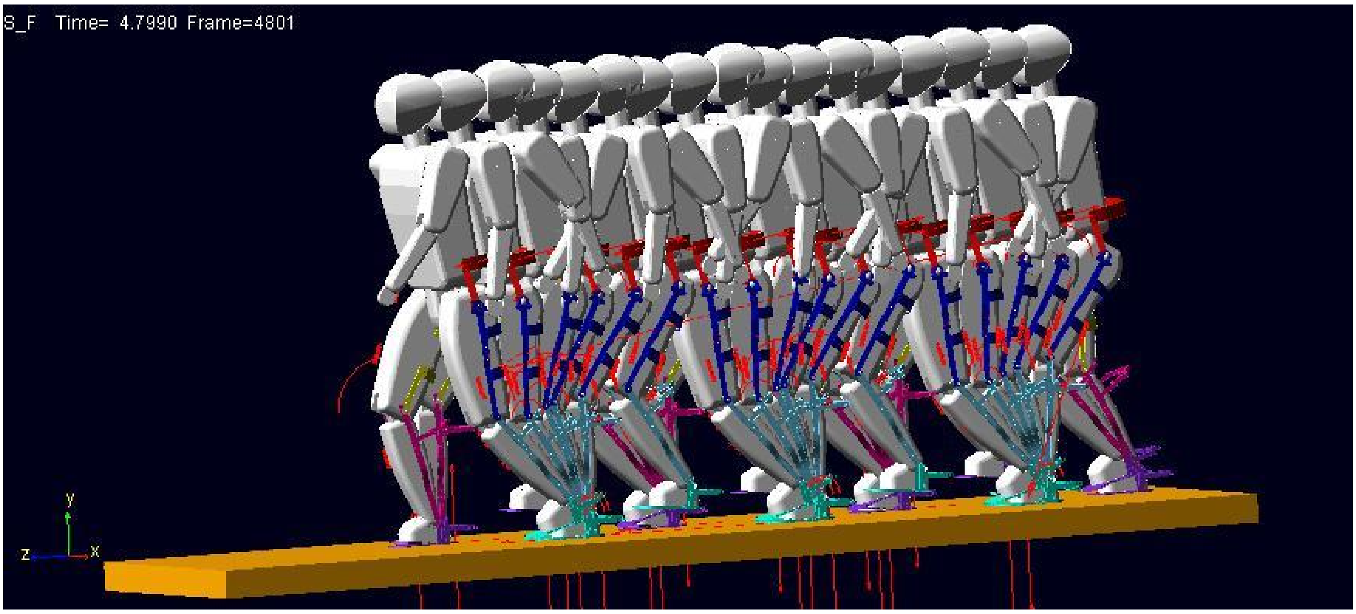


Figure 7. Simulation.

5.1 Joint Trajectories

The desired and actual joint trajectories are shown in Figures 8 to 10, only the results for the joints of the left leg are shown since the movement is symmetrical. We see that the joint positions are very close to the desired ones, but still different from it. One reason for such a discrepancy is the impact of the foot exoskeleton with the ground, we can observe that, in general, the joint positions differ mainly from the desired ones in the points with zero velocity. This effect can possibly be corrected by increasing the derivative gain. However,a higher derivative gain results in excessive torque which makes the trajectory of the bracing unstable. Despite small differences in relation to the desired position, the bracing remains stable.

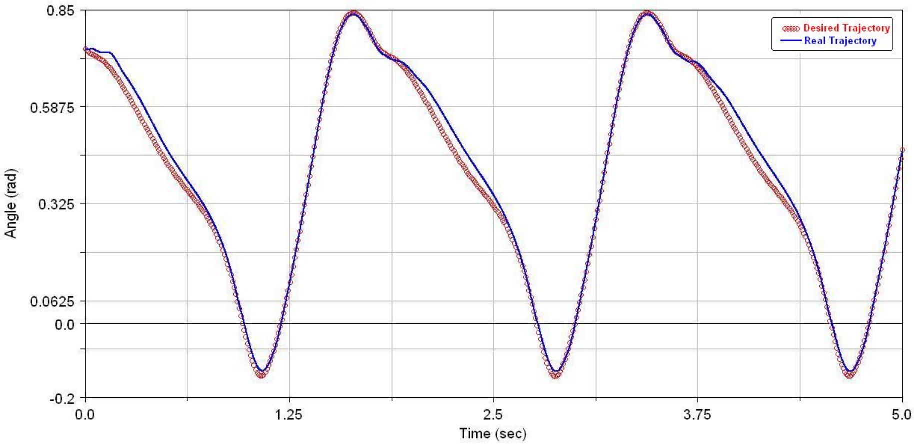


Figure 8. Angle(rad) x time(sec) for joint 1, left hip joint

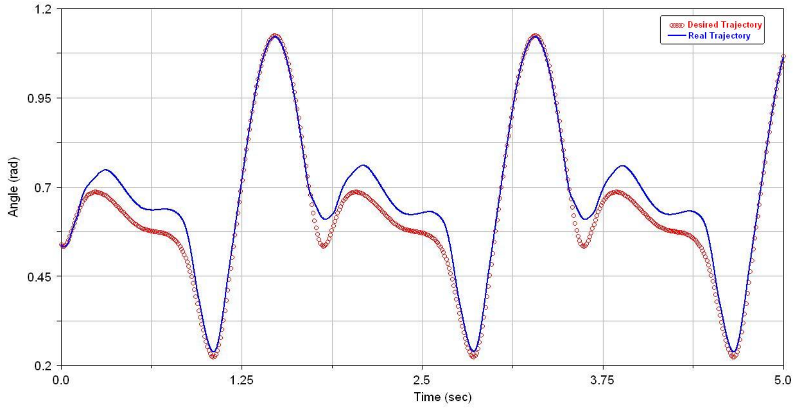


Figure 9. Angle(rad) x time(sec) for joint 3, left knee joint

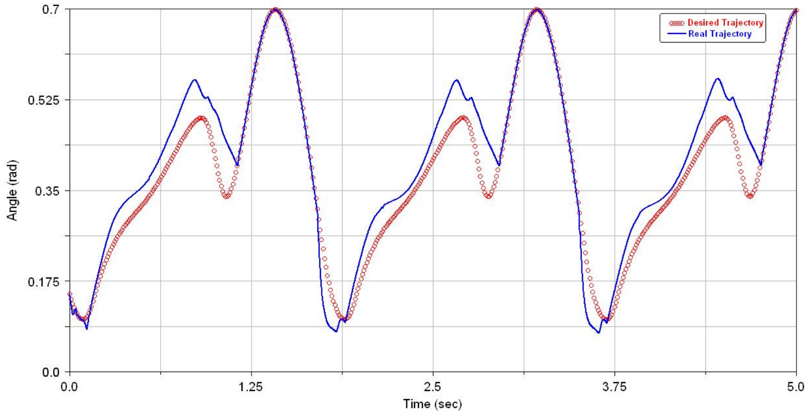


Figure 10. Angle(rad) x time(sec) for joint 5, left ankle joint

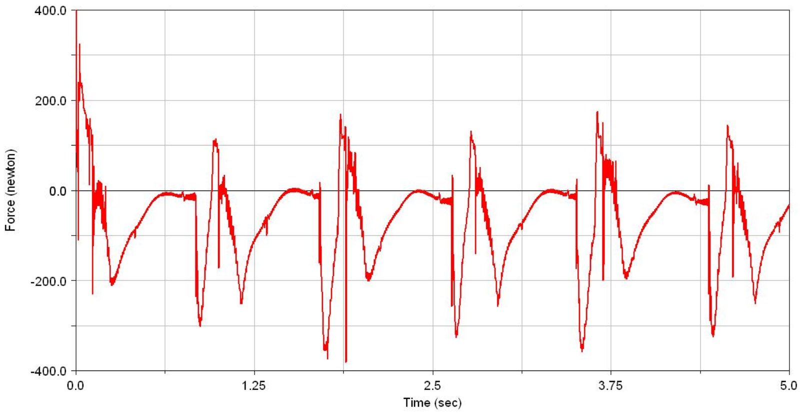


Figure 11. Interaction forces acting at the torso.

5.2 Interaction Forces

One of the goals of the simulation was to determine the magnitude of the forces of interaction between the human model and the exoskeleton model Figures 11 to 13 shows the behavior of these forces. The forces of interaction has the expected size, the more abrupt changes are due to impact with the ground. Looking at the graphs we see that most of these variations occur at the same time

5.3 Torques

Figures 14 to 16 shows the applied torques in the exoskeleton model's joints. The main objective is to find the values of the joint torques required for the system shows a stable trajectory. The values of torques are around 100 N.m, which was expected based on data provided by researches working on this subject (Kirtley n.d.).

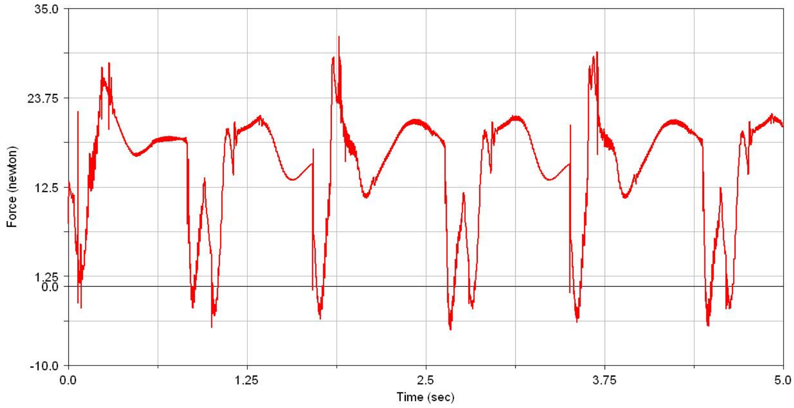


Figure 12. Interaction forces acting at the left thigh.

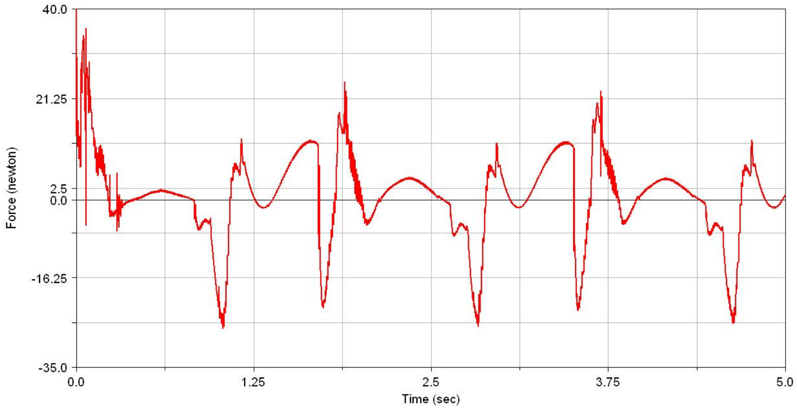


Figure 13. Interaction forces acting at the left leg.

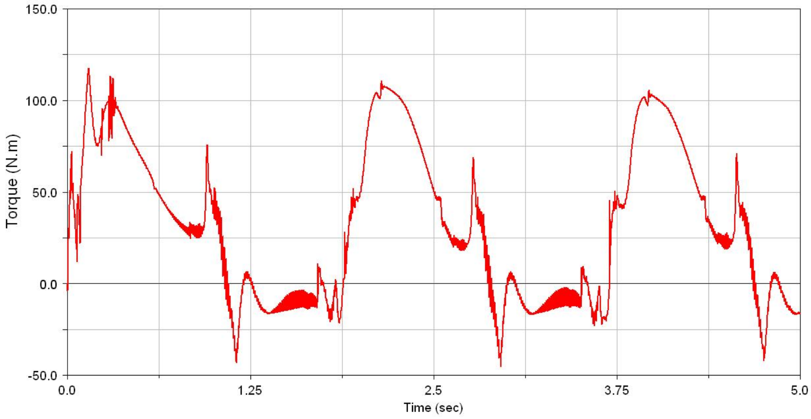


Figure 14. Torque(N.m) x time (sec) Joint 1, left hip joint.

6. CONCLUSIONS

This paper presents the modeling, simulation of the control of an exoskeleton for lower limbs based on a commercial orthosis. An ADAMS-based environment simulation is developed considering the interaction forces between the device and the human wearing it. Further, a co-simulation of the ADAMS software with the Matlab platform is developed, where joint position, velocity and force values are exchanged from ADAMS processor to Matlab workspace. With the results obtained from simulation, it is possible to estimate the human-exoskeleton interaction forces. This information is useful to design gait pattern adaptive algorithms which change the desired trajectory according to human behavior.

7. ACKNOWLEDGEMENTS

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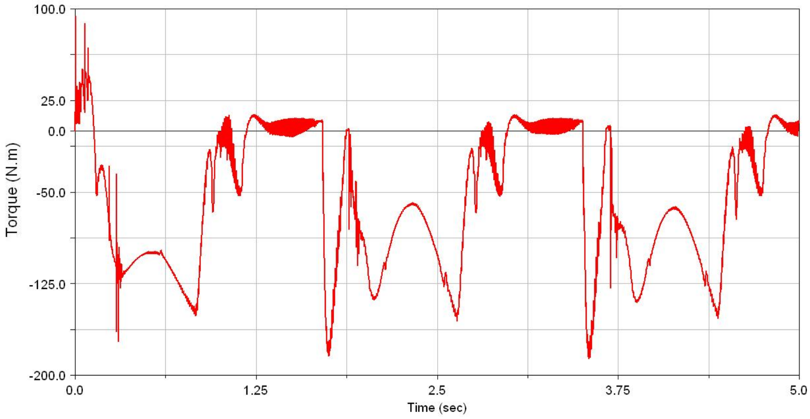

Figure 15. Torque(N.m) x time (sec) joint 3, left knee joint.

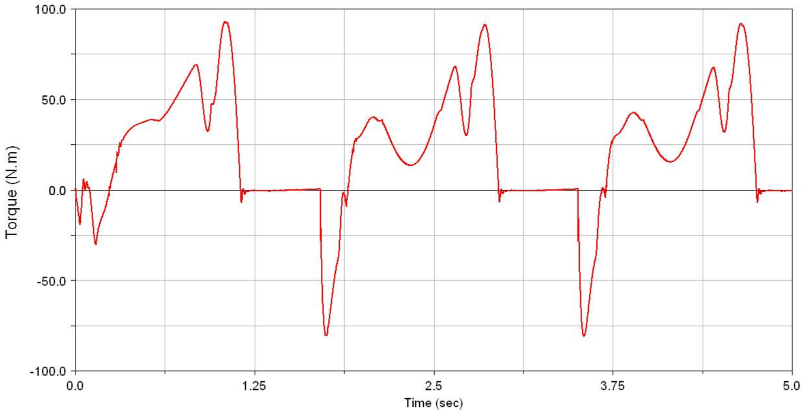

Figure 16. Torque(N.m) x time (sec) joint 5, left ankle joint.

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