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AN UNDERACTUATED MODEL OF BIPEDAL GAIT BASED ON A BIOMECHANICAL ANALYSIS

RODRIGUEZ, Diego A.
RAMIREZ, Ricardo E.
Universidad Nacional de Colombia – Department of Mechanic and Mechatronic Engineering – Robotic Platforms Research Group UN-Robot. Carrera 45 No 26-85 Of. 407-201. Bogotá, 11001000, Colombia
diarodriguezva@unal.edu.co
reramirezh@unal.edu.co

Abstract. *This paper aims to propose an underactuated model of walking in bipeds in order to make a comparison with a biomechanical analysis. This study begins explaining some relevant concepts of underactuated mechanisms, and it shows some advances in this field. Then, a human body model and a simulation frame are created in a dynamic environment like SimMechanics from Matlab for performing bipedal gait simulations posteriorly. Segment Coordinate Systems (SCSs) and Body Segment Inertia Parameters (BSIPs) are set in the human body model, including the pelvis, thighs, calves and feet. Next, biomechanical bases for walking in humans are presented in order to get an overview of this area, in which phases of bipedal walking such as swing and stance are identified. Later, an underactuated model is presented based on the model proposed by Ramirez, where non-actuated joints are modeled as spring-damper systems. The swing phase of this approach is tested through simulation in the earlier created simulation frame starting from a set of initial conditions. Finally, results given by the simulation are compared with biomechanical data from literature.*

Keywords: *Biomechanics, Bipedal Gait, Segment coordinate system, Underactuated Mechanism.*

1. INTRODUCTION

Bipedal walking has been extensively studied in literature. Some authors focus their work in proposing bipedal walking models in machines like robots, and other authors study the biomechanical aspects of gait in order to get a more complete understanding of this movement. One of the earliest mechanical models of bipedal walking was proposed by Mochon and McMahon (1980); they presented a three links model with a knee joint in the swing leg representing a double pendulum. Later, McGeer (1990) explained formally the passive dynamics walking, in which walkers are able to go down a slope without energy input and including a set of initial conditions in order to perform an anthropometric gait. Several passive walking models have been designed such as compass gait (Goswami, *et al*., 1996) and even a 3D knee model (Collins, *et al*., 2001).

According to Tedrake (2009), passive walking models are essentially underactuated mechanisms. An underactuated mechanism is, in a simple way, a system that has fewer control signals than degrees of freedom (Spong, 1997). The most recognized underactuated mechanisms are the cartpole and the acrobot, in both cases the systems have two degrees of freedom, but there is just one control signal. Tedrake (2009) studied in detail the compass gait and the knee walker as underactuated mechanisms for walking.

Ramirez (2012) made an analysis of mobility of an underactuated mechanism in order to prove the feasibility of the gait. The proposed model in this paper is based on the earlier model of Ramirez (2012) but with some adjustments which help to simulate a more complete and anthropometric bipedal walking. In this manner, the current model relies on biomechanical analysis of the movement in which factors like reaction forces of the ground, kinematics and kinetic data from literature are considered. Moreover, Segment Coordinate Systems (SCSs) are implemented in order to facilitate the location of each segment (thighs, calves and feet) without using additional transformation as it happens with Anatomical Coordinate Systems (ACSs). Both Body Segment Inertial Parameters (BSIPs), and the SCSs were taken from Dumas, *et al*. (2007)

The objectives of this paper are: first, to create a functional simulation for bipedal walking in a dynamical environment like SimMechanics from Matlab, and second, to propose an underactuated model of walking taking into account biomedical analysis. Finally, simulations are used in order to prove the feasibility of the model.

2. THE MODEL

The model consists of seven links including: thigh, leg and foot, for the right and left side, and the pelvis connecting the right and left side to each other. The walking analysis is carried out considering only the sagittal plane of the human body; however a 3D body is built, because an anthropometric model that resembles as much as possible a human body is desired which can be drawn on for future analysis.

SCSs are used for the location of each joint center for several reasons: first, the origin of these coordinate systems are the exactly point where rotations take place, in this way, we don´t need to use additional transformations; second,

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torques can be applied directly on these coordinate systems; and third, it is easy to find the position of a point in other segment coordinate systems, since it is necessary to perform just one rotation and one translation to find the transformation between two consecutive segments coordinate systems.

Dumas, *et al*. (2007) presented the location of each SCS according to data given by Young, *et al*. (1983) and McConville, *et al*. (1980). However, Dumas, *et al*. (2007) didn´t show the orientation between consecutive SCSs. To get the orientation between these SCSs, for example the orientation between the pelvis and thigh, original data from Young, *et al*. (1983) were analyzed. Young, *et al*. (1983) provided extensive information about body segment inertia parameters like masses, locations of segment centers of mass and principal moments of inertia, for six women who were 30 years old, with respect to anatomical coordinate systems (ACSs). Nevertheless, origins of ACSs aren't in the joint centers but rather in anatomical landmarks introducing additional transformation in possible simulations.

Due to the SCS data given by Dumas, *et al*. (2007) was based on ACSs from Young, *et al*. (1983), it is necessary first of all to find the orientation between consecutive ACSs. In tables presented by Young, *et al*. (1983), each segment has at least three points in two consecutive ACSs. Furthermore, using the Wahba's problem it is possible to determine the orientation of two coordinate systems with three points expressed in both systems (Landis, 1988).

Then, according to Dumas, *et al*. (2007) SCSs were built whose references are the ACSs of each segment. At this point, the orientation between two consecutive ACSs through the Wahbas's problem is known, and also the orientation of each SCS with respect to its corresponding ACS, for instance, the thigh SCS is constructed with respect to the thigh ACS. Next, the orientation of two consecutive SCSs is found through three transformations: firstly, from SCS to ACS, secondly, from ACS to a consecutive ACS, and finally from ACS to SCS. For example, the following transformations are required to get the orientation between pelvis SCS and thigh SCS: firstly, from pelvis SCS to pelvis ACS, secondly, from pelvis ACS to thigh ACS, and thirdly, from thigh ACS to thigh SCS.

Once the SCSs are established, parameters like masses, segment centers of mass and moments of inertia are included in the model using the tables given by Dumas, *et al*. (2007). At this point, it is possible to build a human body model for simulation. An equivalent ellipsoid approximation included in SimMechanics from Matlab is used in order to represent the human body model (Fig. 1). In Section 3, the dynamic environment SimMechanics is introduced.

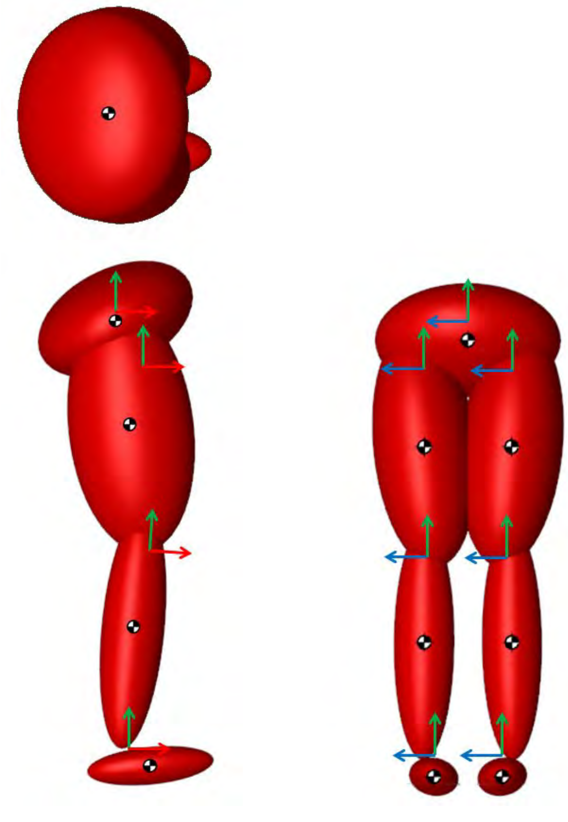

Figure 1. Human Body model

3. GAIT SIMULATION

Gait simulations were carried out in SimMechanics mainly for the following reasons: first, Matlab is a worldwide recognized software in the scientific and academic world; second, in this block-orientated dynamical environment, the common blocks of Simulink are available; and third, this software is continually under development, adding new

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features or fixing bugs. However, due to the fact this software is relatively new (first version launched in 2005) there are some limitations like the lack of collisions in order to model for example the ground contact.

The best known approaches for modeling the ground contact are *Hard Contact* and *Soft Contact*. In the first case, geometric constraints are set and the ground contact is modeled as an instantaneous discrete transition (Näf, 2011). In the second approach, the ground contact is modeled as an applied force. Näf (2011) carried out successfully simulations of a quadruped walking robot in SimMechanics modeling the ground contact as a Soft Contact, through a spring-damper system.

For modeling ground contact in this model, a soft contact as used by Näf (2011) is implemented. The vertical reaction force is defined by:

$$F_y = \begin{cases} -K_y y - D_y \dot{y} & \text{if } y<0 \\ 0 & \text{else} \end{cases} \tag{1}$$

Whereby K_y and D_y are the constants of the spring and the damper, respectively. The damper contributes when collisions between foot and ground take place, because at those instants the vertical position is zero and hence the reaction force in the vertical axis would be null. In addition, the damper doesn´t allow force changes abruptly.

For the horizontal reaction, the same model was used, but in this case the applied force depends on the position relative to the contact point x_0.

$$F_x = - K_x(x - x_0) - D_x \dot{x} \tag{2}$$

Taking into account that this paper focuses on a 2D movement, a possible reaction force in the z axis was not considered.

Reaction forces from the ground are applied to four foot's points, which are contained in one horizontal plane because the gait simulation deals with rigid bodies and only one contact point of the foot that doesn´t counteract the generated torques on the foot. Naturally, these points go along the foot length from calcaneus to the tip of the foot.

Now, values of spring and damper constants must be found. Kinematical data of each joint such as position, velocity and acceleration were taken from Winter (1990) in order to force the model to follow the motion profiles and consequently to get the generated torques and reaction forces from the ground. In this inverse dynamic simulation, the spring and damper constant values were adjusted until torques and reaction forces given by the simulation were comparable with the values proposed by Winter (1990). Figure 2 shows both the values given by Winter (1990), and also the results of the simulation.

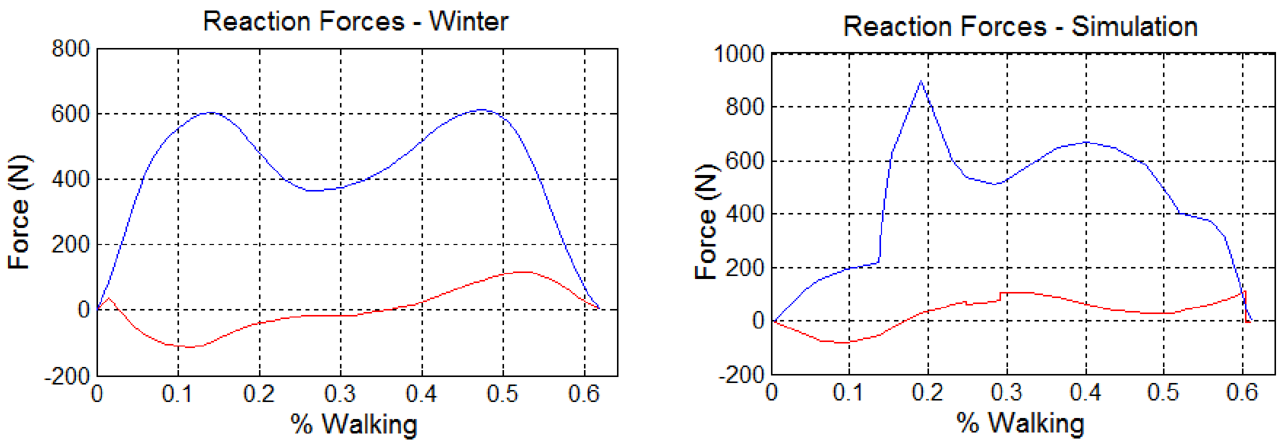

Figure 2. Reaction Forces given by Winter (1990) and by the simulation.

In general, the reaction forces given by the simulation are similar to the reaction forces given by Winter (1990). Nevertheless, it is important to remark: first, the ground contact was modeled like applied forces instead of collisions; second, because of the lack of information about the human body used by Winter (1990), it was not possible to include this human body in this simulation; finally, it is inevitable to have the appearance of errors in simulations like this.

With the values of the constants for the modeled ground contact and the human body model, the frame for bipedal walking simulation is ready to be used in future studies.

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4. THE UNDERACTUATED MODEL

According to Rose (2006), a bipedal walking cycle involves two main phases: swing and stance. The stance phase corresponds approximately to 62% of the walking cycle, whereas the swing phase corresponds to 38%. The stance phase begins when the foot (heel) strikes the ground and ends when the foot (toe) takes off the ground. On the other hand, the swing phase begins when the foot takes off the ground and ends when the foot strikes the ground. During the stance phase there are two periods in which a double support occurs, they are namely from 0% to 12% and from 50% to 62% of the walking cycle. Commonly, these double support periods are called early and late stance, respectively, and the single support period is called medium stance. In this manner, while a single support occurs in a foot, the other foot will be in a swing phase. It is important to notice that the beginning of the walking cycle (0%) is considered when a foot strike takes place.

Ramirez (2012) proposed an underactuated model of bipedal walking in which some joints (hip, knee and ankle) are modeled as spring-damper systems in some phases of walking. In that model, the number of actuators was smaller than the calculated mobility, hence configuring an underactuated mechanism.

Ramirez argued that in medium stance, thigh, leg and foot can be considered like a single link; however, there are some relative movements between these segments. These movements are naturally allowed by these passive elements. The proposed underactuated mechanism in this paper is shown in its initial position (12% of walking cycle) in Figure 3. This model uses torsional spring-damper systems that are represented only by torsional springs; actuated joints are represented by curved arrows.

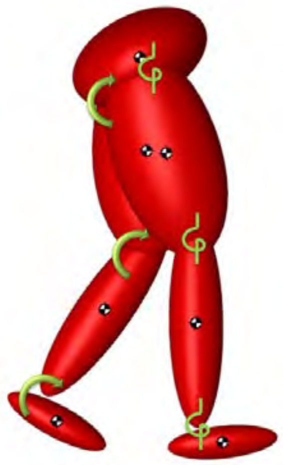

Figure 3**.** Single Support Underactuated Mechanism.

In order to simulate the proposed underactuated model, torques as step functions were implemented in the actuated joints. The single support phase of the right leg (swing phase of the left leg) was simulated, namely from 12% to 50% of the walking cycle. The response is shown in Figure 4.

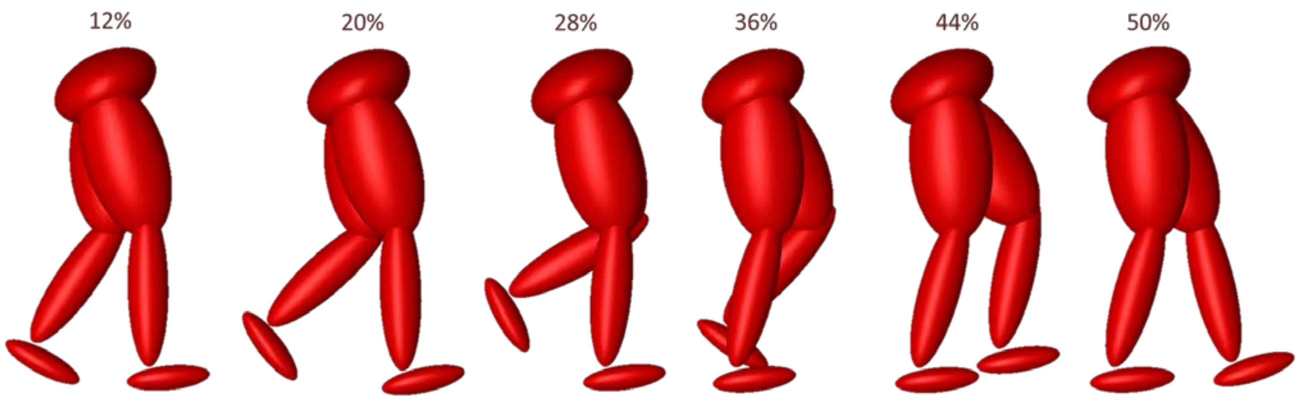

Figure 4**.** Visualization of the response.

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Figure 5 presents the obtained position and velocity for the proposed phases of walking. The dashed-dot lines represent the data given by Winter (1990), whereas the solid lines represent the results of the simulation. There are no big differences regarding the leg in swing both in the position and in the velocity on each joint considered in this study. The response of the leg in swing was expected because this analysis aimed to resemble as much as possible an anthropometric gait in position; the resulting behavior in velocity is a consequence of this goal.

On the other hand, the response on the underactuated (right) leg has some small differences compared with data proposed by Winter (1990). Related to the position, results on the hip and on the ankle show a good approximation; the position on the knee joint presents discrepancies in form, however its values doesn't have a significant gap. The velocity values in each body segment are lower than the values given by Winter (1990), moreover they doesn't have clear similarities in form with data proposed in the literature.

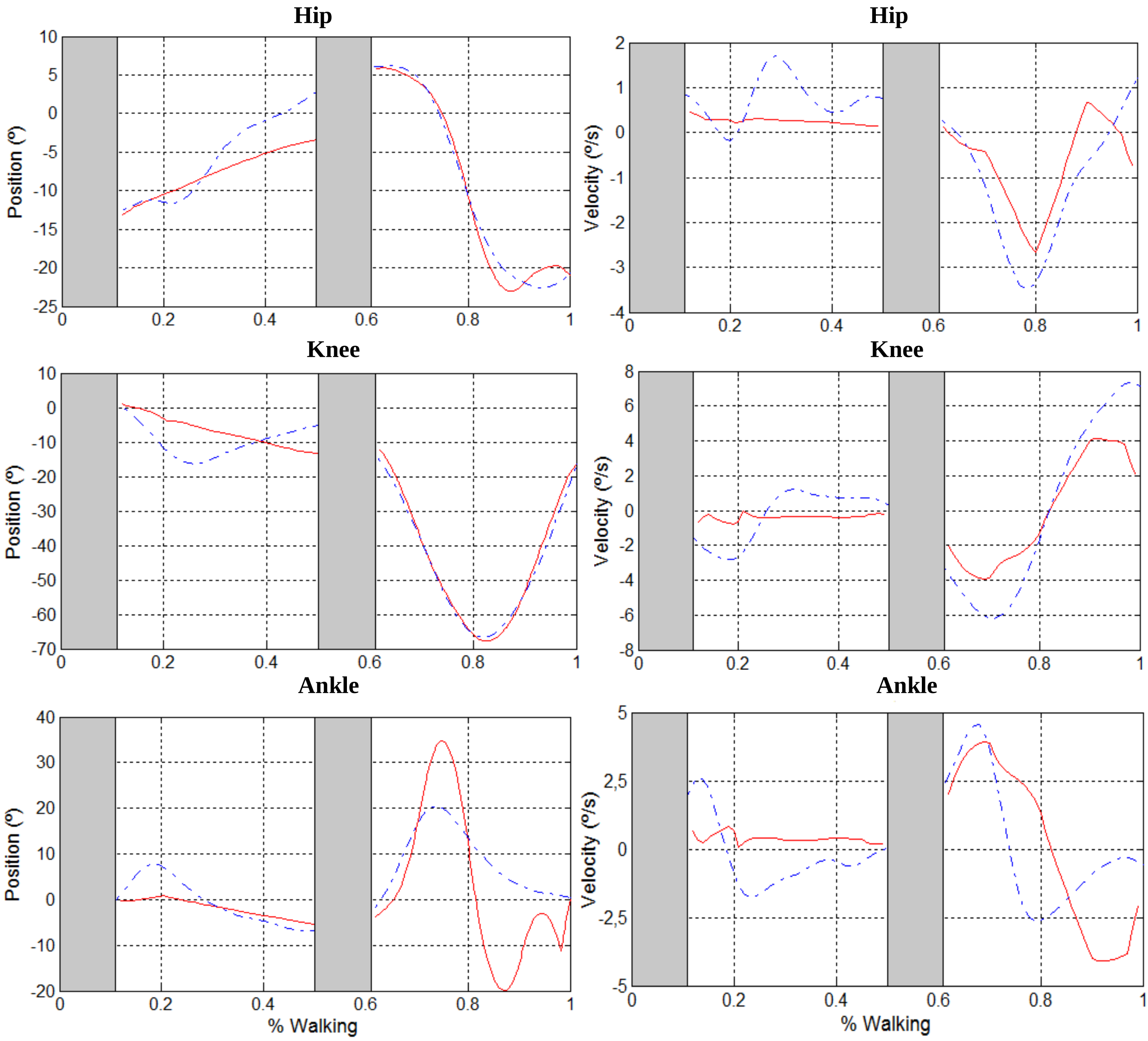

Figure 5. Position and Velocity on hip, knee, and ankle joints, respectively, given by Winter (dashed-dot lines) and given by the simulation (solid line).

The extensor torques on each joint both given by Chapman (2008), and also given by the simulation are shown in Figure 6. The resulting torques are compared with data proposed by Chapman (2008) because this data is more recent than data given by Winter (1990). The dashed-dot lines represent the torques given by Chapman (2008), whereas the solid lines represent the results of the simulation.

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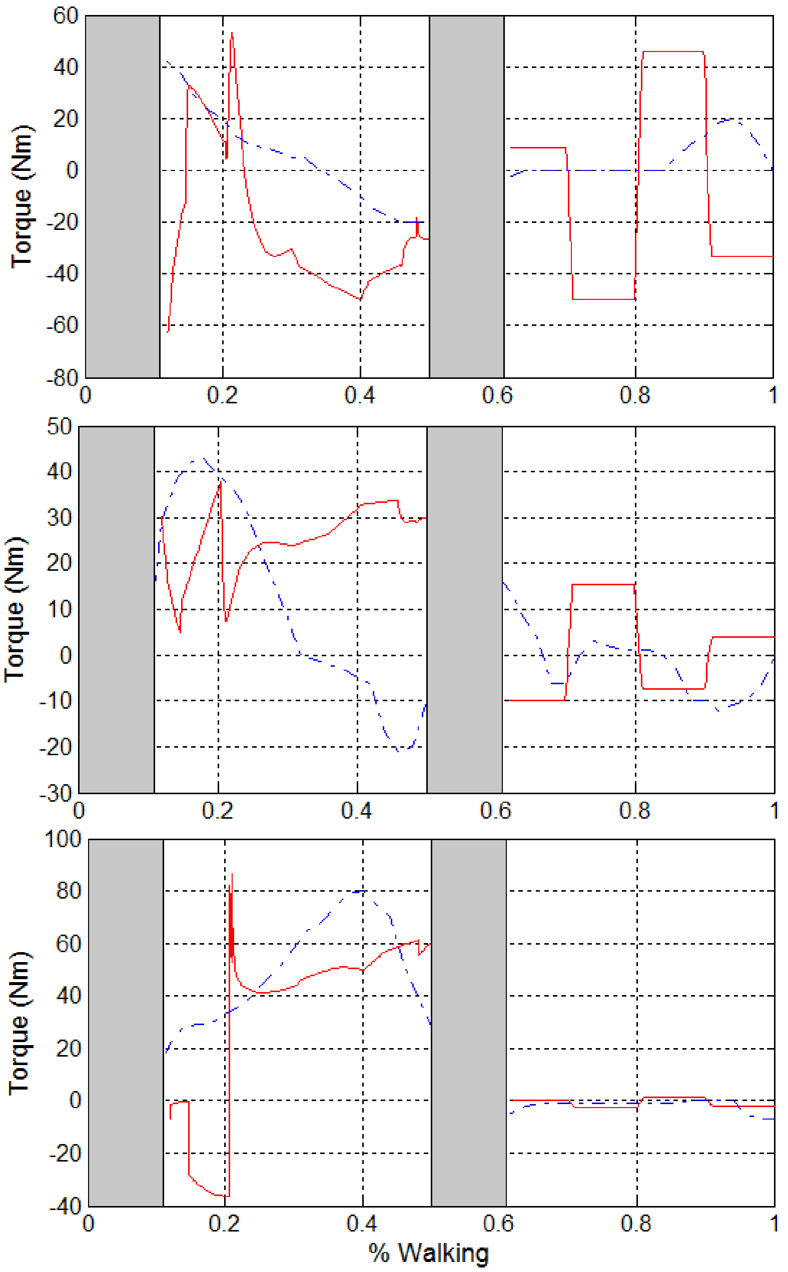

Figure 6 - Torques on hip, knee, and ankle joints, respectively, given by Chapman (dashed-dot lines) and given by the simulation (solid line).

The resulting moments on the hip in the leg in stance are similar to those proposed by Chapman (2008). Torques on the leg in stance phase has in general a decreasing behavior. Torques on the leg in swing phase differ a lot in the whole period. Differences on this joint are due to different conditions in the gait data, for instance different walking speeds. Conditions for the data given by Chapman (2008) are unknown, but we assume that they are different. Naturally, high speed walking will require more torques on the joints.

With regard to torques on the knee joint, moments of the leg in stance differ from the data given by Chapman (2008), since initially they increases, but they never go down again. Moments of the leg in swing have some differences with the torques proposed in literature. It is important to notice that this research is focused in the behavior of the underactuated joints, for this reason a model which is able to resemble as much as possible the position of each joint is more relevant than the resulting torques.

Finally, moments in the ankle joint are somehow similar to data from Chapman (2008). The biggest discrepancy occurs at the end of the stance phase, because moments should be smaller, and the curve should have a decreasing behavior. Moments of the leg in swing are quite similar.

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5. CONCLUSION

A body human model for bipedal gait was constructed based on Segment Coordinate Systems including body segment inertia parameters. This model was implemented in SimMechanics in order to build a frame which permits bipedal walking simulations. Due to the lack of collision modeling in this dynamic environment, a soft ground contact (spring-damper system) was implemented with satisfactory results.

Simulations carried out in this frame indicate that the proposed underactuated mechanism is able to perform the swing and medium stance phases of an anthropometric gait which can be comparable with biomechanical data, namely with positions and velocities. The reactions given by the passive elements, namely the torsional springs and torsional dampers, contribute to the feasibility of the movement, but there are some discrepancies in the extensor moments on the joints when these elements have to recover their initial positions.

There are some differences between the results presented in this paper with data published in literature because some conditions, like walking speed, are different. Moreover, the body human model in this paper differs from the subjects used in experiments in which biomechanical data was presented by some authors.

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7. RESPONSIBILITY NOTICE

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