Contemporary Engineering Sciences, Vol. 10, 2017, no. 30, 1457 - 1471
HIKARI Ltd, www.m-hikari.com
https://doi.org/10.12988/ces.2017.711176

Exploring Models of Normal Human Locomotion

Leonardo Emiro Contreras Bravo

Universidad Distrital francisco José de Caldas, Colombia

José Ignacio Rodríguez Molano

Universidad Distrital francisco José de Caldas, Colombia

Edwin Rivas Trujillo

Universidad Distrital francisco José de Caldas, Colombia

Abstract

The study of the bipedal walk is shown from two approaches: passive and active, through these modeling techniques: Lagrangian dynamics and union graphs, in order to achieve an extension of the theoretical knowledge of the human walk by using different models that are contrasted with real data obtained by marching in a corridor.

Keywords: Bipedal walk, marching dynamics, marching analysis, modeling

1 Introduction

The biomedical field encompasses various issues that deserve the attention of the Engineering sector. One of these issues is the study of bipedal locomotion which can lead to the generation of a model that can recreate human walk with more precision as well as simulate different actions such as running or going up or down stairs. The analysis of bipedal locomotion is very useful in a variety of fields such as medical technologies where it is easier to design prosthesis and implement rehabilitation strategies in virtual animation, robotic applications, etc.

The act of walking is performed in a similar way for all individuals, considering that this action requires support and balancing phases for each extremity. However, every person has specific characteristics linked to the locomotion pattern [1]. Hence, when studying bipedal march, the important thing is to not focus solely on the movements, angles and speeds involved in the march itself but also on the anatomic constitution of the diverse types of articulations that are part of the human body.

In the act of walking, two unique aspects of bipedal walking are presented. The first one is the continuous effect of the reaction force coming from the ground that is exercised over the extremity supporting the body. The second aspect is the balancing phase experienced by every lower extremity when the support phase is over. The body goes through a series of alternating movements from each body segment which include the elevation and descent of the torso and the lateral oscillation of the hip with a slight step when walking [2].

With the purpose of widening the knowledge on walking, an analysis is proposed by using simple two-dimensional models that allow to clearly understand the behavior of the support and oscillation phases and moving on to more complex models that involve different corporal segments that can reproduce with more similarity the translation process of their centers of mass and the effects of the ground's reaction forces.

2 A brief look at the study of locomotion

Human march has been a matter of great interest for mankind since limitations where experimented in locomotion. According to British paleoanthropologist Mary Douglas Leakey the march comes from the evolution of men as a product of the need to manipulate tools and go from one place to the other in a swift manner [3].

Nevertheless, there only has been significant work on this area up to recently due to the creation of new techniques for the study of movement. In 1836, the Weber brothers reported one of the first quantitative studies of the spatial and temporal parameters in the human walk. By the end of the 19^{th} century, Marey and Muybridge were pioneers in the study of walk-related parameters based on photographic techniques [4].

Up to the 20^{th} century, human movement had been researched as a physical-mechanical problem which led Von Baeyer to attempt to analyze it as a somatic being with the exact methods of natural sciences. The muscle issue was then moved to the secondary plane and the study of the articulated parts of the body began.
After World War II, the interest for human movement was reignited with the purpose of improving the processing techniques of crippled and injured veterans. The University of California in Berkeley was commissioned to perform this research which led to major contributions in understanding the mechanisms of human march. From that period, the work of Bernstein, Elfman, Ducroquet, Perry and Sutherland stand out [5].

Based on the technological advances of the current century, it is intended to know a bit more about the bipedal locomotion process which has been difficult due to the lack of a satisfactory method that can replicate human movements in order to be analyzed and reach the objective of prosthesis and orthotics. The need to delve on that topic has translated into many software packages that are used by Engineers in the design of dynamic and mechatronic systems to be at service of a matter where there is no last word. This is well-known considering the huge amount of work published nowadays in specialized publications such as the Journal of Biomechanics, the Journal of Orthopedics, IEEE Transactions on Biomedical Engineering or Biological Cybernetics, etc.

3 Experimental techniques

With the purpose of feeding the proposed models, it was necessary to recollect data from normal patients through anthropometric and system acquisition techniques.

Anthropometric techniques
They are measurements of corporal dimensions performed on a specific group with the purpose of characterizing its members. This data is stored with tables called “anthropometric tables” that must be used for simplicity and economic reasons (by sacrificing accuracy) or when the desired measures from the population are very hard to obtain from the in vivo subject [6].

Acquisition system
The data acquisition system known as March Laboratory; which consists in an advanced technology system that includes a video camera system, a marker-based game (Figure 1a), lights and demarcations of the site with adequate colors and an acquisition and processing data system.
The processed data is shown through videos and comparative curves for each marker displayed on specific points of the patient. This is submitted to the analysis of the normal or the pathological marching cycle. In this phase, the Kinescan/IBV system was used as a complex movement-based analysis system that uses imagery digital register techniques (Figure 1b). The markers mentioned are spherical elements of reflective color that are attached to the patient’s body in the articulation region allowing the system to show a step-by-step analysis of the patient’s march.

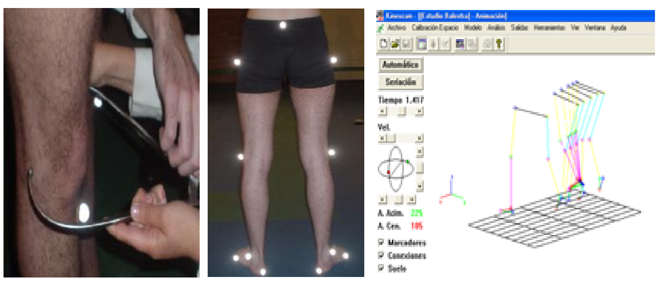

Figure 1. a) Markers on the patient’s body for movement analysis
b) Kinematic results KINESCAN/IBV

4 Modeling techniques

Lagrangian dynamics method

This technique is considered as a reformulation of the Newtonian mechanics that can be used to determine the interactions that can occur between the body segments that represent bipedal locomotion. According to this, the path of an object is determined by finding the path that minimizes the action which is equal to the integral of the LaGrange term in time and is obtained with equation (1).

$$L = T - V \tag{1}$$

Where:
L is the Lagrangian function of the system.
T is the kinetic energy of the system
V is the potential energy of the system

The system equations can be obtained through the Euler – Lagrange formulation defined by (2)

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \left(\frac{\partial L}{\partial q_i}\right) = Q_i \qquad i = 1,2,3...n \tag{2}$$

Where the first term of equation (2) implies that the shift in the energetic speed varies over time; the second term implies that there is an influence of coordinate q_i in the energy shift and the term Q_i, called generalized force, which can be a force or moment of torsion [7].

Graph joint data method

This technique, also known as Bondgrahs, is used to model mechanic systems that can incorporate rigid bodies and force fields where there is a power exchange [8], which is represented through a half arrow with the force variable located underneath (Figure 2) with connection points with other elements that are known as joints. The relations of power are established in terms of a couple of variables: effort (e) and flow (f). Depending on the system to be modeled, these variables could be torque and angular speed (rotational mechanical system), force and speed (translational mechanic system) and heat flow and temperature (technical system).

Additionally, two variables are required in the modeling of dynamic systems which are known as energy variables: moment (p) and displacement (q). The first one is defined as the integral of the effort in terms of time and the second one is defined as the integral of the flow in terms of time [9].

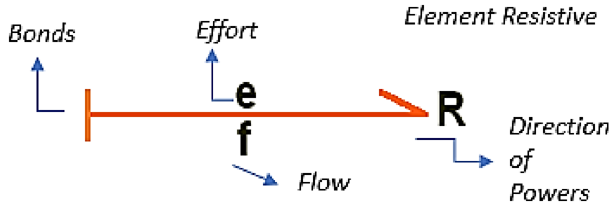

Figure 2. Common nomenclature of a joint graph

5 Models of the Bipedal Locomotion Process

In this section, some of the developed models are briefly described. While some involve passive walking where the importance is given on the effect of gravity on the walking mechanism, others involve active walking where an energy force or actuator is required to drive the locomotion.

Compass-type passive walking model

It is a simple model where legs are considered as rigid bars without knees or feet, connected by a string pin without friction on the hips. Evidently, the model is far from reality since the lack of knees prevents the leg's balancing movement and the foot would crash with the floor in the middle of the balancing phase. Newtonian equations (3) and (4) from the model are a result of the balancing and support actions of the leg (Figure 3).

$$\sum F = ma \tag{3}$$

$$\sum T = \sum r \, x \, ma \tag{4}$$

This leads to the following equations:

$$\begin{aligned} &\ddot{\theta}\left[m_c l^2 + 2ml^2(1-\cos\phi)\right] - ml^2(1-\cos\phi)\ddot{\phi} \\ &- ml^2 sen\phi\left[\phi^2 - 2\dot{\theta}\dot{\phi}\right] + mgl\left[sen(\theta-\phi-\gamma)\right] \\ &- m_c glsen(\theta-\gamma) = 0 \end{aligned} \tag{5}$$

$$ml^2(1-\cos\phi)\ddot{\theta} - ml^2\ddot{\phi} + ml^2\dot{\theta}^2 sen\phi + mglsen(\theta-\phi-\gamma) = 0 \tag{6}$$

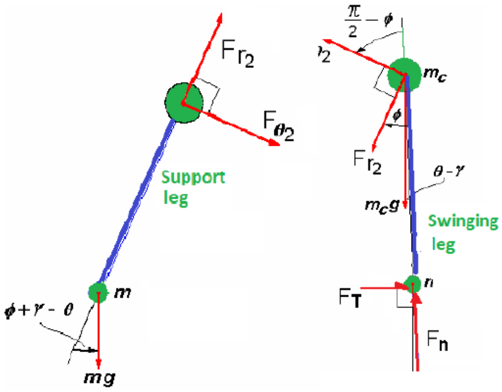

Figure 3. Free body diagram of the compass walk simplified model

Passive walking model with knees

This model considers the mass of the hip and three segments that represent the thigh, the leg in balancing phase and the lower limb in support phase. The equations for this model (equation 7) are established through the Lagrangian Dynamics according to equation (1) while also considering that the system's potential energy is measured in comparison to a horizontal reference level that passes through the contact point between the support feet and the floor.

$$L = T - V = \begin{bmatrix} \frac{1}{2}m_1 v_1^2 + \frac{1}{2}m_2 v_2^2 + \frac{1}{2}m_3 v_3^2 + \\ \frac{1}{2}m_c v_c^2 \end{bmatrix} - \begin{bmatrix} m_1 a_1 g\cos(\theta_1+\gamma) + m_c l_1 g\cos(\theta_1+\gamma) + \\ m_2 g(l_1\cos(\theta_1+\gamma) - b_2\cos(\theta_2+\gamma) + \\ m_3 g\begin{pmatrix} l_1\cos(\theta_1+\gamma) - l_2\cos(\theta_2+\gamma) \\ - b_3\cos(\theta_3+\gamma) \end{pmatrix} \end{bmatrix} \tag{7}$$

The matrix form of the model using the Euler – Lagrange formulation is:

$$D(\theta)\ddot{\theta} + H(\theta,\dot{\theta})\dot{\theta} + G(\theta) = 0 \tag{8}$$

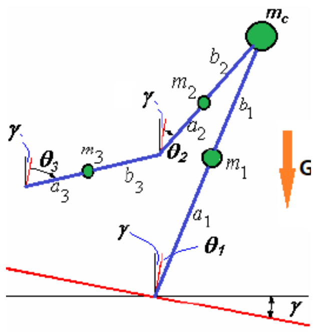

Figure 4. Passive walk model with knees. Adapted from [2]

Active walking model with one leg

Before developing this model through multiport models of joint graphs, several models were proposed such as the oscillating inverted pendulum, the inverted pendulum with a linear actuator and the inverted pendulum with flywheel, in which the mass of the elements was considered as punctual. A double inverted pendulum and double body segment were proposed later on where the mass is considered to be located in the gravity center of the link and not to a distal and/or proximal coordinate to every articulation of the body segments as seen in the model of a leg. This model can represent the lower extremity as the union of three articulated body segments which include a moment of inertia and a gravity center located at a proximal and/or distal distance from close articulations being visualized in the sagittal plane (Figure 5). Additionally, during the act of walking, some phenomena occur that violate these suppositions: the movement of the human march occurs in the sagittal plane (lateral) and coronal (frontal) and not only in the first one; the feet is considered a more articulated link (which is not really true); the real forces that act on the feet are not punctual since the distribution of pressures in the contact of the feet with the floor occurs over an area that keeps changing according the march cycle.

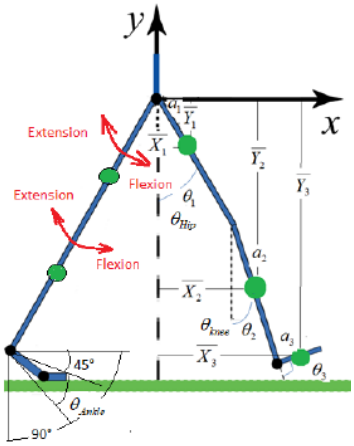

Figure 5. Some variables of the kinematic model of a leg

The input data of the model using inverse dynamics will be the kinematic data (positions, speeds and accelerations for each articulation) and the reaction force of the floor next to the location of the center of pressure. The output data will be the net torque over each articulation, the inertial torque supported by each segment and the articular reactive forces. Hence, the result is the estimation on the mechanic demands from the acting lower limb. The construction of this model can be achieved from the analysis of the movement kinematics (Figure 5), by initially determining vectors q_k (displacement vector), V_i (speed vector) and q_I (inertial displacement vector) according to (9):

$$q_k = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta 3 \end{bmatrix} \quad \dot{q}_I = \begin{bmatrix} \omega_1 & \omega_2 & \omega_3 \\ Vx1 & Vy1 & Vx2 \\ Vy2 & Vx3 & Vy3 \end{bmatrix} = V_i \tag{9}$$

Carrying out a transform between vectors q_k and V_i defined as $Vi = T_{ik}(q_k)\dot{q}_k$ the obtained matrix will be:

$$T_{ik}(q_k) = \begin{bmatrix} Vx_1 \\ Vy_1 \\ Vx_2 \\ Vy_2 \\ Vx_3 \\ Vy_3 \end{bmatrix} = \begin{bmatrix} (l_1 \cos\theta_1) & & \\ (-l_1 sen\theta_1) & & \\ (l_1 \cos\theta_1) & (a_2 \cos\theta_2) & \\ (-l_1 sen\theta_1) & (-a_2 sen\theta_2) & \\ (l_1 \cos\theta_1) & (l_2 \cos\theta_2) & (a_3 \cos\theta_3) \\ (-l_1 sen\theta_1) & (-l_2 sen\theta_2) & (-a_3 sen\theta_3) \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} \tag{10}$$

The terms inside the previous matrix will be the ones included in the MTF models shown in Fig. 6. The sinus and cosines terms of this matrix must be replaced by the geometric relations between angles while considering the lengths of each body segment l_1, l_2 and l_3.

The model is then simulated in the 20SIM software and offers information on the extension and flexion (singular position) in every articulation during the marching cycle as well as the relative angles between segments (Figure 7).

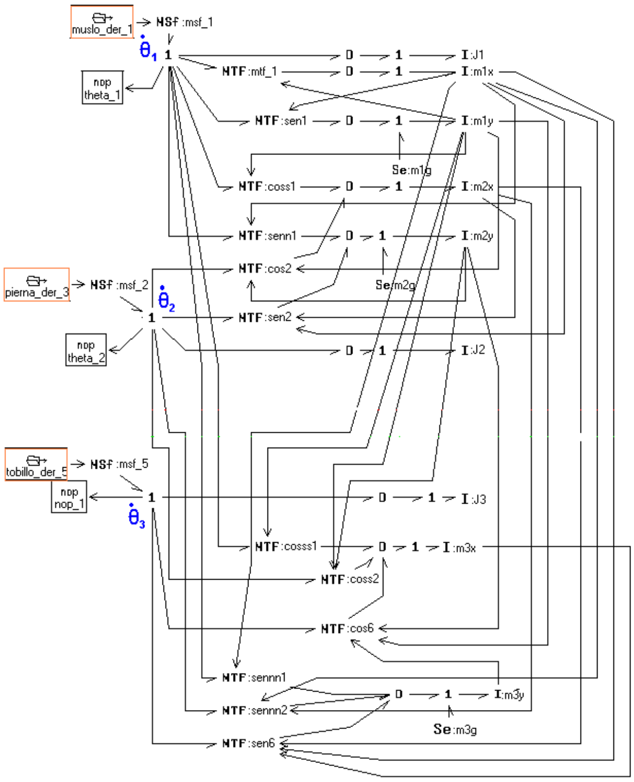

Figure 6. Multiport model of a leg through the union graph technique

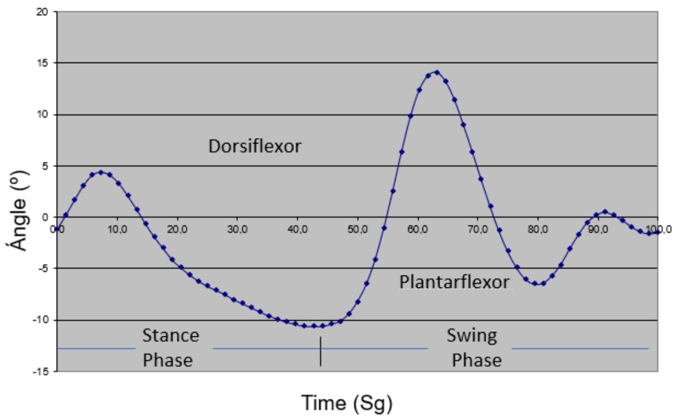

Figure 7. Angular position of the ankle (relative)

Active walking model with five degrees of freedom

This model can represent two legs and the segment including torso and arms during the support and balancing phases of bipedal locomotion, without considering the legs and their plantar forces. By applying the Euler-Lagrange formulation, the array noted in (11) is obtained:

$$D(\phi)\phi + H(\phi,\dot{\phi}) + G(\phi) = T \qquad (11)$$

Where $D(\phi)$ is a matrix containing the inertial terms of size 5x5; $H(\phi,\dot{\phi})$ is matrix that includes the effects of centripetal forces and Coriolis of size 5x1; T corresponds to the external torques matrix related to each link with a 5x1 size. This matrix is modeled in the 20SIM software (Figure 8).

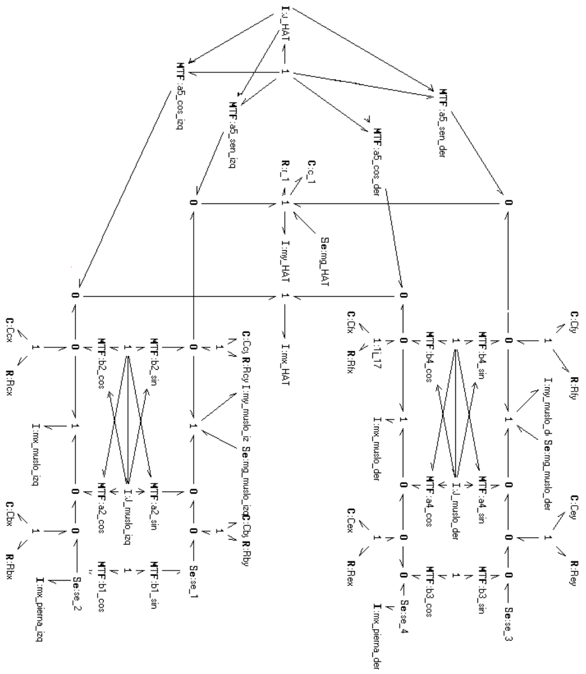

Figure 8. Joint graph for five-degree model

One of the curves resulting from the model corresponds to the plot of the angular position of the right (blue) and left (orange) thighs VS time during a marching cycle (Figure 9) where the movements are alternating. This model does not contemplate a double support phase as documented in literature. In contrast, it will be considered that the support change is instantaneous. It can be determined that the instant when the right leg is in the support phase, the left leg is in the balancing phase and vice versa. Additionally, the positioning curve in respect to the vertical of the knees (right and left) can be determined. This type of curve validates the model based on the input data.

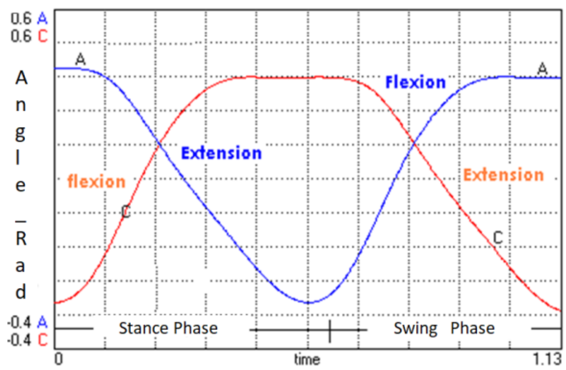

Figure 9. Data angles given by the model of the thighs during the march

Active walking model for seven degrees of freedom

To create this model that includes the feet added to the previous model, inverse dynamics are used that consist in determining the forces and moments that occur in the given system based on angular positions (θ_1, θ_2, θ_3, θ_4, θ_5, θ_6, θ_7) and their first and second order derivatives. In this model, it is supposed that the moment of inertia of each body segment around their center of mass and the location of their center of gravity remain constant during movement; the lower limb can be segmented into articulated links; the bipedal locomotion only has strong articular effects in 2D, the links are connected by four articulations of the string type. The segments have distal and proximal coordinates and the angles are measured in respect to the vertical and not in respect to the preceding segment (relative angles) as shown in Figure 10.

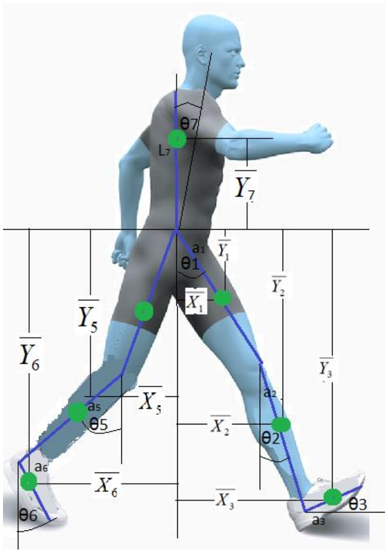

Figure 10. Seven-link model for multiport methods. Adapted from [10].

The equations of the model are generated through the displacement vectors and the inertial displacement speed vectors q_k and q_I respectively as shown in (12).

$$q_k = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \\ \theta_5 \\ \theta_6 \\ \theta_7 \end{bmatrix} \quad \dot{q}_I = \begin{bmatrix} \omega_1 & \omega_2 & \omega_3 & \omega_4 & \omega_5 & \omega_6 & \omega_7 \\ V_{x1} & V_{x2} & V_{x3} & V_{x4} & V_{x5} & V_{x6} & V_{x7} \\ V_{y1} & V_{y2} & V_{y3} & V_{y4} & V_{y5} & V_{y6} & V_{y7} \end{bmatrix} = V_I \qquad (12)$$

Then, the transformation matrix is determined based on the vectors q_k and V_i. $Vi = T_{ik}(q_k)\dot{q}_k$.

$$T_{ik}(q_k) = \begin{bmatrix} Vx_1 \\ Vy_1 \\ Vx_2 \\ Vy_2 \\ Vx_3 \\ Vy_3 \\ Vx_4 \\ Vy_4 \\ Vx_5 \\ Vy_5 \\ Vx_6 \\ Vy_6 \\ Vx_7 \\ Vy_7 \end{bmatrix} = \begin{bmatrix} (l_1 \cos\theta_1) & & \\ (-l_1 sen\theta_1) & & \\ (l_1 \cos\theta_1) & (a_2 \cos\theta_2) & \\ (-l_1 sen\theta_1) & (-a_2 sen\theta_2) & \\ (l_1 \cos\theta_1) & (l_2 \cos\theta_2) & (a_3 \cos\theta_3) \\ (-l_1 sen\theta_1) & (-l_2 sen\theta_2) & (-a_3 sen\theta_3) \\ (l_4 \cos\theta_4) & & \\ (-l_4 sen\theta_4) & & \\ (l_4 \cos\theta_4) & (a_5 \cos\theta_5) & \\ (-l_4 sen\theta_4) & (-a_5 sen\theta_5) & \\ (l_4 \cos\theta_4) & (l_5 \cos\theta_5) & (a_6 \cos\theta_6) \\ (-l_4 sen\theta_4) & (-l_5 sen\theta_5) & (-a_6 sen\theta_6) \\ (l_7 \cos\theta_7)\dot{\theta}_7 & (-l_7 \cos\theta_7)\dot{\theta}_7 & \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \\ \dot{\theta}_5 \\ \dot{\theta}_6 \\ \dot{\theta}_7 \end{bmatrix} \quad (13)$$

It is the basis to generate the multiport active walking model with seven degrees of freedom as shown in figure 11. The right and left limbs have a block called *"randgen_2"*. This block receives the position signals (displacement) from different inductive (I) elements that need to have their equations and outputs programmed. The position (x, y) curves are also introduced. Additionally, they include the equations generated through a kinetic analysis for each body segment (not shown in this article) through the reaction forces from the ground that act on the link called foot.

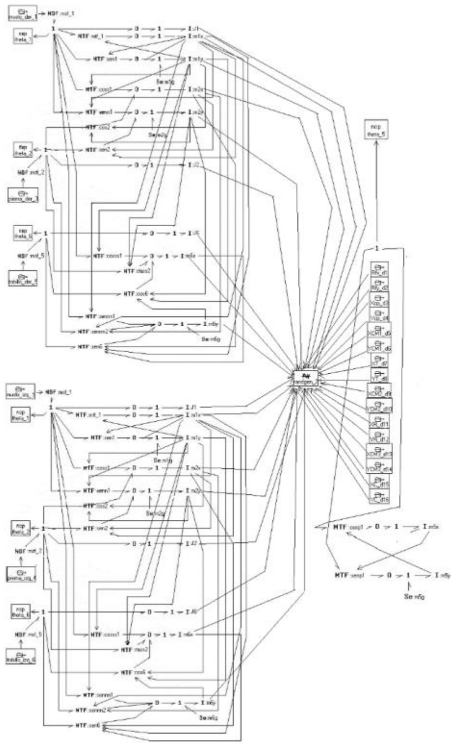

Figure 11. Active walking model with seven degrees of freedom in joint graphs with 20SIM

As a result of this model there are different curves such as accelerations (linear and angular) for each body segment (center of mass) both right and left; articular moments for each limb and/or articulation and reaction forces between segments (Figure 12). The movement of the articulation of the hip is the only position chart that corresponds to the result extracted with 20SIM; the other results will be treated through relations between absolute (in respect to the vertical) and relative angles. To validate this model, the comparative results are shown for the moments obtained in the walking corridor and those calculated from the multiport models with joint graphs (Figure 13) in 20SIM for the seven-degree model in all of the articulations. As seen in the chart, the real curve (obtained from the walking corridor) and obtained by the model are very similar. There is a small variation in the results since the error is around 0,05.

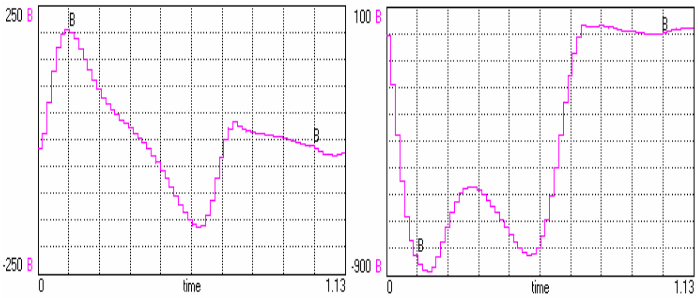

Figure 12. Reaction force between segments in the x-axis direction (left) and y-axis direction (right)

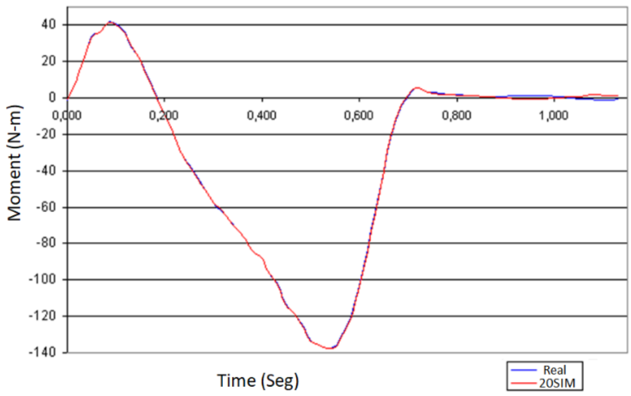

Figure 13. Moment in the ankle resulting from the walking corridor and the joint graph models (20-SIM)

Conclusions

When creating bipedal walking models, it is possible to notice the effect that gravity has over the act of human walking and the importance of the actuator-type elements that introduce energy to the system since they are simple mathematical models that enable the observation of fundamental aspects and concepts related to them.

The results of active and passive models obtained through the described techniques are very similar and their understanding allows inferring possible control actions that can be applied in the case of a biped walking robot. This is similar to what happens when people lose static or dynamic balance and must recover with torques in the articulations during bipedal march.

The purpose of the models developed in this work (not all of them are shown) was to enrich the knowledge on different elements that intervene in the human locomotion process. The results can be used in several research fields: physiological analysis, development of medical products, robotic applications, rehabilitation treatments for patients with mobility issues, etc.
The final model offers results that are very similar to those of a non-pathological patient walking through a corridor in terms of articular moments, speeds and accelerations. They are still simple models based on the fact that the enriched model would consider the forces exercised by the muscles and tendons for example which would deliver a model closer to reality.

References

[1] M. Peasgood, E. Kubica, and J. McPhee, Stabilization of a Dynamic Walking Gait Simulation, *J. Comp. Nonlinear Dynam.*, **2** (2007), 65-72. https://doi.org/10.1115/1.2389230

[2] M.A. Roa, *Modelamiento y Simulación de la Caminata Bípeda*, M.S. Tesis, Universidad Nacional de Colombia, Bogota, Colombia, 2004.

[3] Stanley A. Rice, *Encyclopedia of Evolution (en inglés)*, Infobase Publishing, 2009.

[4] M. Latash and V. Zatsiorsky, *Classics in Movement Science*, Human Kinetics Publishers, 2001.

[5] T.P. Andriacchi and E.J. Alexander, Studies of Human Locomotion: Past, Present and Future, *Journal of Biomechanics*, **10** (2000), 1217-1224. https://doi.org/10.1016/s0021-9290(00)00061-0

[6] J. Estrada, J. Camacho, M. Restrepo and C. Parra, *Parámetros Antropométricos De La Población Laboral Colombiana*, Ed: Editorial Universidad de Antioquia, 2002.

[7] J. E. Pratt, *Exploiting Inherent Robustness and Natural Dynamics in the Control of Bipedal Walking Robots*, Ph.D Thesis, Massachusetts Institute of Technology, 2000.

[8] D. Karnopp, D. Margolis and R.C. Rosenberg, *System Dynamics: a Unified Approach*, John Wiley & Sons, Inc., 1975.

[9] B. Kuo, *Sistemas Automáticos de Control,* Compañía Editorial Continental S.A., 1979.

[10] Hugh M. Herr, Alena M. Grabowski, Bionic ankle–foot prosthesis normalizes walking gait for persons with leg amputation, *Proceedings of the royal Society Biological Sciences*, **279** (2012), 457–464. https://doi.org/10.1098/rspb.2011.1194

Received: November 29, 2017; Published: December 15, 2017