IAK 2008
Conference on Interdisciplinary Applications of Kinematics
A. Kecskeméthy (eds.)
Lima, Peru, 9-11 January 2008

AN ALTERNATIVE FOR HUMAN GAIT MODELLING USING THE BONDGRAPH TECHNIQUE

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Keywords: Human gait, Bond Graph, Inverse kinematics, Skeletal muscle systems.

Abstract: *The systematic analysis of the human gait with a skeletal or neuromuscular disorder is a valuable clinical instrument to determine the nature and severity of the disease. At present, there are many institutions that have developed a series of numerical models that simulate and analyze biomechanics systems such as the human gait.*
Many of these models require diverse and segmented programming to incorporate various effects of the dynamics of the body such as the performance of the muscles and tendons, the passive and active resistance to movement, and other physiological effects. One of the alternatives to simulate biomechanical systems is the use of the Bond Graph modeling technique. The modular modeling with multi-domains, a feature of the Bond Graph technique, is one of its potential advantages compare to other methods. The equations generated with the use of this technique are equivalent to those techniques developed with more traditional methods, but the modules can be easier and more comfortable to use in conjunction with models of neuromuscular control functions, models that incorporate the elasticity properties in the bones and tendons, etc. The proposed model, comprised of seven segments, is developed to estimate the torque and the power in the joints. This model is simulated and validated using the processed experimental data of a normal gait in GCD (Gait Cycle Data) format file.

1 INTRODUCTION

Nowadays, the field of simulation covers fields as diverse as the calculation of mechanisms, the solution of electrical circuits or hydraulic circuits or the heat transfer within an air conditioning installation. These simulations are reflected in graphs that give an idea of how a certain system would work in reality, but also to optimize its functioning and get certain concrete results.

Lately, one of the areas of computer simulation is of the skeletal-muscular system of the human body which can resemble a mechanism that is complemented with the torques in the joints caused by the action of muscles and tendons, either for the purpose of surgery training or to understand their behavior among others things.

In this paper a model of the human gait is developed using the techniques of Bond Graph. The elements used in it, called "doors", focus on the transfer of energy through "*flows*" and "*efforts*" (for example, velocities and forces in the field of linear mechanics). The "*graphs*" combined suitably allow to incorporate effects such as mechanical, electrical, thermodynamic, elastic, etc. into the dynamic system.

The developed model corresponds to the human gait in the sagittal plane and contains 7 segments. Six of the segments represent the feet, shanks and thighs. The remaining segment is for the upper body –head, arms and trunk (HAT)– rigidly joined to the rest through the pelvis. Each segment is regarded as a rigid solid and therefore, the mechanism can be represented as 7 links united by simple joints. The model using this technique of Bond Graph has been designed and simulated using the software *Bondin* ©, developed by Dr. G. Romero of the Polytechnics University of Madrid, Spain (Grupo de Ingeniería Gráfica y Simulación, Departamento de Ingeniería Mecánica y Fabricación).

For the simulation and validation of the model, data was used from a normal gait cycle supplied in GCD (Gait Cycle Data) format [1], obtained in a *Hospital of Austria* using the systems of motion-capture from *Vicon Motion Systems*.

2 THE HUMAN GAIT USING THE BOND GRAPH MODELING

As mentioned by Pop [2] the application of Bond Graph to human gait modelling was first proposed by Matthijsse et al. [3] , [4]. Two 13-segment models were described with which the single and double support phases could be individually simulated. Foot elevation was used to switch between models. However, no inverse or direct dynamic simulation or experimental results were reported.

Validation is an important aspect of model development. Pezzack et al. [5] used Newtonian mechanics to develop a model which was then validated in three steps: first, computational accuracy was checked against hand calculations; next, ground reaction forces (GRFs) predicted by the model were checked against forceplate measurements; and finally, the accuracy with which the model predicted zero GRF at the distal end of the swing limb during the single support phase was verified. The results reported were accurate to within 15%, and the errors were attributed to errors in the body segment accelerations. Kingma et al. [6] validated their 3D model in two steps: first, by comparing the GRFs computed by the model with those from forceplate data, and then by comparing the torques at the hip joint resulting from bottom-up and top-down mechanical analysis. They concluded that the most rigorous method of validating the model is by comparison with forceplate measurements. However, it was shown by McCaw and DeVita [7] that errors in spatial alignment of the COP can introduce considerable errors in the lower extremity torques when forceplate readings are used in kinetic calculations.

Pop [8] developed a human gait Bond Graph 8-segment model using the kinetic method. Contreras et al. [9] developed a Bond Graph 7-segment model using both the kinetic and the multiport method proposed by Karnopp y Rosemberg [10]. In this paper, a Bond Graph 7-segment model is developed using the kinematic method, proposed by Vera [11] for rigid body beams.

2.1 Bond Graph of a rigid solid using the global coordinate system

Fig. 1 shows the spatial motion of a rigid solid. In a global coordinate system, the speeds of displacement and of rotation of the mass-center are independent one to the other respectively.

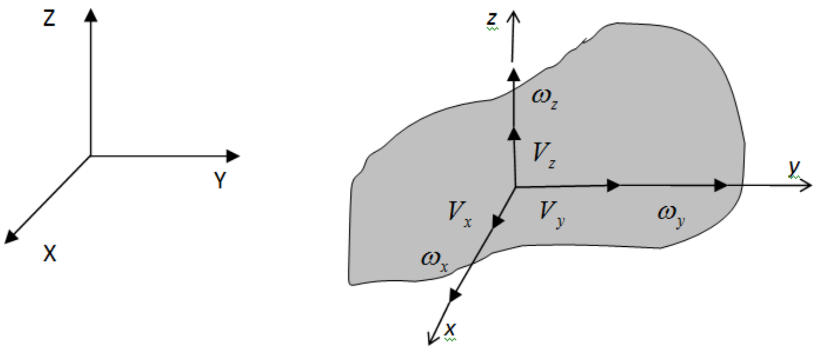


Figure 1: Reference system of a solid.

The 2D analysis of the velocities at the ends of the beam in a global coordinate system will be given by:

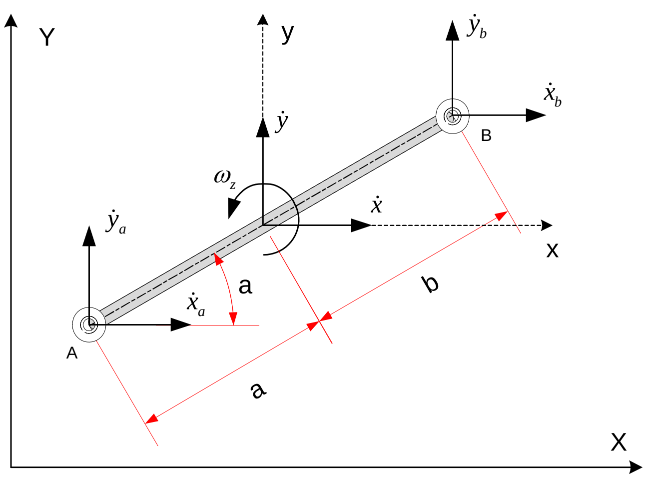


Figure 2: Planar 2D rigid beam in global coordinates.

The equations related to the speeds at the ends will be:

$$\begin{aligned} \dot{x}_a &= \dot{x} + \omega_z \cdot a \cdot \sin\alpha \\ \dot{y}_a &= \dot{y} - \omega_z \cdot a \cdot \cos\alpha \\ \dot{x}_b &= \dot{x} - \omega_z \cdot b \cdot \sin\alpha \\ \dot{y}_b &= \dot{y} + \omega_z \cdot b \cdot \cos\alpha \end{aligned} \qquad (1)$$

The diagram of graphs of the beam will be defined as:

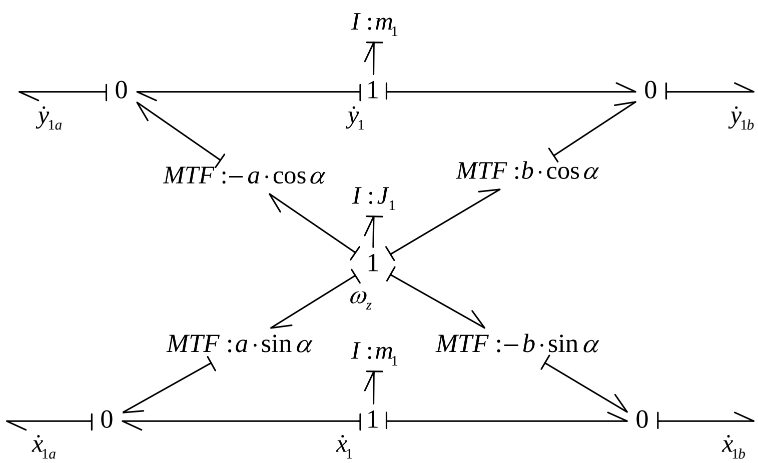


Figure 3: Bond Graph of the 2D rigid beam with movement in the plane *xy* using global coordinates.

In a global coordinate system, the union between two beams is very simple to achieve since the speeds of these two beams are exactly the same at the joint point. For the two beams articulated as shown in fig. 4, the diagram of graphs is defined in fig. 5.

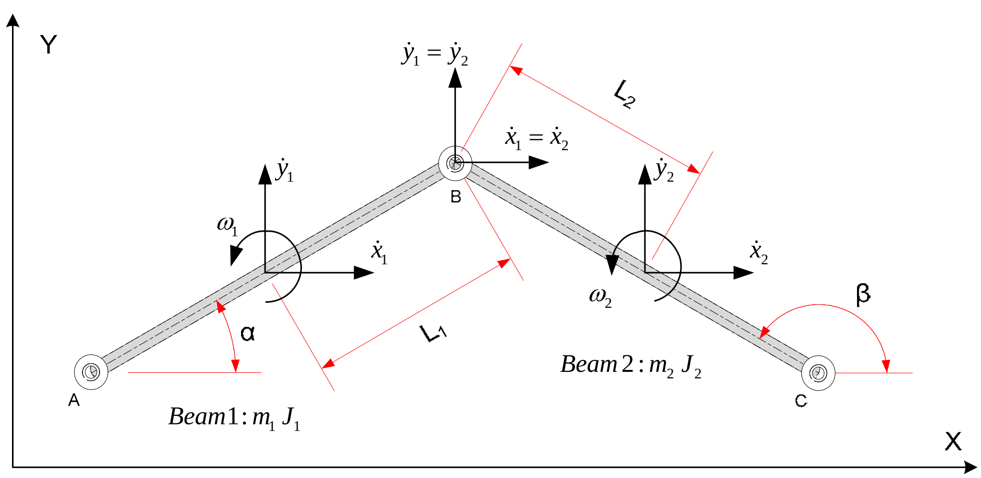


Figure 4: Two 2D rigid beams articulated in global coordinates.

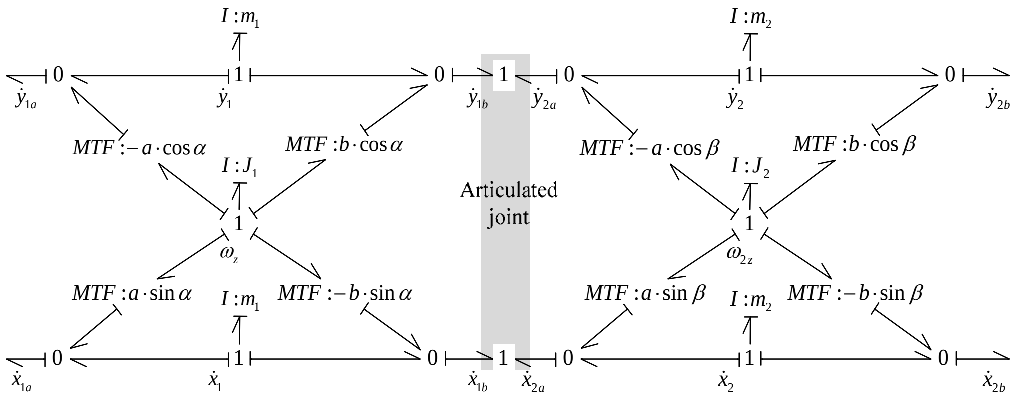


Figure 5: Bond graph of the articulation of two 2D rigid beams with movement in the plane *xy* using global coordinates.

In the Bond Graph modelling it is important to eliminate the differential causalities of the inertia elements (inductive) i.e. there are dependent variables that in certain programs of Bond Graph modelling do not allow developing the proposed models. Normally this disadvantage can be surpassed by adding capacitive and resistive elements in the joints. Using the *Bondin* software, it is not necessary to add these elements because it solves the causality problems or conflicts and calculates all the differential and algebraic equations. By this reason, the program has the capacity to solve models with both integral and differential causalities according to the needs, Romero et al. [12].

2.2 The Bond Graph 7-segment model of the human gait

There are two approaches to solving the model: direct and inverse dynamic models. A direct dynamic model is one that expresses the temporary evolution of joint coordinates in function of the forces and torques involved. An inverse dynamic model on the other hand is one that expresses the forces and torques that intervene in the function of the evolution of joint coordinates and its derivatives.

The model to follow is the inverse dynamic problem where the input values will be the displacement of the mass-center of the pelvis and the flexure/extension angles of the hip, knee and ankle.

4-segment model is considered for the kinematic analysis, the pelvis rigidly coupled to the head, arms and trunk (HAT) and the lower limb consisting of the right thigh, shank and foot united through a simple articulation (see fig. 6).

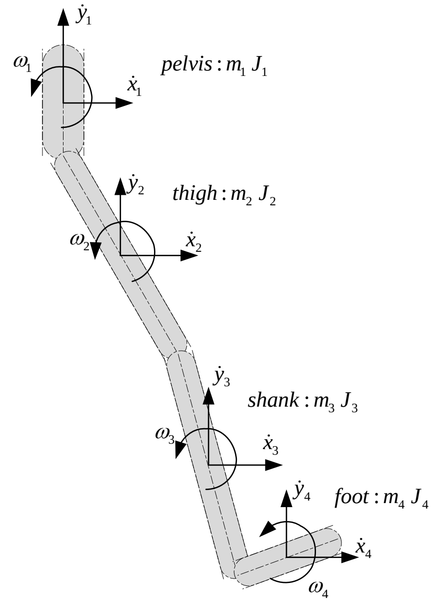


Figure 6: Scheme of the right leg for a 4-segment model.

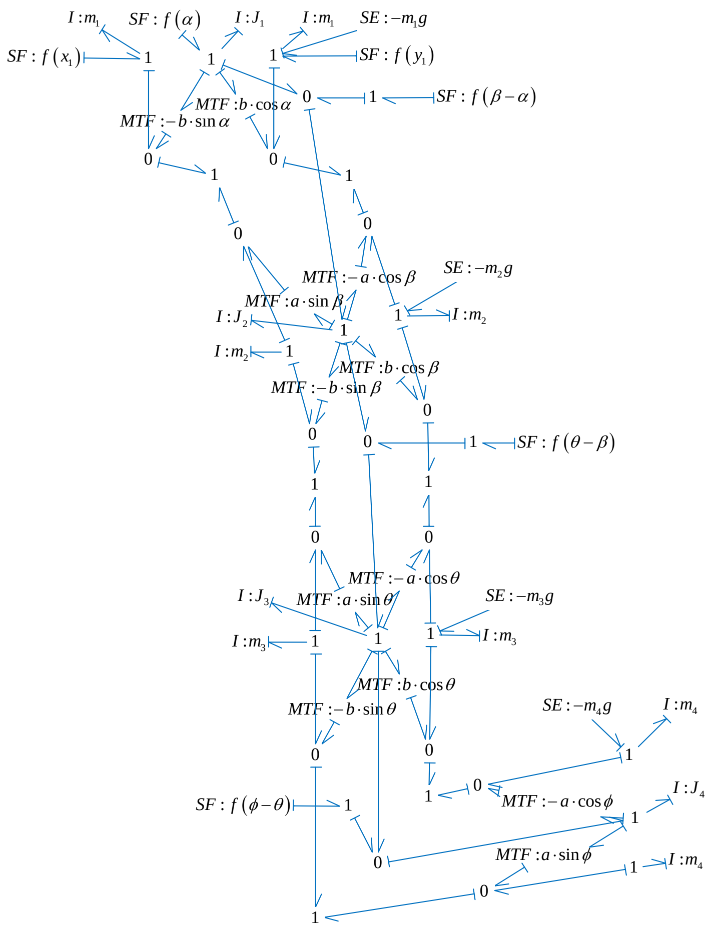
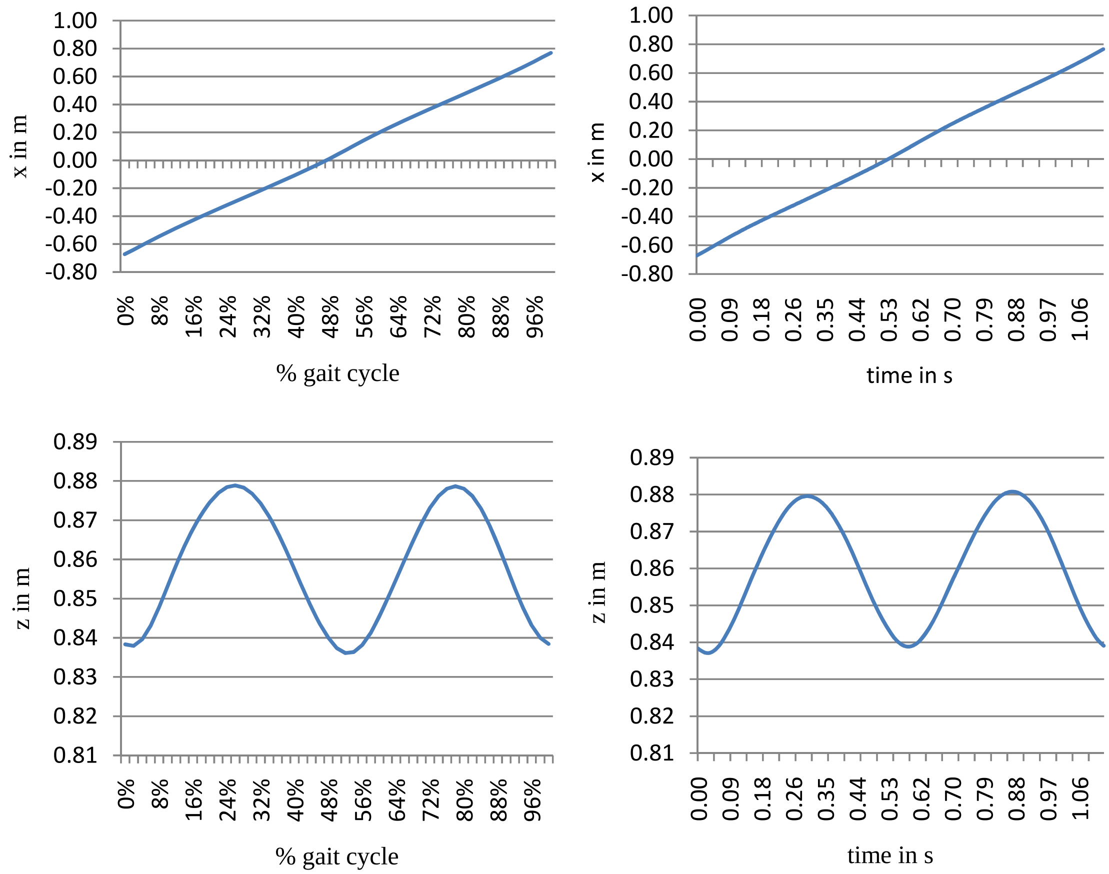


Figure 7: Detailed Bond Graph diagram of the right leg for a 4-segment model.

The data introduce in the model are the *RightPelvicOrigen* displacement and the *RightHipFlexExt*, *RightKneeFlexExt* and *RightDorsiPlanFlex* angles obtained from the GCD file. This data has been adapted using *Maple* (a mathematical software from MapleSoft ™) to be applied in the Bond Graph model using the *Bondin* software.

The kinematic results of the simulation are shown in the following graphics of fig. 8, 9 and 10. These figures show the 2D displacement of the joints using the *GDC* file (left side) and the results using the *Bondin* software (right side). The model uses the *CAMARC II* standard AVR (Anterior, Vertical and Right) right-handed Cartesian axes. On the sagittal plane is the *x* axis for the anterior direction and *z* axis for the vertical one.

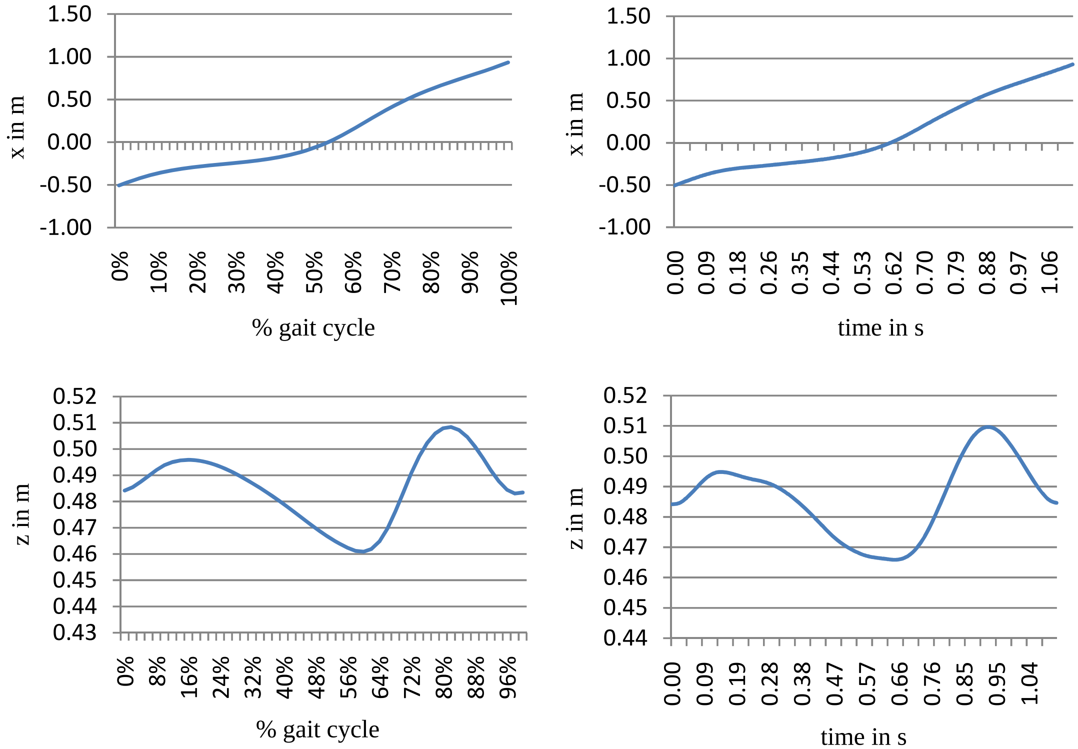
Kinematically, the results are optimum, showing the standard trajectories of the hip, knee and ankle joints for a normal gait.



a) Time histories from GDC file.

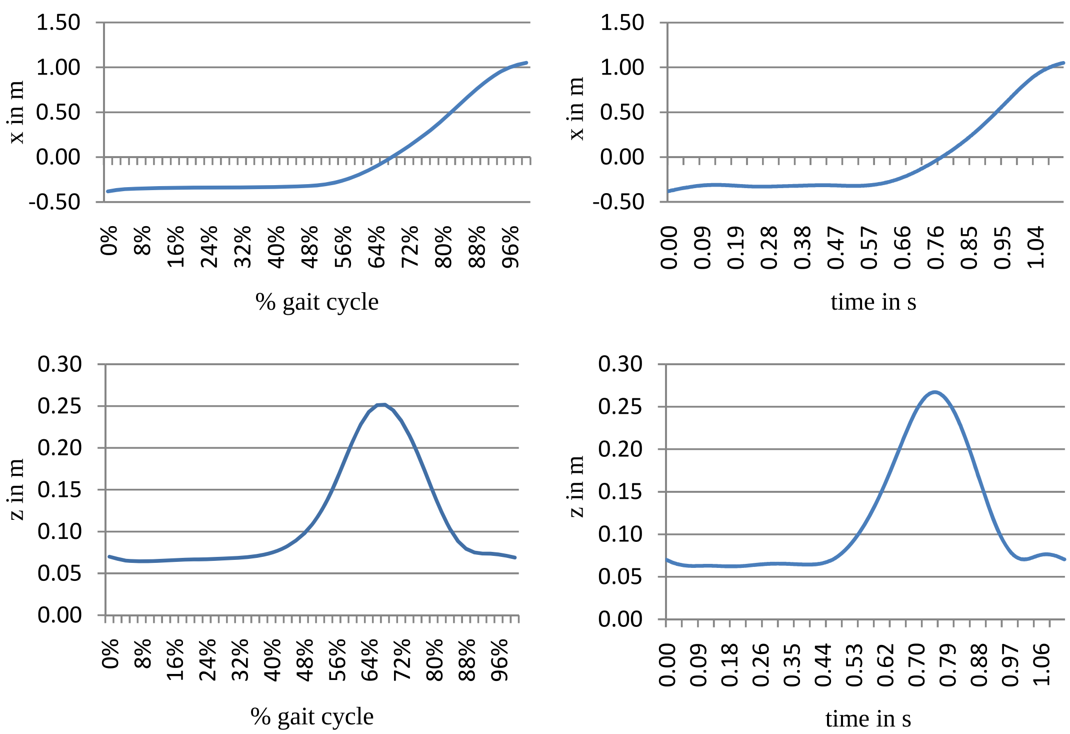
b) Time histories simulated with *Bondin*.

Figure 8: *RightHipJointCentre* displacement.



a) Time histories from GDC file. b) Time histories simulated with *Bondin*.

Figure 9: *RightKneeJointCentre* displacement.



a) Time histories from GDC file. b) Time histories simulated with *Bondin*.

Figure 10: *RightAnkleJointCentre* displacement.

To make the dynamic analysis, it is necessary to work with the complete 7-segment model. There are two options for the validation of the model. The first option is to add –in the contact between the feet and the ground– spring-damper elements to simulate the ground reaction forces (GRFs) in order to calculate these forces and to compare them with the forceplate measurements. This way is relevant for direct dynamics. The second option is to input the forceplate measurements as external forces on each foot (see fig. 11) and then to compare the calculated torques in the joints with the values of the normal human gait contained on the GCD file. This is an inverse dynamics method and this is the option used to validate the 2D model simulated in this paper.

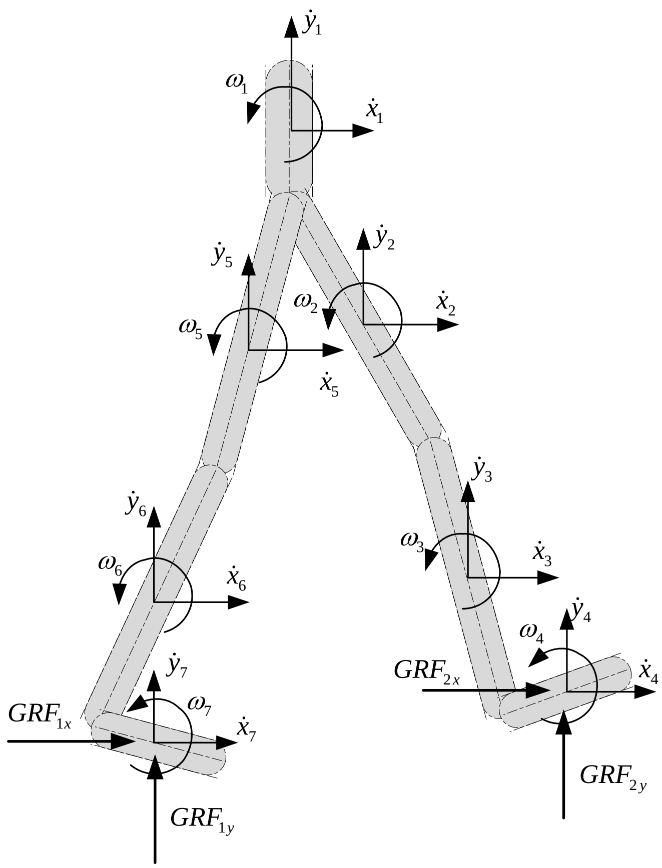


Figure 11: Scheme with reaction forces for a 7-segment model.

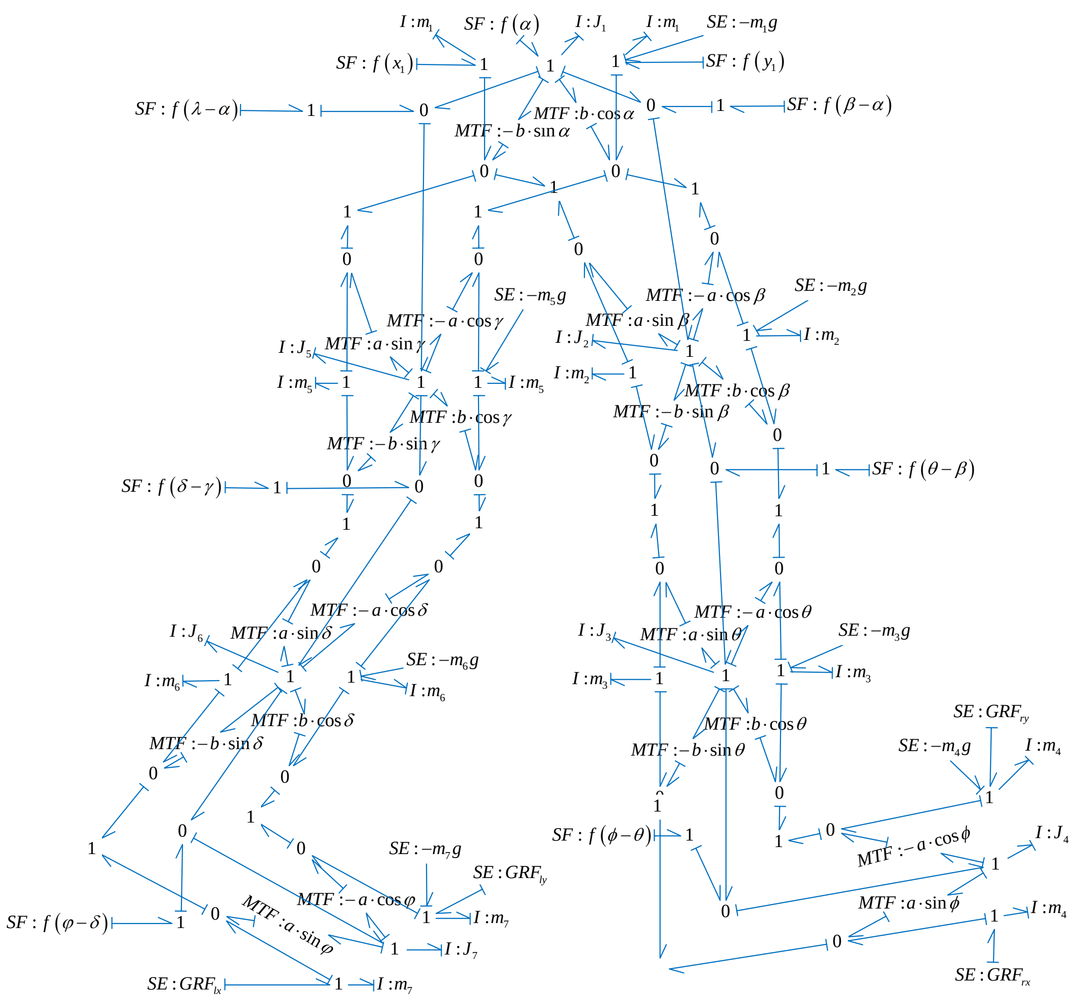
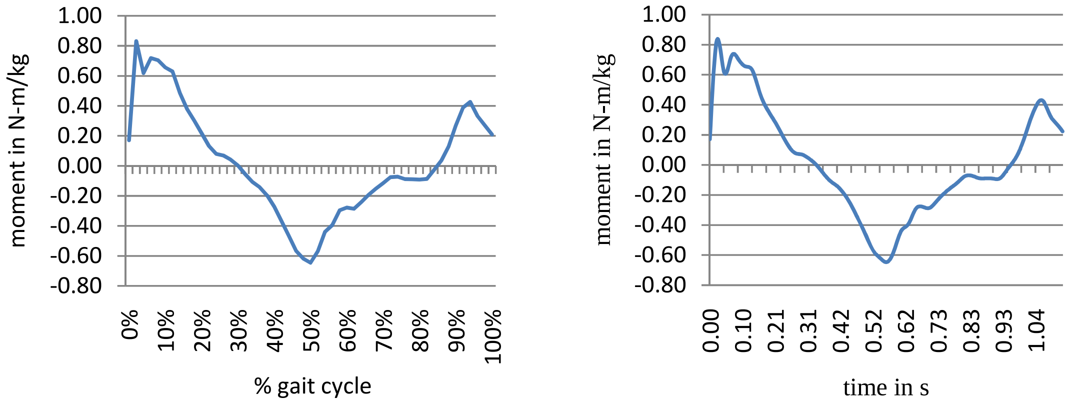


Figure 12: Detailed Bond Graph diagram for with reaction forces for a 7-segment model.

From the simulation of the inverse dynamics, the time histories of torques in the joints of the right leg in fig. 13, 14 and 15 are obtained. The left leg, not shown in this paper, has corresponding properties. In addition, it is possible to obtain the joint powers as shown in Figure 16.

Generally, torques and powers are plotted graphically as a function of the gait cycle. In this case, they are plotted graphically as a function of the time in order to facilitate the matching of the experimental data. The time base default used on the GCD format file is 51 samples of 2% through the gait cycle. For the model of this paper, 100% of the gait cycle corresponds to 1.129 seconds.

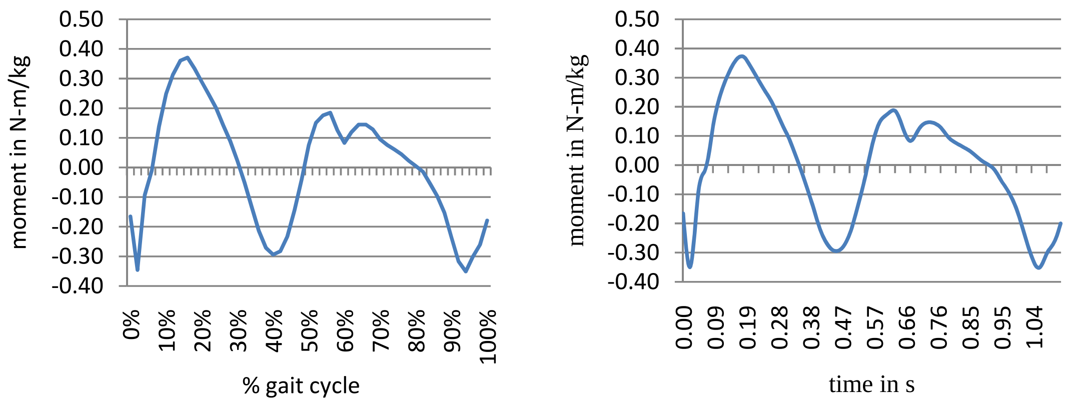
It can also be observed in fig. 13, 14 and 15 that there are few variations in relation to the torques read from the GCD file for a normal human gait compared with the results achieved in the 7-segment model using the Bond Graph technique.



a) Time histories from GDC file.

b) Time histories simulated with *Bondin*.

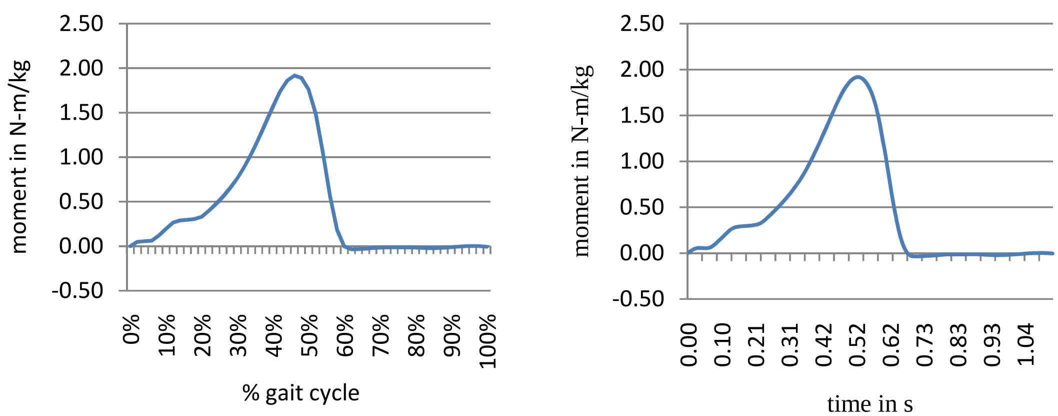
Figure 13: Right hip flexion/extension moment results.



a) Time histories from GDC file.

b) Time histories simulated with *Bondin*.

Figure 14: Right knee flexion/extension moment results.



a) Time histories from GDC file.

b) Time histories simulated with *Bondin*.

Figure 15: Right dorsi/plantar flexion joint moment results.

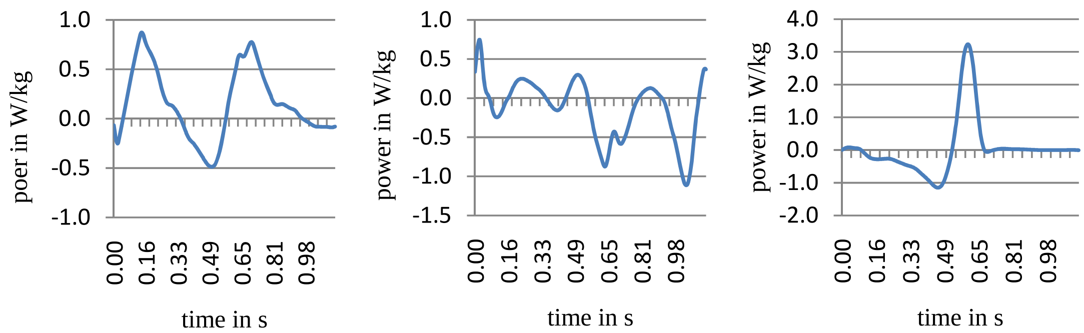


Figure 16: Right hip, knee and ankle joint powers results using *Bondin*.

The variations that appear in the results are due to the fact that the model has been developed at the sagittal plane, which does not consider the amplitude of movement of the front and vertical planes. Also, the knee and ankle joints have been considered as simple articulations, where sliding displacements have been despised. However, the model serves as a first major approximation to simulate the human gait in the sagittal plane using the Bond Graph technique.

3 CONCLUSIONS

As per the obtained results, we conclude that the Bond Graph technique using the kinematic method is valid for the modeling approach of the human gait. The next step is to work the model in three dimensions.

The modular and multi-domain characteristics of the Bond Graph technique allow one to add or to remove components very easily. This, in addition to improve the model, has a valuable teaching component that is manifested in the gradual development of the model. In future simulations, the knee and ankle articulations would be considered as sliding joints by inserting a four-link model. Moreover, the forces in the joints would be replaced by the muscular models also developed using the Bond Graph technique. On this last one, a modification of the model proposed by Wojcik [13] would be used.

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