Human Gait Analyses Using Multibody Systems Formulation: Normal and Pathological Scenarios

P. Moreira, J. Peixoto, U. Lugrís, J. Cuadrado, P. Flores and P. Souto

Abstract The main goal of this work is to present planar biomechanical multibody model, suitable to be used in inverse dynamic analyses. The proposed approach is straightforward and computationally efficient for the study of different human gait scenarios e.g. normal and pathological. For this, a biomechanical model of the lower limb of the human body was considered. The model consists of three rigid bodies (thigh, calf and foot), corresponding to relevant anatomical segments of lower limb. The three bodies are connected by revolute joints and described by eight natural coordinates, which are the Cartesian coordinates of the basic points located at the joints (hip, knee, ankle, metatarsal-phalangeal). The anthropometric dimensions of the model correspond to those of a normal male of 1.77 m and 80.0 kg and a poliomyelitis (polio) patient of 1.78 m and 92 kg. The total biomechanical system encompasses 5 degrees-of-freedom: 2 degrees-of-freedom for hip trajectory, 1 degree-of-freedom for hip flexion-extension motion, 1 degree-of-freedom for knee flexion-extension and 1 degree-of-freedom for ankle plantarflexion-dorsiflexion. The developed model was applied to solve an inverse dynamics problem of human

P. Moreira (✉) · P. Flores
CT2M—Center for Mechanical and Material Technologies, University of Minho, Braga, Portugal
e-mail: pfsmoreira@dem.uminho.pt

P. Flores
e-mail: pflores@dem.uminho.pt

J. Peixoto · P. Souto
Department of Textile Engineering, University of Minho, Braga, Portugal
e-mail: jjorge@det.uminho.pt

P. Souto
e-mail: souto@det.uminho.pt

U. Lugrís · J. Cuadrado
Laboratorio de Ingenieria Mecanica, Escuela Politecnica Superior, University of A Coruña, A Coruña, Spain
e-mail: ulugris@udc.es

J. Cuadrado
e-mail: javicuad@udc.es

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motion. Therefore, the main objective of this study is to determine the joint kinematics, moments-of-force and reaction forces during an entire gait cycle.

Keywords Biomechanics · Human gait · Multibody dynamics · Matrix-R · Inverse dynamics

1 Introduction

Over the last years, there is a huge interest in analyze the normal and pathological human gait. Usually, it includes the motion tracking by means of an optical system, and the evaluation of ground reaction forces through force plates.

The obtained positions of a specific number of skin markers are applied to the calculation of corresponding velocities and accelerations histories, defining a computational biomechanical model. These data are filtered in order to remove the noise introduced by the motion capture system and differentiated to yield the histories of the coordinates at velocity and acceleration level. The equations of motion of the biomechanical model are solved using a forward or inverse dynamics problem. The obtained results could be extremely useful to support traditional medical diagnosis and therapy planning, such as anticipate the result of a surgery or to help in the optimization design of the prosthetic and orthotic devices [4, 5].

The analysis of human gait is a complex task, relies mostly on the use of the multibody formulations applied as kinematic and dynamic tools. The human body can, thus, be considered a multibody system, composed by rigid or flexible bodies and connected by kinematic joints [2, 6].

2 Methodologies

2.1 Experimental Approach

The experimental data utilized in this work was obtained in a human gait laboratory, Fig. 1. A normal adult male of age 26, mass 80 kg and height 177 cm and a polio patient male of age 43, mass 92 kg and height 178 cm have been dressed with a special suit with 37 reflective markers attached, as illustrated in Fig. 1. The polio patient was wearing a traditional KAFO orthosis on the right leg.

For the experimental procedure, the subjects walk on a walkway with two AMTI AccuGait force plates, located in such a way that each plate measures the ground reactions of one foot during the gait cycle. The motion is captured by an optical system composed by 12 Natural Point OptiTrack FLEX: V100 cameras (100 Hz).

The trajectories of the markers present noise associated with the motion capture. The Singular Spectrum Analysis (SSA) filter is applied to the marker's position,

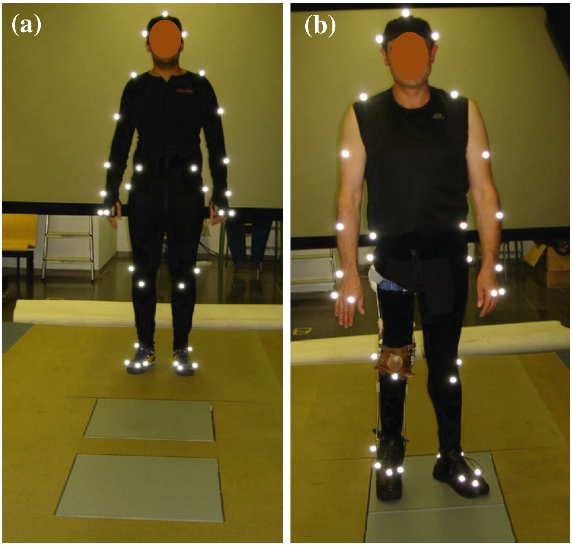

Fig. 1 Experimental gait analysis procedure **a** Normal male; **b** Pathological male (polio)

which are then used to predict internal positions by means of simple algebraic relations [1]. The values of the positions at each instant of time are not kinematically consistent due to errors of the motion tracking. The kinematic consistency of the natural coordinates at position level is imposed, by means of the augmented Lagrangian minimization process expressed by:

$$\begin{gathered}\left(\mathbf{W} + \Phi_{\mathbf{q}}^{\mathrm{T}} \alpha_{\mathrm{p}} \Phi_{\mathbf{q}}\right) \Delta\mathbf{q}_{i+1} = -\mathbf{W}(\mathbf{q}_i - \mathbf{q}^*) - \Phi_{\mathbf{q}}^{\mathrm{T}} (\alpha_{\mathrm{p}} \Phi + \lambda_i) \\ \lambda_{i+1} = \lambda_i + \alpha_{\mathrm{p}} \Phi; i = 1, 2, \ldots \end{gathered} \tag{1}$$

where $\mathbf{q}^*$ is the vector of inconsistent natural coordinates, $\Delta\mathbf{q}_{i+1} = \mathbf{q}_{i+1} - \mathbf{q}_i$, Φ is the corresponding Jacobian matrix, λ is the vector of Lagrange multipliers, α_{p} is the penalty factor, and $\mathbf{W}$ is a weighting matrix that allows to assign different weights to the different coordinates according to their expected errors. Different weighting factors can be assigned to each natural coordinate, thus for example, the skin movement artifact on the thigh is larger than on the shank [1].

2.2 Computational Model

A 2D biomechanical model of the right leg of the human body was developed. The biomechanical model consists of three rigid bodies (thigh, calf and foot), corresponding to relevant anatomical segments of lower limb, Fig. 2. These three bodies are connected by revolute joints and described by eight natural coordinates, which

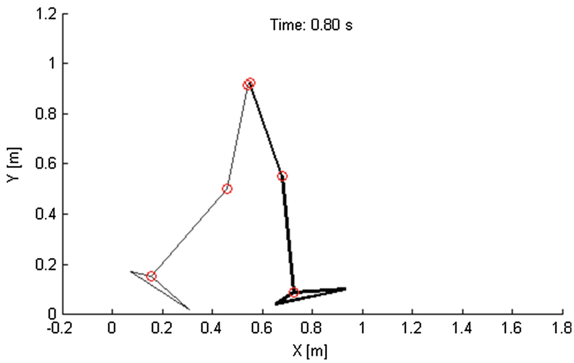

Fig. 2 Biomechanical model of lower limb

Table 1 Inertial properties of rigid bodies used in the biomechanical models

Body	Mass (kg)	Moment of inertia (kg.m^2)
Normal male		
Foot	0.77	0.0035
Calf	3.28	0.0490
Thigh	6.86	0.1238
Pathological male		
Foot	0.82	0.0016
Calf	4.00	0.0537
Thigh	9.28	0.1173

are the Cartesian coordinates of the basic points located at the human articulations (hip, knee, ankle, metatarsal-phalangeal).

The anthropometric data of the three anatomical segments and their corresponding bodies is listed in Table 1, and it is extracted from the data present in [7] and from the anthropometric dimensions measured directly from the subject. The biomechanical system encompasses 5-degrees-of-freedom: 2 degrees-of-freedom for hip trajectory, 1 degree-of-freedom for hip flexion-extension motion, 1 degree-of-freedom for knee flexion-extension and 1 degree-of-freedom for ankle plantar-flexion-dorsiflexion. The developed model was applied to solve an inverse dynamic problem of human motion. In this work, two distinct methodologies were adopted to perform the inverse dynamic analysis of human gait: the classical Newton-Euler equations and the multibody methodology based on the projection matrix-R.

2.3 Newton Euler Equations

The Newton-Euler formulation is considered here to study the dynamic behaviour of the biomechanical model described above. The present analysis closely follows

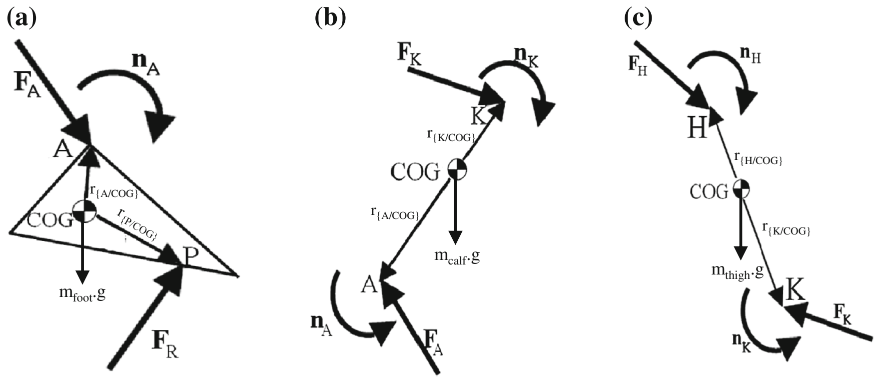

Fig. 3 Free-body diagram of rigid bodies; **a** Foot; **b** Calf; **c** Thigh [6]

the development done by Silva [6]. Thus, the dynamic equations of motion of a free rigid body can be expressed in the following form [6]:

$$\begin{cases} \sum \mathbf{F} + m\mathbf{a}_g = m\mathbf{a} \\ \sum \mathbf{n} = I\alpha \end{cases} \tag{2}$$

in which $\sum \mathbf{F}$ represents the external applied forces, m denotes the mass of the body, $\mathbf{a}$ is the linear acceleration, $\mathbf{a}_g$ is the gravitational acceleration. In a similar way, $\sum \mathbf{n}$ represents the sum of the external applied moments of force, I denotes the mass moment of inertia and α denotes the angular acceleration of the body. This procedure is repeated for all the rigid bodies that constitute the biomechanical model. Figure 3 includes the free body diagram of the foot, calf and thigh, which are represented in static balance of forces. For the particular case of the foot segment, the ground reaction force $\mathbf{F}_\mathrm{R}$ and its application point P are obtained by direct measurement in the force plate. Point A denotes the revolute joint between foot and calf, location of which is obtained as described in Sect. 2.1. The experimental data is utilized to calculate the linear and angular acceleration components, as well as, the angular velocity vector for the rigid body.

Analysing the diagram of Fig. 3a, it can be observed that for the case of the foot, the reaction force at ankle joint $\mathbf{F}_\mathrm{A}$ and the net moment-of-force $\mathbf{n}_\mathrm{A}$ needed to be calculated. These variables are obtained from the resolution of the dynamic equations of motion (2), written for the foot segment, yielding:

$$\begin{cases} \mathbf{F}_\mathrm{A} = m(\mathbf{a} - \mathbf{a}_\mathbf{g}) - \mathbf{F}_\mathrm{R} \\ \mathbf{n}_\mathrm{A} = I\alpha - (\mathbf{r}_\mathrm{COG} - \mathbf{r}_\mathrm{P}) \times \mathbf{F}_\mathrm{R} - (\mathbf{r}_\mathrm{COG} - \mathbf{r}_\mathrm{A}) \times \mathbf{F}_\mathrm{A} \end{cases} \tag{3}$$

The complete description of the Newton Euler methodology can be found in [6]. The procedure used to calculate the forces and moments on the calf (Fig. 3b) and thigh (Fig. 3c) is quite similar to the one used for the foot example.

2.4 Multibody Methodology Based on the Projection Matrix-R

The dynamics of a multibody system can be described by the constrained Lagrangian equations:

$$\begin{aligned} &\mathbf{M}\ddot{\mathbf{q}} + \Phi_{\mathbf{q}}^{t}\lambda = \mathbf{Q} \\ &\Phi = \mathbf{0} \end{aligned} \tag{4}$$

where $\mathbf{M}$ is the mass matrix, $\ddot{\mathbf{q}}$ is the accelerations vector, Φ is the constraints vector, Φ_q is the Jacobian matrix of the constraints, λ represents the Lagrange multipliers vector and $\mathbf{Q}$ is the applied forces vector. Equation (4) represents a system of differential-algebraic equations [3, 6]. The purpose of the method based on the projection matrix-R is to obtain a system of ordinary differential equations with dimension n_i equal to the number of degrees of freedom, using a set $\mathbf{z}$ of independent coordinates [3]. The following relation between velocities is established:

$$\dot{\mathbf{q}} = \mathbf{R}\underline{\mathbf{z}} \tag{5}$$

where $\mathbf{q}$ are all the n_d dependent variables and $\mathbf{z}$ is a set of n_i independent variables. After differentiating the Eq. (5):

$$\ddot{\mathbf{q}} = \mathbf{R}\ddot{\mathbf{z}} + \dot{\mathbf{R}}\dot{\mathbf{z}} \tag{6}$$

Thus, substitution of Eq. (6) into Eq. (4) yields,

$$\mathbf{MR}\ddot{\mathbf{z}} + \mathbf{M}\dot{\mathbf{R}}\dot{\mathbf{z}} + \Phi_{\mathrm{q}}^{\mathrm{T}}\lambda = \mathbf{Q} \tag{7}$$

Premultiplying by $\mathbf{R}^{\mathrm{T}}$ results,

$$\mathbf{R}^{\mathrm{T}}\mathbf{MR}\ddot{\mathbf{z}} = \mathbf{R}^{\mathrm{T}}(\mathbf{Q} - \mathbf{M}\dot{\mathbf{R}}\dot{\mathbf{z}}) \tag{8}$$

In order to solve the inverse dynamics of human motion, a set of independent coordinates $\mathbf{z}$ is calculated from the previous set of natural coordinates: the two Cartesian coordinates of hip joint, along with the hip, knee and ankle rotation angles. After that, the SSA filter is applied in order to reduce the noise introduced by the kinematic consistency imposed to the natural coordinates [1]. Once obtained the histories of the independent coordinates $\mathbf{z}$, and their derivatives, $\dot{\mathbf{z}}$ and $\ddot{\mathbf{z}}$, the inverse dynamics problem is solved using the velocity transformation formulation matrix-R [3], which provides the motor efforts required to generate motion. The motor efforts are obtained as an external force and moment-of-force acting on the hip and the corresponding internal joint torques. However, they are not the correct ground reaction force, moment-of-force and joint's moment-of-force. The external force and moment-of-force must be applied at the foot contacting the ground, instead of hip. Thus, a simple linear relation can be established between the two sets of motor efforts. The relation is obtained by equating the vector of generalized forces due to the set of force and moment-of-forces applied at the hip and the vector of generalized forces due to the set of force and moment-of-forces applied at the foot [1, 6].

3 Results and Discussion

The original kinematic data obtained from the gait tracking process has some noise, which could lead to kinematic inconsistency and also could cause unacceptable errors in dynamic analysis. The raw and filtered kinematic data of a skin marker (right femoral epicondyle) for the normal male is presented in the plots of Fig. 4.

The presented methodologies has been used to study the biomechanical response of human motion considering different pathologies that induce irregular an unsafe gait patterns. Figure 5 shows the knee joint angles for the polio patient, during a entire gait cycle. It can be observed that the right knee angle does not exhibit any knee flexion movement (Fig. 5a). The orthosis locks the knee during the entire gait cycle. The left knee angle presents a normal pattern. This data is corroborated by the analysis of the center-of-pressure plots (Fig. 5b).

The methodology presented through this work is applied to the inverse dynamic analysis of human gait. The proposed biomechanical model is able to calculate not only the moments-of-force occurring in the joints, but also the joint reaction forces. The results concerning the hip Y reaction force and ankle moment-of-force occurring in the right leg is presented in the plots of Fig. 6.

From the analysis of the obtained results, it can be concluded that a good correlation is found between the two methodologies. As expected for the same input data, the multibody methodology based on the projection matrix-R, produces similar results to those obtained using the classical Newton Euler equations Fig. 6.

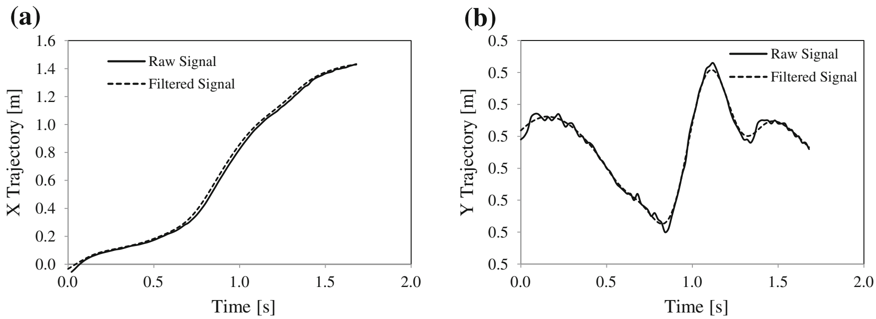

Fig. 4 Right femoral epicondyle skin marker trajectory (normal male); **a** X trajectory; **b** Y trajectory

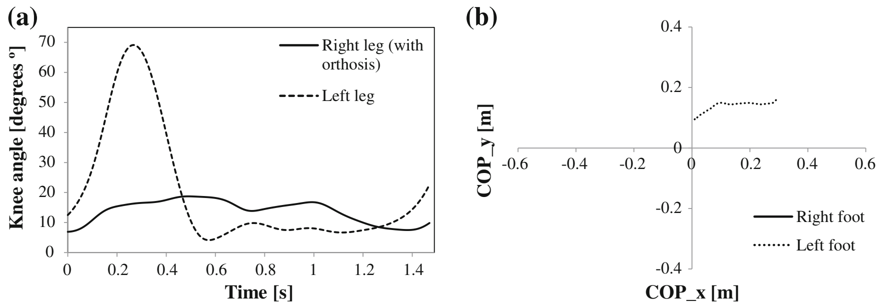

Fig. 5 **a** Knee joint angle during the entire gait cycle for the polio patient cop and **b** center-of-pressure curves (COP) during an entire gait cycle for the polio patient

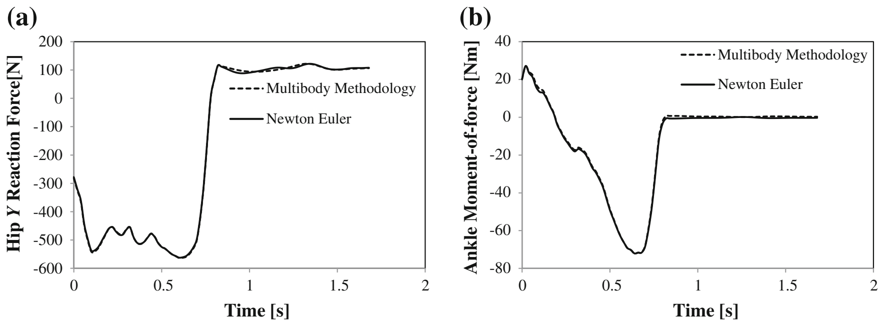

Fig. 6 Comparison of results for the hip Y reaction force (**a**) and ankle moment-of-force (**b**) using two distinct methodologies: multibody methodology based on matrix-R and classical Newton-Euler equations for the normal male

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