Influence of Input Data Errors on the Inverse Dynamics Analysis of Human Locomotion

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ABSTRACT

Inverse dynamic techniques are used in gait analysis to calculate the net joint moments that the musculo-skeletal system produces during human locomotion. Errors present in the input data may affect significantly the results of the inverse dynamics problem. In this work, the influence of inaccuracies in body segment parameters (BSP) and ground reaction force measurements on the obtained results is analyzed. The uncertainties in these data are computer-generated as perturbations added to their actual values. On the one hand, the uncertainties in BSP are modelled as statistical errors using zero-mean Gaussian distributions. On the other hand, inaccurate ground reaction forces are represented adding a percentage of error to the theoretical force. Errors present in the ground reaction forces allow to estimate the uncertainty introduced to the analysis when ambiguous force plate measurements are used as input parameters. The paper presents detailed results and discussions to quantify the effects of the above errors on the inverse dynamics analysis. The several simulations carried out show that the results are more sensitive to errors in the ground contact forces –when these are used– than in the body inertial parameters.

Keywords: Gait analysis, biomechanics, body segment parameters, ground reaction force, error analysis.

1 INTRODUCTION

Multibody dynamics techniques have been widely used in the last decade for the inverse dynamics analysis (IDA) of human locomotion [1]. The objective of inverse dynamics is to determine net joint contact forces and net joint moments about these joints, using as input data the captured body motion and the body segment parameters (geometric and inertial) [14]. These joint moments are the result of the muscular action. Once these moments are determined, it is possible to calculate the forces applied by the different muscles involved in human gait by means of optimization techniques [1]. Net joint forces and moments will be called the gait results of the IDA in this study.

An IDA requires a large set of input data, in particular, body segment parameters (BSP) and kinematics information. Uncertainties present in these parameters will affect the results of the inverse dynamics problem [10,11,18]. The knowledge of these effects is very important to quantify the accuracy of the gait results [15,19], and to be aware of the parameters that have to be more accurately estimated.

Different errors in gait analysis have been described in [10]. The influence of using different BSP values is not clear, some studies suggest that BSP can produce significant errors [4,5,12,16], whereas others have noted that BSP effects are not very important in kinetic gait results [13,20]. The main problem is that most of the BSP cannot be directly measured and their estimation depends on the measurement techniques applied. Discrepancies about 40% have been detected among different anthropometric tables [6].

In biomechanical gait studies, besides the body motion, foot-ground contact forces are also measured using a force plate. This measurement can be compared to the ground contact force obtained from the IDA in order to validate the results of that analysis. However, sometimes force plate data are directly used as an input of the IDA [3,7,8,13]. This practice could lead to inconsistent results if error is contained in force data. To determine the magnitude of the error when this procedure is carried out, we introduce an error to the actual ground reaction force in order to see how the results are affected.

The objective of this work is to investigate the effects of input data uncertainties on the gait results. For this purpose, a planar biomechanical multibody model made up of rigid bodies connected by revolute joints is used. These effects will be studied in two cases. In the first case, the mass and length of the body segments, the distance from the centre of mass (CM) to the proximal joint, and the moments of inertia about the CM will be perturbed to see the influence of BSP uncertainties on the joint moments obtained. In the second case, the ground reaction force is employed as input data of the inverse problem. It is used as a force acting on the stance foot. Error will be added to the actual force data in order to quantify its influence on the gait results. In this work, the movement of the biomechanical system is assumed to be perfectly known in order to avoid additional uncertainties on the inverse dynamics. This movement is defined by means of trigonometric analytical expressions.

2 DYNAMICS MODELLING

2.1 Biomechanical Model

The biomechanical model used has 12 degrees of freedom. It consists of ten rigid bodies linked with revolute joints (Figure 1), and it is constrained to move in the sagittal plane. Each rigid body is characterized by mass, length, moment of inertia about the centre of mass, and distance from the centre of mass to the proximal joint. These anthropometric parameters are taken from [6].

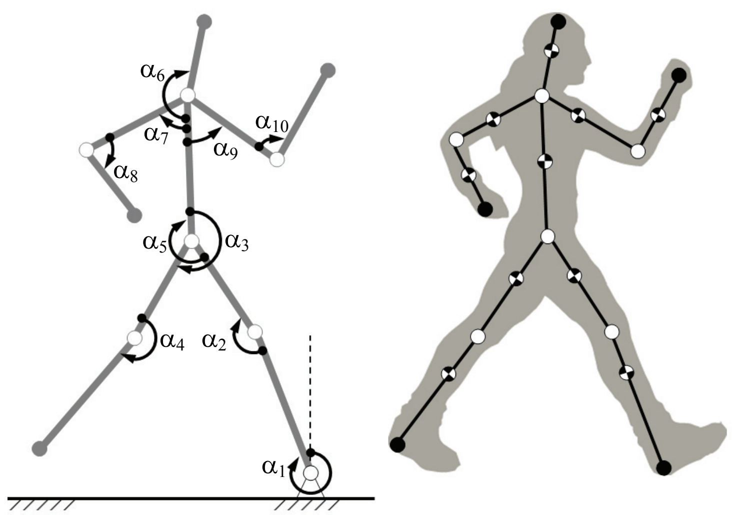


Figure 1. Planar biomechanical model of the human body.

2.2 Multibody Dynamics Formulation

The IDA is formulated using a multibody dynamics methodology. The generalized coordinates vector $\mathbf{q}$ is composed of thirty-two variables: twenty-two are position variables, defined with natural coordinates, which are related to the endpoints of each segment. The other ten variables are angular coordinates α_i that define the orientation of the different segments, Figure 1.

Constraint equations $\mathbf{\Phi}(\mathbf{q},t)=0$ include the physical constraints between variables and the rheonomic constraints $\alpha_i(t)$ that drive the motion. The latter are defined by means of trigonometric functions.

The equations of motion can be written as

$$\begin{bmatrix} \mathbf{M} & \mathbf{\Phi}_{\mathbf{q}}^{\mathrm{T}} \\ \mathbf{\Phi}_{\mathbf{q}} & \mathbf{0} \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{q}} \\ \boldsymbol{\lambda} \end{Bmatrix} = \begin{Bmatrix} \mathbf{Q} \\ \boldsymbol{\gamma} - 2\xi\omega\dot{\mathbf{\Phi}} - \omega^2\mathbf{\Phi} \end{Bmatrix} \tag{1}$$

where $\mathbf{M}$ is the mass matrix, $\mathbf{\Phi}_{\mathbf{q}}$ is the Jacobian matrix of the constraint equations, $\ddot{\mathbf{q}}$ is the acceleration vector, $\mathbf{Q}$ is the generalised force vector, $\boldsymbol{\lambda}$ are the Lagrange multipliers, and $\boldsymbol{\gamma}$ contains the terms that are function of velocity, position and time. The Baumgarte's stabilisation method is used with $\xi = 1; \omega = 10$.

This formulation has been used in two cases. In the first case, $\mathbf{\Phi}(\mathbf{q}, t)$ contains the foot-ground constraints. The contact between the ankle and the ground is defined as a revolute joint and the contact force can be calculated via the corresponding multipliers. Therefore, input data of the IDA are only BSP and kinematic movement. In the second case, the ground reaction force is introduced in vector $\mathbf{Q}$ and the corresponding constraint in $\mathbf{\Phi}(\mathbf{q}, t) = 0$ is relaxed. Therefore, in this case inverse dynamics is computed using kinetic, kinematic and anthropometric information.

The purpose of using analytical expressions to drive the movement –rheonomic constraints– is to define a completely known movement that guarantees kinematic consistency. Therefore, the position, velocity and acceleration associated to each coordinate can be known without error and no extra inaccuracies are involved in the inverse dynamics problem. In that way, the effects of input data errors (in BSP and force plate measurements) can be analyzed separately. For the sake of simplicity, the driving functions are defined as

$$\alpha_i(t) = A_i \cos(\omega_i t + \varphi_i) \tag{2}$$

where the angular frequency ω_i, the phase φ_i, and the amplitude A_i have been chosen for each joint in order to obtain a realistic-looking human motion. All the angular velocities are zero at heel strike, therefore, when the foot gets in contact with the ground, its velocity is zero so as to avoid impact condition. The period to perform a human step simulation has been fixed to one second. Note that the use of trigonometric functions to drive the motion allows to determine analytically the contstraint ecuations $\mathbf{\Phi}$, the Jacobian $\mathbf{\Phi}_{\mathbf{q}}$ and $\dot{\mathbf{\Phi}}$ in Equation (1).

2.3 Error Analysis

As explained above, two different cases are studied. The first case considers that there is uncertainty in BSP. Net joint moments of force are calculated to show how sensitive they are to these inaccuracies. In the second case, the ground reaction force is perturbed and it is used as an input of the inverse problem. The joint moments are also calculated and compared to the ones obtained with the actual non-perturbed data. In this case, it is possible to quantify the error introduced when the ground reaction force is used as an input to the IDA [11]. Note that there is a number of studies that use directly force plate data as input parameter, without taking into account that the ground contact force should be an output of the IDA [3,7,8,13].

Errors in BSP can be described as spread data around their actual value. In order to model inaccuracies in BSP, normal (or Gaussian) distributions with zero mean and a certain variance are used. Hence, we perform a statistical analysis taking a sample of errors from a normal population instead of adding fixed errors as in [17]. In order to define the variance of the Gaussian distribution, we associate the maximum error, defined as a percentage of the actual value (for example, 10%), to 3σ. In that way, we assume that the 99.7% of the values are within the error interval (for example, the actual value ±10%).

A sample size of 1000 values from the Gaussian distribution modelling the error is obtained for each parameter. Five different maximum errors are simulated, from 2 to 10% using 2% increments. Therefore, five different error variances have been considered. When a mass perturbation is performed, the mass of each segment is normalized so that the total body mass remains always constant. In the same way, when the length of each segment is perturbed the height of the subject also remains constant. These are reasonable assumptions, since the total mass and height are parameters that can be known with little error.

Using the 1000 values of each inertial parameter for a fixed maximum error, inverse dynamics analyses are carried out. The joint moments are calculated and compared with the set of moments obtained from the non-perturbed IDA –which emulates reality–. The root mean square error (RMSE), a normalized root mean square error (NRMSE), and the bias error are used as indicators of the analysis accuracy.

The RMSE is calculated to estimate the global error magnitude in joint moments at each dynamic simulation. The NRMSE is obtained as the quotient between the RMSE and the range of the non-perturbed moment. While the RMSE assesses the overall error in each simulation, the NRMSE evaluates the relative error with respect to the actual result. For example, an RMSE of 1 Nm of a moment whose actual range of values is 1 Nm (NRMSE = 1) is much more important than the same RMSE of a moment with a range of values of 100 Nm (NRMSE = 0.01); the NRMSE parameter accounts for this difference. The bias error ε_{BIAS} is computed to detect a systematic discrepancy between perturbed and actual joint moments. They are calculated by means of the following expressions:

$$RMSE_i = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(M_i^{NP}[k]-M_i^{P}[k])^2} \tag{3}$$

$$NRMSE_i = \frac{RMSE_i}{M_i^{\max}-M_i^{\min}} \tag{4}$$

$$\varepsilon_{BIAS_i} = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(M_i^{NP}[k]-\overline{M}_i^{P}[k])} \tag{5}$$

In the previous equations, index i refers to the same index as the angles in Figure 1, $M_i^{NP}[k]$ is the actual net joint moment at instant k using non-perturbed –actual– parameters; $M_i^{P}[k]$ is the net joint moment at instant k when input parameters are perturbed, and N is the number of time steps of the simulation. $M_i^{\max}$ and $M_i^{\min}$ are, respectively, the maximum and the minimum value of M_i^{NP}. Finally, $\overline{M}_i^{P}[k]$ is the average moment at instant k obtained from the 1000 simulations when each inertial parameter is perturbed.

In the second approach, the ground reaction force is used as an input to the inverse problem. In order to estimate the inaccuracies in plate force data, a percentage of this force is added as an error. Ten different errors are simulated from 1 to 10% using 1% force increments. To analyse the results, RMSE and NRMSE are computed and compared to those obtained using the first approach.

3 RESULTS AND DISCUSSION

3.1 Influence of Body Segment Parameters (BSP) Errors

In this study, the perturbed inertial parameters are the mass and length of the body segments, the distance from the centre of mass to the proximal joint, and the moments of inertia about the centre of mass. These are perturbed following the procedure described in Section 2.3. As a sample of the whole simulations, Table 1 shows the results for the variances associated with maximum errors of ±2, ±6 and ±10% for each inertial parameter.

When the mass of each body segment is perturbed, the most significant NRMSE is obtained at M_3 and M_4, i.e., the hip and knee moments at the swing leg, respectively. The results show that inaccuracies in the mass of the segments with a maximum error of ±10% (keeping the total mass constant), can produce a NRMSE of 14% in M_4. However, the RMSE is small enough (about 0.798 Nm). The highest RMSE is found at M_1 with 2.894 Nm. This shows that the absolute error (RMSE) is more important at the stance leg and the relative error (NRMSE) is higher at the swing leg. Figure 2 shows the range of M_1 and M_4 values when the mass of the segments is perturbed adding a Gaussian error associated with ±10% of maximum error. The red curves represent the actual value of each moment (no error in masses of segments), the two dashed curves represent the maximum and minimum values of the moments obtained in the simulations when the parameters are computed.

	M_1			M_2			M_3			M_4			M_5		
% Max. Error	2%	6%	10%	2%	6%	10%	2%	6%	10%	2%	6%	10%	2%	6%	10%
Mass															
RMSE (Nm)	0.699	1.737	2.894	0.481	1.234	2.161	0.350	0.733	1.415	0.181	0.402	0.798	0.486	1.115	1.922
NRMSE (%)	0.092	0.230	0.383	0.132	0.338	0.592	1.586	3.324	6.414	3.276	7.253	14.402	0.866	1.987	3.426
BIAS (Nm)	$3.76 \cdot 10^{-5}$	$7.66 \cdot 10^{-4}$	$1.85 \cdot 10^{-4}$	$1.90 \cdot 10^{-5}$	$6.49 \cdot 10^{-4}$	$5.17 \cdot 10^{-4}$	$4.76 \cdot 10^{-6}$	$9.07 \cdot 10^{-5}$	$2.96 \cdot 10^{-4}$	$6.38 \cdot 10^{-7}$	$5.64 \cdot 10^{-5}$	$1.50 \cdot 10^{-4}$	$9.74 \cdot 10^{-7}$	$2.53 \cdot 10^{-4}$	$2.09 \cdot 10^{-3}$
Moment of Inertia															
RMSE (Nm)	0.274	0.887	1.351	0.171	0.527	0.836	0.041	0.113	0.203	0.040	0.110	0.199	0.083	0.110	0.401
NRMSE (%)	0.036	0.117	0.179	0.047	0.144	0.229	0.184	0.510	0.922	0.726	1.994	3.589	0.147	0.197	0.715
BIAS (Nm)	$5.10 \cdot 10^{-6}$	$2.10 \cdot 10^{-5}$	$1.19 \cdot 10^{-4}$	$1.86 \cdot 10^{-6}$	$1.21 \cdot 10^{-5}$	$4.33 \cdot 10^{-5}$	$1.42 \cdot 10^{-8}$	$4.72 \cdot 10^{-6}$	$9.29 \cdot 10^{-7}$	$1.63 \cdot 10^{-9}$	$4.77 \cdot 10^{-6}$	$8.25 \cdot 10^{-7}$	$4.60 \cdot 10^{-7}$	$4.77 \cdot 10^{-6}$	$8.28 \cdot 10^{-6}$
CM Location X_G															
RMSE (Nm)	0.034	0.121	0.182	0.019	0.069	0.120	0.011	0.039	0.061	0.002	0.005	0.008	0.015	0.054	0.084
NRMSE (%)	0.004	0.016	0.024	0.005	0.019	0.033	0.049	0.178	0.274	0.032	0.083	0.153	0.027	0.095	0.149
BIAS (Nm)	$1.46 \cdot 10^{-7}$	$9.22 \cdot 10^{-7}$	$1.38 \cdot 10^{-5}$	$7.29 \cdot 10^{-8}$	$2.21 \cdot 10^{-7}$	$4.07 \cdot 10^{-6}$	$1.33 \cdot 10^{-9}$	$6.60 \cdot 10^{-9}$	$1.22 \cdot 10^{-7}$	$1.00 \cdot 10^{-12}$	$1.64 \cdot 10^{-9}$	$3.26 \cdot 10^{-9}$	$2.86 \cdot 10^{-8}$	$1.64 \cdot 10^{-8}$	$2.85 \cdot 10^{-7}$
CM Location Y_G															
RMSE (Nm)	0.092	0.268	0.468	0.048	0.139	0.229	0.067	0.198	0.327	0.023	0.064	0.113	0.066	0.203	0.334
NRMSE (%)	0.012	0.035	0.062	0.013	0.038	0.063	0.302	0.900	1.484	0.423	1.164	2.035	0.118	0.361	0.595
BIAS (Nm)	$2.77 \cdot 10^{-7}$	$6.33 \cdot 10^{-6}$	$1.87 \cdot 10^{-7}$	$1.41 \cdot 10^{-7}$	$1.12 \cdot 10^{-6}$	$1.78 \cdot 10^{-7}$	$6.89 \cdot 10^{-7}$	$2.47 \cdot 10^{-6}$	$3.08 \cdot 10^{-7}$	$1.02 \cdot 10^{-8}$	$3.15 \cdot 10^{-7}$	$1.03 \cdot 10^{-8}$	$4.63 \cdot 10^{-7}$	$2.04 \cdot 10^{-6}$	$3.38 \cdot 10^{-7}$
Length															
RMSE (Nm)	4.297	11.653	19.207	2.524	8.461	14.559	0.104	0.306	0.459	0.081	0.258	0.375	0.131	0.408	0.616
NRMSE (%)	0.569	1.542	2.542	0.691	2.317	3.986	0.471	1.386	2.082	1.460	4.652	6.774	0.233	0.727	1.097
BIAS (Nm)	$3.22 \cdot 10^{-1}$	$1.54 \cdot 10^{-5}$	1.18	$8.69 \cdot 10^{-2}$	$5.64 \cdot 10^{-3}$	$2.51 \cdot 10^{-1}$	$1.11 \cdot 10^{-4}$	$8.28 \cdot 10^{-6}$	$3.19 \cdot 10^{-4}$	$5.27 \cdot 10^{-5}$	$2.76 \cdot 10^{-6}$	$2.20 \cdot 10^{-4}$	$1.43 \cdot 10^{-3}$	$1.85 \cdot 10^{-4}$	$5.22 \cdot 10^{-3}$

Table 1. Errors in the joint moments of force when inertial parameters (mass, moment of inertia, CM location and length of each segment) are perturbed with zero-mean Gaussian errors with variances associated with maximum error intervals of ±2, ±6 and ±10% of their actual value.

Figures 2a and 2b show the moments of force M_1 and M_4 obtained during one step, i.e., half of the gait cycle. The results obtained cannot be compared with the gait results reported in the literature because the simulated human motion is just an approximation of the real movement. Note that, although the RMSE value in M_1 (2.894 Nm) is higher than in M_4 (0.798 Nm), the dashed curves in M_1 indicate an accurate result; whereas the dashed curves in M_4 indicate that the error is high compared to the actual moment result. As said before, this relative error is measured by the NRMSE. As it can be seen in Table 1, in this case the NRMSE of M_1 is 0.383% and the one of M4 is 14.402%.

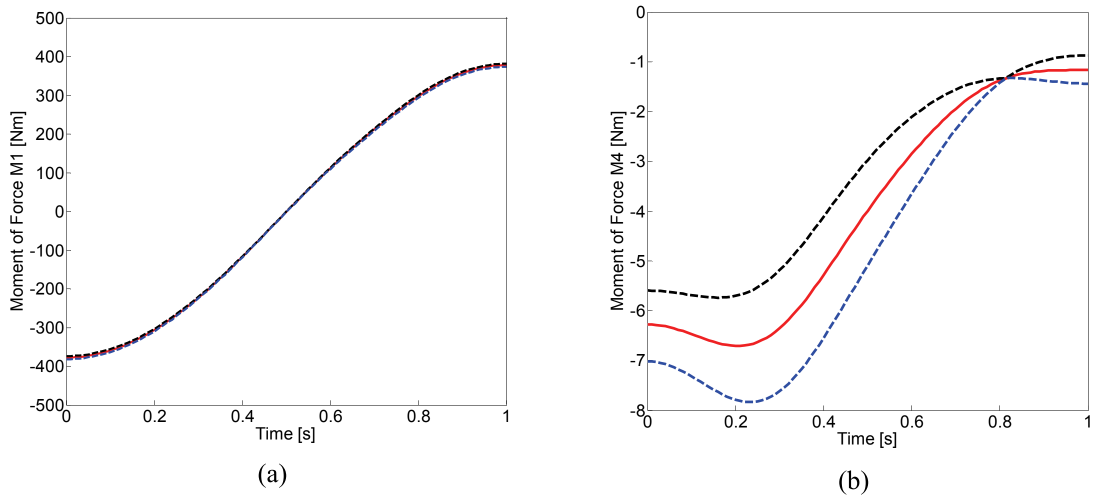


Figure 2. Net joint moment when the mass of the segments are perturbed ±10%.
(a) Moment of stance ankle M_1. (b) Moment of swing knee M_4.

When the Gaussian error is introduced in the moments of inertia of the segments, the analysis of the results shows that a ±10% perturbation in this parameter can produce a NRMSE of 3.589% in the net joint moment M_4. Again, in this case, the maximum RMSE is obtained at M_1.

When the centre of mass (CM) locations are perturbed, both NRMSE and RMSE are in general close to zero. Only perturbations in coordinate Y (axis connecting the two joints) show an NRMSE greater than 1% in M_3 and M_4. The error in CM locations gives a slight influence in the final results, specifically, the error in the X coordinate (axis perpendicular to Y) has the smallest effect. The gait results, in terms of net joint moments, are not very sensitive to a disturbance in those inertial parameters.

Inaccuracies in the lengths of the segments produce the highest RMSE, e.g., up to 19.207% in M_1. The most important errors are detected in the moments related to the joints that belong to the stance leg (M_1 and M_2), which are one order of magnitude higher than the others. Nevertheless, uncertainties of 10% in the length of a body segment are improbable.

Bias error is low in all simulations except when segment lengths are perturbed. In this case, the bias error does not always increase when the percentage of perturbation grows and the value can be 1 Nm when high length perturbations are simulated. When length parameters are perturbed close to 2% –which are the realistic conditions for those parameters–, the bias error has a similar order of magnitude than the one obtained for the other perturbed inertial parameters. Thus, it can be concluded that the bias error is negligible in all cases.

The results indicate differences between the errors in swing and stance leg moments. The largest NRMSE, whatever the perturbed parameter is, appears always in the swing leg and the smallest is obtained in the stance leg. Specifically, relative errors in M_4 (knee, swing leg) are always higher than those obtained in M_2 (knee, stance leg), and NRMSE values in M_3 (hip, swing leg) are also higher than those obtained in M_5 (hip, stance leg). This fact can be related with the angular accelerations of these segments. Angular accelerations of the segments belonging to the swing leg are higher than those of the stance leg segments. This effect suggests that BSP values could be more important when human motions involve larger limb accelerations in an open chain, for example, for running or jumping motions.

3.2 Influence of Ground Reaction Force Errors

In the second case, the ground reaction force is used as an input to the inverse problem. We add a percentage error to the horizontal and vertical components of this force and see its effect on the calculated joint moments. Table 2 contains the RMSE and NRMSE values when the forces are perturbed 2, 6 and 10%. The results show that a perturbation of the ground reaction force affects mainly the joints of the stance leg. An important RMSE value of nearly 24 Nm is obtained in M_1 (ankle moment) with a perturbation of 10% in both the X and Y components of the external contact force.

M_1

% Perturbation	2%	6%	10%
RMSE	4.830	14.489	24.149
NRMSE	0.639	1.918	3.196

M_2

% Perturbation	2%	6%	10%
RMSE	2.204	6.611	11.018
NRMSE	0.6034	1.810	3.017

M_3

% Perturbation	2%	6%	10%
RMSE	0.334	1.001	1.668
NRMSE	1.512	4.536	7.560

M_4

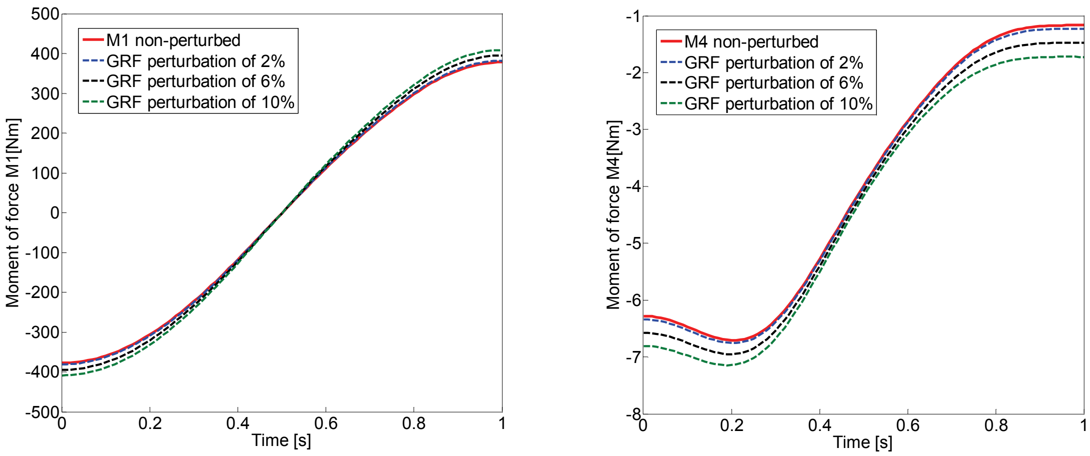
% Perturbation	2%	6%	10%
RMSE	0.090	0.271	0.451
NRMSE	1.628	4.884	8.140

M_5

% Perturbation	2%	6%	10%
RMSE	0.506	1.519	2.532
NRMSE	0.903	2.708	4.513

Table 2. Error values when ground contact forces are perturbed adding a percentage of 2, 6 and 10%.

Although the highest absolute error is obtained in moments of force belonging to the stance leg, NRMSE indicates that the highest relative error is found in the swing leg, as in the first case. Figures 3a and 3b show, respectively, how M_1 and M_4 change when the ground contact force is perturbed. The actual net joint moment is plotted in red, and the dashed curves indicate the value of the net joint moment when the ground contact force is perturbed 2, 6 and 10% of its actual value.



(a) (b)

Figure 3. Net joint moment when the ground reaction force is perturbed 2, 6 and 10% of its actual value. (a) Moment of stance ankle M_1. (b) Moment of swing knee M_4.

This second case shows that having error in the ground reaction force produces a higher RMSE and NRMSE than those obtained when BSP are inaccurate. The inverse dynamics analysis is comparatively more sensitive to errors present in external ground forces than in BSP. As expected, RMSE and NRMSE grow proportionally to the percentage of error introduced in the ground reaction forces, but this growth is different in each net joint moment. As found in the first case, M_1 is the moment with the highest RMSE, while M_4 is the moment with the maximum NRMSE.

4 CONCLUSIONS

A multibody methodology has been applied to perform a statistical study input data errors using an inverse dynamic analysis of human locomotion. In order to estimate how errors present in the input data affect the kinetic results of the inverse dynamics problem, two different cases are studied. First, with the purpose of modelling the error present in body segment parameters (BSP) –due to inaccurate measurements or the use of tabulated parameters–, Gaussian perturbations are added to their actual values. Second, to estimate the error when inaccurate force plate data are introduced in the inverse dynamics, ground reaction forces are perturbed adding an error proportional to its actual value. The analysis of the results shows that:

(i) The location of the centre of mass of the segments has a little effect in the joint moments of force. Specifically, the effect of the coordinate X (in the segment local coordinate system) is almost negligible.

(ii) The joint moments of force are sensitive to angular accelerations of the linked segments in terms of relative error. Uncertainties in BSP become important if the human movement involves high accelerations.

(iii) The net joint moments are more sensitive to errors in the force plate measurements than in BSP parameters. Consequently, using force plate data as an input to the IDA can introduce important errors in the analysis.

The presented results can be useful to know which input data have to be accurately measured in order to obtain reliable results of the inverse dynamics analysis of biomechanical systems. In this work we impose a specific human motion and the body model is constrained to move in the sagittal plane (two-dimensional motion). Future works will use a realistic three-dimensional multibody model of the human body together with the capture of a real gait motion.

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REFERENCES

[1] AMBRÓSIO, J., AND KECSKEMÉTHY, A. Multibody dynamics of biomechanical models for human motion via optimization. *Multibody Dynamics: Computational Methods and Applications* (2007), 245-272.

[2] CAHOUËT, V., LUC, M., AND AMARANTINI, D. Static optimal estimation of joint accelerations for inverse dynamics problem solution. *Journal of Biomechanics 35, 11* (2002), 1507-1513.

[3] CAPPOZZO, A., TOMMASO, L., AND PEDOTTI, A. A general computing method for the analysis of human locomotion. *Journal of Biomechanics 8* (1975), 307-320.

[4] DAVIS B.L. Joint Moments: Evaluation of ground reaction, inertial and segmental weight effects. *Gait Posture 2, 1* (1994), 58.

[5] DAVIS B.L. Uncertainty in calculating joint moments during gait. In *Proceedings of the 8th Meeting of the European Society of Biomechanics* (Rome, Italy, 21 - 24 June 1992), 276.

[6] DUMAS, R., CHEZE, L., AND VERRIEST, J.P. Adjustments to McConville et al. and Young et al. body segment inertial parameters. *Journal of Biomechanics 40, 3* (2007), 543–553. Corrigendum *Journal of Biomechanics 40, 7* (2007), 1651-1652.

[7] DUMAS, R., NICOL, E., AND CHÈZE, L. Influence of the 3D inverse dynamic method on the joint forces and moments during gait. *Journal of Biomechanical Engineering 129, 5* (2007), 786-790.

[8] FORNER-CORDERO, A., KOOPMAN, H.J.F.M., AND VAN DER HELM F.C.T. Inverse dynamics calculations during gait with restricted ground reaction force information from pressure insoles. *Gait and Posture 23, 2* (2006), 189-199.

[9] GRUBER, K., RUDER, H., DENOTH, J., AND SCHNEIDER, K. A comparative study of impact dynamics: wobbling mass model versus rigid body models. *Journal of Biomechanics 31, 5* (1998), 439-444.

[10] HATZE, H., The fundamental problem of myoskeletal inverse dynamics and its implications. *Journal of Biomechanics 35*, (2002), 109-115.

[11] KUO, A. D. A least-squares estimation approach to improving the precision of inverse dynamics computations. *Journal of Biomechanical Engineering 120* (1998), 148-159.

[12] LIU, W., AND NIGG, B.M. A mechanical model to determine the influence of masses and mass distribution on the impact force during running. *Journal of Biomechanics 33* (2000), 122-134.

[13] MCCAW, S.T., AND DEVITA P. Errors in alignment of center of pressure and foot coordinates affect predicted lower extremity torques. *Journal of Biomechanics, 28, 8* (1995), 985-988.

[14] NIGG B.M., AND HERZOG W. (Eds.), *Biomechanics of the musculo-skeletal system*, 2nd Edition, Wiley: West Sussex, England, 1999.

[15] PEARSALL, D.J., AND COSTIGAN, P.A. The effect of segment parameter error on gait analysis results. *Gait and Posture 9* (1999), 173-183.

[16] RAO, G., AMARANTINI, D., BERTON, E., AND FAVIER, D. Influence of body segments' parameters estimation models on inverse dynamics solutions during gait. *Journal of Biomechanics 39, 8* (2006), 1531-1536.

[17] SILVA, M. P. T., AND AMBRÓSIO, J. A. C. Sensitivity of the results produced by the inverse dynamic analysis of a human stride to perturbed input data. *Gait and Posture 19* (2004), 35-49.

[18] STAGNI, R., LEARDINI, A., CAPPOZZO, A., GRAZIA BENEDETTI, M., AND CAPPELLO, A. Effects of hip joint centre mislocation on gait analysis results. *Journal of Biomechanics, 33, 11* (2000), 1479-1487.

[19] VAUGHAN, C. L., ANDREWS, J. G., AND HAY, J. G. Selection of body segment parameters by optimization methods. *Journal of Biomechanical Engineering 104* (1982), 38-44.

[20] WU, G., AND LADIN, Z. The effect of inertial load on human joint force and moment during locomotion. In *Proceedings of the Second International. Symposium on Three-Dimensional Analysis of Human Movement* (Poitiets, France, 30 June - 3 July 1993), 106-107.