

# Influence of perturbed gait data on four 3D inverse dynamic methods

DUMAS Raphaël, NICOL Elsa, CHEZE Laurence  
Laboratoire de Biomécanique et de Modélisation Humaine  
Université Claude Bernard Lyon 1 -  
Institut National de Recherche sur les Transports et leur Sécurité  
Lyon - France  
raphael.dumas@univ-lyon1.fr

**Abstract**— The joint forces and moments are commonly used in gait analysis. They can be computed by four different 3D inverse dynamic recursive methods proposed in the literature, either based on vectors and Euler (or Cardanic) angles, wrenches and quaternions, homogenous matrices, or generalized coordinates and forces. The influence of perturbed data on the four inverse dynamic methods was analyzed using the gait data (first unperturbed and then perturbed) of nine healthy subjects. For all methods, the influence was found negligible at the ankle but important at the knee and the hip joints. The influence was found somewhat more important for the method based on vectors and Cardanic angles and for the method based on the generalized coordinates and forces.

**Keywords:** 3D inverse dynamics, Cardanic angles, quaternions, homogenous matrices, generalized coordinates, perturbed data

## I. INTRODUCTION

The 3D inverse dynamics is widely used in gait analysis. Commonly, the proximal joint forces and moments are computed recursively as a function of the kinematics, the Body Segment Inertial Parameters (BSIPs) and the distal forces and moments. The computation starts at the foot where the distal forces and moments are the ground reaction forces and moments. Four 3D inverse dynamic recursive methods have been proposed in the literature. These methods are either based on vectors and Euler (or Cardanic) angles [1-5], wrenches and quaternions [6], homogenous matrices [7], or generalized coordinates and forces [8]. These four methods diverge on both kinematic (e.g. Euler angles vs. quaternions) and dynamic computations (e.g. vectors vs. wrenches), although they follow the same bottom-up scheme. As a result, from a theoretical point of view, the computations of the joint forces and moments should be all equivalent. However, the comparison of the joint forces and moments computed by the four methods with unperturbed gait data has been previously done [9] and demonstrated similar patterns and amplitudes although significant differences.

The objective of this paper is to investigate the influence of perturbed gait data on the joint forces and moments computed by the four inverse dynamic methods, in order to discriminate which method may be more sensitive to noise.

## II. MATERIAL AND METHODS

### A. Gait data

The gait data at comfortable speed of nine voluntary subjects (six healthy males and three healthy females,  $23 \pm 2$  years old,  $174 \pm 7$  cm,  $62 \pm 7$  kg) were obtained at 100 Hz by Motion Analysis System (Santa Rosa, USA) and AMTI force platform (Watertown, USA). All the data were expressed in the same Inertial Coordinate System (ICS). The ICS was oriented with the Y-axis vertical and the X-axis along with the direction of gait [10]. The trajectories of thirteen markers on anatomical landmarks of the pelvis and of the right lower limb were first filtered (fourth-order butterworth, 6 Hz cutoff frequency) and solidificated [11] in order to obtain unperturbed gait data. Conversely, Gaussian noise ( $2*SD = 5$  mm) was added in order to obtain perturbed (but monitored) gait data.

With both unperturbed and perturbed gait data, the attitude of the Segment Coordinate Systems (SCSs) with respect to the ICS were then expressed as Cardanic angles, quaternions, homogenous matrices and generalized coordinates. Besides, the BSIPs were estimated through scaling equations [12].

### B. Inverse dynamic methods

The four inverse dynamic methods were implemented in Matlab 7.0 using classical matrix operators (e.g. square matrix inversion).

In the method based on vectors and Cardanic angles, the linear acceleration and the angular velocity and acceleration were computed with the Cardanic angles and their derivatives. The joint forces and moments were computed successively (respectively in the ICS and SCS). In the method based on wrenches and quaternions, the linear acceleration and the angular velocity and acceleration were computed with the quaternion algebra. The wrench (built from the joint forces and moments) was computed in one single time. In the method based on homogenous matrices, all the linear and angular kinematics were included in an acceleration matrix. Another homogenous matrix (built from the joint forces and moments) was computed in one single time. In the method based on

generalized coordinates and forces, the kinematics was directly the derivatives of four chosen vectors. The generalized forces (interpolated from the joint forces and moments) were computed in one single time, together with the Lagrange multipliers related to the rigid body constraints.

### C. Means, normalization and assessment of the influence

For each method, the 3D joint forces and moments (computed with both unperturbed and perturbed gait data) were re-expressed as percentage of gait cycle, normalized by weight (for the forces) and weight and height (for the moments) and averaged for the nine subjects. The joint forces and moments were expressed in the ICS and did not strictly correspond to adduction-abduction, internal-external rotation and flexion-extension.

For every inverse dynamic method, the difference between the joint forces and moments obtained with unperturbed and perturbed gait data was computed at each percentage of the gait cycle. The mean difference was computed for all the gait cycle. Also, for every inverse dynamic method, the amplitudes of the joint force curve and the joint moment curve (between the maximal and the minimal values among the gait cycle) were computed with the unperturbed gait data. The influence of the perturbed data was assessed (in percentage) as the mean difference relative to the curve amplitude.

## III. RESULTS AND DISCUSSION

### A. Joint forces and moments with unperturbed gait data

Figure 1 presents the mean normalized moments about the Z-axis of the ICS obtained, at the knee joint, by the four inverse dynamic methods with unperturbed gait data.

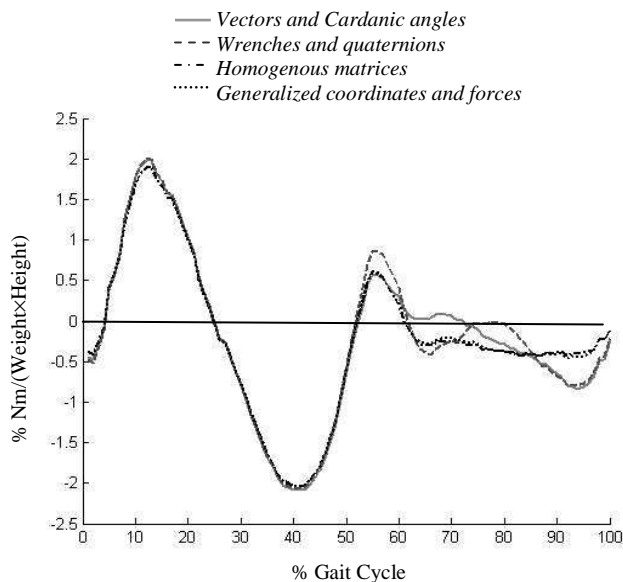


Figure 1. Mean normalized moments (about the Z-axis) obtained with unperturbed gait data by the four inverse dynamic methods at the knee joint

The joint force and moment curves obtained by the four inverse dynamic methods were found coherent both in pattern and amplitude with the literature [4]. The influence of the method on the joint forces and moments was found negligible at the ankle joint but important at the knee and the hip joints [9]. The dispersion increased from the ankle up to the hip because the disparities merely cumulate in a recursive computation. Non recursive computations can be alternatively used with other inverse dynamic schemes including kinematical models and explicit joint constraints [13]. The comparison of these schemes with the four recursive methods is beyond the scope of this paper.

The influence seemed to be due mainly to the differences of formulation in the dynamic computations. In the methods based on vectors and Cardanic angles, the force vector is computed in the ICS and the moment vector in the SCS. The successive coordinate transformations may have an effect. On the opposite, in the methods based on wrenches and quaternions, the forces and moments are computed in one single time (in the ICS). In the methods based on homogenous matrices, the forces and moments are also computed in one single time but in a redundant manner. In the homogenous matrix structure, the force appears in last row and last column and the moment appears as a skew matrix. The forces and moments are the means of both computations. In the method based on generalized coordinates and forces, the forces and moments are also computed in one single time (in the ICS) but the rigid body constraints are additionally taken into account through the Lagrange multipliers.

### B. Joint forces and moments with perturbed gait data

Figure 2 presents the mean normalized moments about the Z-axis of the ICS obtained, at the knee joint, by the four inverse dynamic methods with perturbed gait data. Table I presents, the mean difference between the joint moments obtained with unperturbed and perturbed gait data expressed in percentage relative to the curve amplitude.

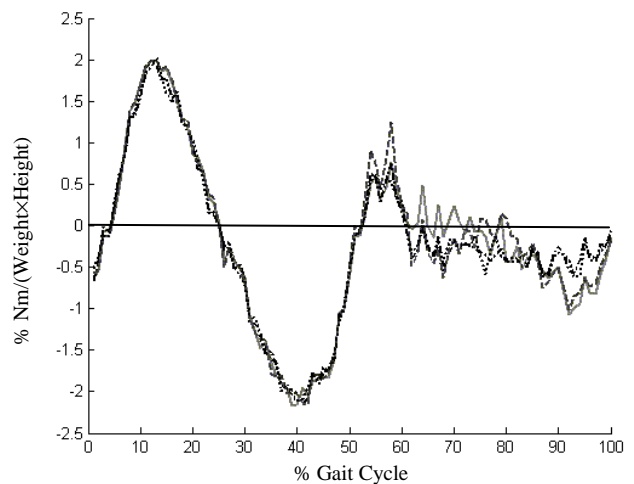


Figure 2. Mean normalized moments (about the Z-axis) obtained with perturbed gait data by the four inverse dynamic methods at the knee joint

The influence of perturbed gait data was found negligible at the ankle joint but important at the knee and the hip joints, especially on the Y-axis of the ICS. However, the moments on the Y-axis (nearly internal-external) correspond to very small curve amplitudes. Again, the difference increased from the ankle up to the hip because the disparities cumulate in the recursive computation. The perturbed gait data were obtained by adding Gaussian noise to previously filtered and solidificated data. This is not entirely realistic but this allows discriminating without bias which method may be more sensitive to a monitored noise.

The influence of perturbed gait was found somewhat more important for the method based on vectors and Cardanic angles and for the method based on the generalized coordinates and forces, indicating higher sensitivity to noise. This higher sensitivity can be due to the differences of formulation in both kinematic and dynamic computations. The Cardanic angles deal with only 3 parameters for the 3 angular degrees of freedom while the quaternions deal with 4 parameters and 1 implicit constraint and while the homogenous matrices deal with 9 parameters and 6 implicit constraints. The sensitivity to noise is reduced in the kinematic computation with redundancy as far as the constraints are implicit (i.e. they are not taken into account in the dynamic computation). Moreover, in the method based on vectors and Cardanic angles, the successive coordinate transformations (from ICS to SCS) do have an effective influence when using perturbed gait data. The generalized coordinates deal with 12 parameters and 6 explicit constraints for all of the 6 (angular and linear) degrees of freedom. The sensitivity to noise is increased because the explicit constraint are taken into account in the dynamic computation and these constraints (especially the rigid body ones) become violated when using perturbed gait data.

TABLE I. MEAN DIFFERENCE EXPRESSED IN PERCENTAGE RELATIVE TO THE CURVE AMPLITUDE

Mean difference / Curve amplitude (in %)	Method	Joint		
		Ankle	Knee	Hip
Moment on X-axis	VC	1	7	9
	WQ	1	4	6
	HM	1	3	6
	GC	1	6	9
Moment on Y-axis	VC	1	27	19
	WQ	1	9	11
	HM	1	9	13
	GC	1	36	49
Moment on Z-axis	VC	1	2	10
	WQ	1	3	9
	HM	1	2	11
	GC	1	2	10

VC: method based on vectors and Cardanic angles  
WQ: method based on wrenches and quaternions  
HM: method based on homogenous matrices  
GC: method based on generalized coordinates and forces

#### IV. CONCLUSION

Four 3D inverse dynamic recursive methods have been reported in the literature. The four methods diverge on both kinematic and dynamic computations, although they follow the same bottom-up scheme. Significant differences have been previously observed with unperturbed data and, in the current study, the influence of perturbed gait data was found important for the knee and the hip joints forces and moments. The influence of perturbed gait was found somewhat more important with the methods based on vectors and Cardanic angles and based on generalized coordinates and forces than with the methods based on wrenches and quaternions and on homogenous matrices. For that, these last methods may be prioritized for 3D recursive inverse dynamics.

#### REFERENCES

- [1] P. Allard, R. Lachance, R. Aissaoui, and M. Duhaime, "Simultaneous bilateral 3-D able-bodied gait," *Human Movement Science*, vol. 15, pp. 327-346, 1996.
- [2] R. B. I. Davis, S. Ounpuu, D. Tyburski, and J. R. Gage, "A gait analysis data collection and reduction technique," *Human Movement Science*, vol. 10, pp. 575-87, 1991.
- [3] J. J. Eng and D. A. Winter, "Kinetic analysis of the lower limbs during walking: what information can be gained from a three-dimensional model?," *Journal of Biomechanics*, vol. 28, pp. 753-8, 1995.
- [4] M. P. Kadaba, H. K. Ramakrishnan, M. E. Wootten, J. Gainey, G. Gorton, and G. V. Cochran, "Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait," *Journal of Orthopaedic Research*, vol. 7, pp. 849-60, 1989.
- [5] C. L. Vaughan, B. L. Davis, and J. C. O'Connor, *Dynamics of human gait*. Champaign, Illinois: Human Kinetics, 1992.
- [6] R. Dumas, R. Aissaoui, and J. A. de Guise, "A 3D generic inverse dynamic method using wrench notation and quaternion algebra," *Computer Methods in Biomechanics and Biomedical Engineering*, vol. 7, pp. 159-66, 2004.
- [7] N. Doriot and L. Chèze, "A three-dimensional kinematic and dynamic study of the lower limb during the stance phase of gait using an homogeneous matrix approach," *IEEE Transactions on Biomedical Engineering*, vol. 51, pp. 21-7, 2004.
- [8] R. Dumas and L. Chèze, "3D inverse dynamics in non orthonormal segment coordinate system," *Journal of Biomechanical Engineering*, Submitted, 2005.
- [9] R. Dumas, E. Nicol, and L. Chèze, "Comparison of four 3D inverse dynamic methods for gait analysis," presented at 30th Congress of the Societé de Biomécanique, 14-16 septembre, Bruxelles, Belgique, 2005.

- [10] G. Wu and P. R. Cavanagh, "ISB recommendations for standardization in the reporting of kinematic data," *Journal of Biomechanics*, vol. 28, pp. 1257-61, 1995.
- [11] L. Chèze, B. J. Fregly, and J. Dimnet, "A solidification procedure to facilitate kinematic analyses based on video system data," *Journal of Biomechanics*, vol. 28, pp. 879-84, 1995.
- [12] R. Dumas, L. Chèze, and J.-P. Verriest, "Adjustments to McConville et al. and Young et al. body segment inertial parameters," *Journal of Biomechanics*, Accepted, 2006.
- [13] M. P. Silva and J. A. Ambrosio, "Kinematic data consistency in the inverse dynamic analysis of biomechanical systems," *Multibody System Dynamics*, vol. 8, pp. 219-239, 2002.