

A Computational Benchmark for 2D Gait Analysis Problems

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Abstract. The aim of this paper is to present a computational benchmark for gait analysis that has been developed in order to share real data captured in a biomechanics laboratory and the results of the inverse dynamic analysis. This work belongs to the library of computational multibody benchmark problems that the Technical Committee for Multibody Dynamics of the International Federation for the Promotion of Mechanism and Machine Science (IFTToMM) is developing. The work presents the kinematic and dynamic study of human motion by means of multibody system dynamics techniques. The subject selected to perform the experiments walks on a walkway that encloses two force plates. The motion is captured by 12 optical cameras that acquire the position of 37 passive markers. The inverse dynamic analysis (IDA) is carried out using a 12-segment 2D model with 14 degrees of freedom. Displacement signals are filtered using an algorithm based on Singular Spectrum Analysis (SSA) and the natural coordinates of the model are calculated using algebraic relations among the marker positions. Afterwards, a procedure ensures the kinematic consistency and the data processing continues with the approximation of the position histories using B-spline curves. The velocity and acceleration values are then obtained by analytical derivation. The double support indeterminacy is solved using the Corrected Force Plate (CFP) sharing method. The IDA provides the joint drive torques that the musculoskeletal system generates during human locomotion from acquired kinematic data, foot-ground contact forces and estimated body segment parameters (BSP). All this information is available online in <http://iftomm-multibody.org/benchmark>. Therefore, it can be viewed by other researchers, which can submit their own results using the same input data or proposing new solutions.

Key words: Gait analysis, Inverse dynamics, Benchmark, Biomechanics.

1 Introduction

The 2D gait benchmark is presented as a tool for researchers to share the gait analysis experience and to discuss different methodologies in a comprehensive reference. The resource is intended to be a tool for facilitating collaboration and for discussing systematic treatment of gait analysis methods. This benchmark includes the kinematics of a full-body model and the reaction forces measured via two force-plate devices. Moreover, the obtained results via an Inverse Dynamic Analysis (IDA), that is, the torques developed by the musculoskeletal system during the movement, are also shared. This information is available in the library of computational benchmark problems, concretely inside the biomechanical models section, and more specifically in the musculoskeletal models folder (<http://iftomm-multibody.org/benchmark>).

The experiments take place in a laboratory that includes an optoelectronic system that captures the motion and two force plates for measuring the foot-ground contact wrench (Fig. 1). The motion data is collected using twelve 100 Hz Optitrack FLEX:V100R2 cameras and the software which provides the 3D trajectories of the thirty-seven passive markers attached to the human body. The foot-ground contact wrenches are measured using two AMTI AccuGait force plates located on a walkway where the subject walks (also sampled at 100 Hz). Each force plate measures the ground reactions on one foot during the gait cycle.

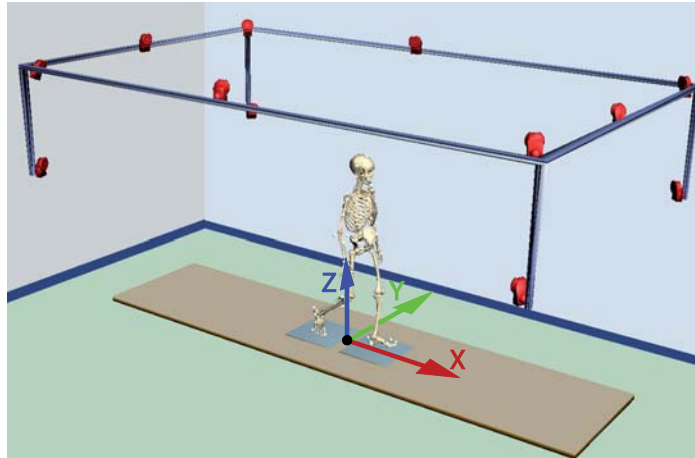


Fig. 1 Gait analysis laboratory configuration.

Marker positions are expressed in the global coordinate system, which is defined using the axes $\{X, Y, Z\}$ (Fig. 1). Each force plate registers the ground reactions on one foot during the gait cycle, obtaining as a result one force (three components) and one moment about the centre of the plate (also three components).

These force and moment components define the mentioned contact wrench at the plate centre.

The recorded motion contains more than one cycle. It covers all instants with force plate information available. It starts at the heel strike of the right foot (0 % of gait cycle), includes also the next heel strike of the same foot (100 %) and finishes at the toe off of the left foot belonging to the next cycle (116 %).

2 Dynamics Modeling

2.1 Biomechanical Model

The human body is modelled as a multibody system formed by rigid bodies, an approach which has been widely used to analyze human gait. The subject selected to perform the experiments is a healthy adult male, 27 years old, mass 80 kg and height 1,75 m. Fig. 2 shows the position of the 37 markers used, and Table 1 contains the anatomical points used to place the markers.

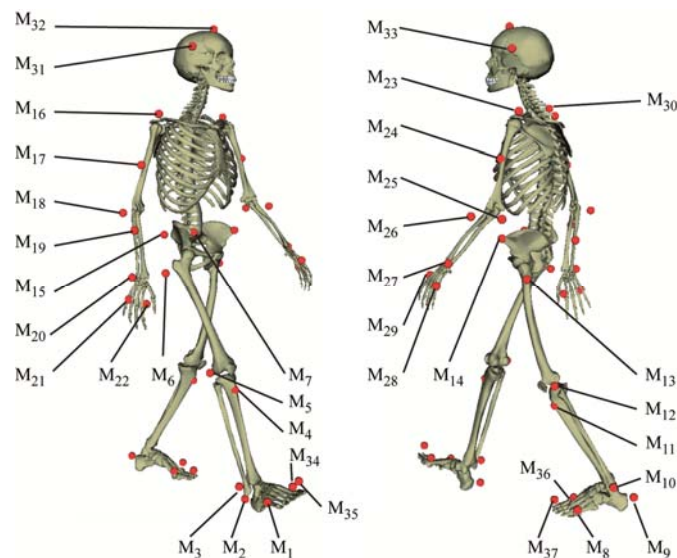


Fig. 2 View of the human skeleton with the considered motion capture marker protocol.

A text file containing the position history of each marker is available on the website. In a similar way, a text file containing the force plate measurements is also accessible.

The natural coordinates of a 3D model are calculated by means of simple algebraic relations among the filtered displacement signals [6].

Table 1. Placement of the set of markers used.

<i>No.</i>	<i>Placement</i>	<i>No.</i>	<i>Placement</i>
M ₁	Right metatarsal head V	M ₈	Left metatarsal head V
M ₂	Right calcaneus	M ₉	Left calcaneus
M ₃	Right lateral malleolus	M ₁₀	Left lateral malleolus
M ₄	Right tibial tuberosity	M ₁₁	Left tibial tuberosity
M ₅	Right lateral femoral epicondyle	M ₁₂	Left lateral femoral epicondyle
M ₆	Right femoral greater trochanter	M ₁₃	Left femoral greater trochanter
M ₇	Right ASIS	M ₁₄	Left ASIS
M ₁₅	Sacrum		
M ₁₆	Right acromion in the shoulder girdle	M ₂₃	Left acromion in the shoulder girdle
M ₁₇	Right deltoid tuberosity	M ₂₄	Left deltoid tuberosity
M ₁₈	Right lateral humeral epicondyle	M ₂₅	Left lateral humeral epicondyle
M ₁₉	Middle of right forearm	M ₂₆	Middle of left forearm
M ₂₀	Right radial styloid in the wrist	M ₂₇	Left radial styloid in the wrist
M ₂₁	Right metacarpal head V	M ₂₈	Left metacarpal head V
M ₂₂	Right metacarpal head II	M ₂₉	Left metacarpal head II
M ₃₀	1 st vertebra of the thoracic spine		
M ₃₁	Right side of the head	M ₃₃	Left side of the head
M ₃₂	Top of the head		
M ₃₄	Right metatarsal head I	M ₃₆	Left metatarsal head I
M ₃₅	Right distal phalange of the third toe	M ₃₇	Left distal phalange of the third toe

The IDA is carried out using a 12-segment 2D model (Fig. 3) with 14 degrees of freedom. X and Z components of the 3D joints are selected to obtain the planar coordinates $\tilde{\mathbf{q}}$. In order to solve the violation of the kinematic constraints (due to skin motion, muscle deformation, and 2D simplification), a new set of coordinates \mathbf{q} is calculated by imposing the kinematic consistency at position level through a minimization problem:

$$\min_{\mathbf{q}} V = \frac{1}{2}(\mathbf{q} - \tilde{\mathbf{q}})^T \mathbf{W}(\mathbf{q} - \tilde{\mathbf{q}}) \quad \text{s.t.} \quad \Phi(\mathbf{q}) = \mathbf{0} \quad (1)$$

where \mathbf{W} is a weighting diagonal matrix that allows assigning different weights to the coordinates. Higher weighting factors are associated to those coordinates with lower expected error. The minimization is only subjected to scleronomic constraints $\Phi(\mathbf{q}) = \mathbf{0}$, and \mathbf{q} includes only the end points of the segments. The process used to guarantee kinematic data consistency follows an augmented Lagrangian minimization process as described in [2].

From the kinematically consistent data set obtained above, a set of independent coordinates \mathbf{z} is calculated: the two Cartesian coordinates of the proximal pelvis joint (P_4), and the relative orientation of each segment (see Fig. 3)

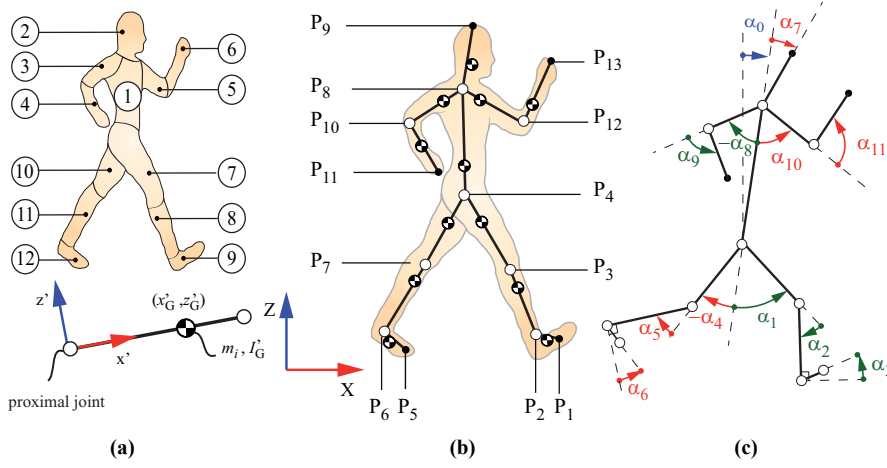


Fig. 3 Two-dimensional biomechanical model: (a) Body numeration, (b) points used to define the configuration, (c) biomechanical angles.

The obtained signals usually present low-amplitude high-frequency noise, which is amplified when numerical differentiation is used to calculate their corresponding velocities and accelerations. In this work, a filter based on Singular Spectrum Analysis (SSA) is applied to the displacement signals [1]. The algorithm decomposes the original signal into independent additive components with decreasing weight. This processing facilitates extracting the signal latent trend from the inherent random noise that the motion capture process introduces. Moreover, the algorithm only requires the selection of two parameters, namely, the window length (L) and the number of components to use for reconstruction (r). A way to overcome the uncertainty in the choice of L is to apply sequentially the SSA filter, as explained in [1]. When this sequential procedure is applied, the results are not very sensitive to the window length. In this work, the SSA filter is applied three consecutive times, the window length is fixed as $L = 10$ and the two main components of the decomposition are used in the signal reconstruction.

The data processing continues with the approximation of the position histories using B-spline curves and obtaining, by analytical derivation, the velocity and acceleration values: for each coordinate of the independent coordinate vector \mathbf{z} , and for a given tolerance, a B-spline form of the temporal function is calculated. De Boor algorithm with a tolerance of 10^{-9} , which guarantees that the RMSE between the original data and the new values is less than 0,001 %, is used [3]. The B-form function of the input data is obtained and, the velocities $\dot{\mathbf{z}}$ and the accelerations $\ddot{\mathbf{z}}$ can be obtained using analytical spline differentiation techniques. Consequently, the kinematic data set required to perform the IDA is completely known $(\mathbf{z}, \dot{\mathbf{z}}, \ddot{\mathbf{z}})$, and it is consistent with the rigid body assumption of the multi-body system at position, velocity and acceleration levels. The resulting X and Z

coordinates of the points P1, P2, ..., P13, and the biomechanical angles shown in Fig. 3 are also available on the website.

Finally, in order to complete the biomechanical model definition, the anthropometric parameters are needed. They are summarized in Table 2. It should be noted that the moment of inertia of the segments is referred to their COM.

Table 2. Anthropometric data for the 2D model with twelve segments

No.	Name	Length	COM Location		Mass	Principal Moment of Inertia
			L_t [m]	x'_G [m]		z'_G [m]
1	Trunk	0,498	0,230	0	37,801	44,448
2	Head	0,136	0,139	0,039	5,119	2,163
3	Right arm	0,311	0,146	0	1,922	1,190
4	Right forearm	0,267	0,171	0	2,299	0,974
5	Left arm	0,311	0,146	0	1,922	1,190
6	Left forearm	0,267	0,171	0	2,299	0,974
7	Right thigh	0,417	0,154	0	9,284	12,215
8	Right shank	0,422	0,170	0	4,008	5,153
9	Right hindfoot	0,143	0,037	-0,023	1,027	0,441
10	Left thigh	0,417	0,154	0	9,284	12,215
11	Left shank	0,422	0,170	0	4,008	5,153
12	Left hindfoot	0,143	0,037	-0,023	1,027	0,441

2.2 Multibody Formulation

The equations of motion are expressed as:

$$\begin{cases} \mathbf{M}\ddot{\mathbf{q}} + \Phi_{\mathbf{q}}^T \lambda = \mathbf{Q} \\ \Phi(\mathbf{q}) = \mathbf{0} \end{cases} \quad (2)$$

Once the histories of the independent coordinates \mathbf{z} , and their time derivatives, $\dot{\mathbf{z}}$ and $\ddot{\mathbf{z}}$, have been obtained, the inverse dynamics problem is solved by means of the velocity transformation formulation known as matrix-R, which provides the required actuation in the form of generalized forces associated to the independent coordinates \mathbf{z} [4]:

$$\mathbf{R}^T \mathbf{M} \mathbf{R} \ddot{\mathbf{z}} = \mathbf{R}^T (\mathbf{Q} - \mathbf{M} \mathbf{S} \mathbf{c}) \quad (3)$$

which can be rewritten as:

$$\mathbf{R}^T \mathbf{M} \mathbf{R} \ddot{\mathbf{z}} = \mathbf{R}^T (\hat{\mathbf{Q}} - \mathbf{M} \mathbf{S} \mathbf{c}) + \mathbf{Q}_m \quad (4)$$

being $\mathbf{R}^T \mathbf{Q} = \mathbf{R}^T \hat{\mathbf{Q}} + \mathbf{Q}_m$, where $\hat{\mathbf{Q}}$ are the known generalized forces associated to constant forces or forces that only depend on the system states (such as the gravitational forces), and \mathbf{Q}_m are the generalized forces associated to the independent coordinates, i.e., the unknowns of the inverse dynamics problem:

$$\mathbf{Q}_m = \mathbf{R}^T \mathbf{M} \mathbf{R} \ddot{\mathbf{z}} - \mathbf{R}^T (\hat{\mathbf{Q}} - \mathbf{M} \mathbf{S} \mathbf{c}) \quad (5)$$

Nevertheless, since the independent coordinates \mathbf{z} are the position of the lumbar joint and the absolute angles of all the bodies, the generalized forces \mathbf{Q}_m calculated via IDA do not correspond to the actual contact forces and the net joint motor torques. Therefore, in order to obtain the joint motor torques, the contact wrench must be expressed at its actual location, i.e., the contacting foot/feet. The procedure to obtain the actual forces and torques involves different steps as it is explained in [5]. During the single support phase, the problem is determined, so that, the resultant reaction can be translated to the contacting foot, and the actual joint torques can be recalculated properly equating their corresponding generalized forces to those obtained when the contact wrench acts on the pelvis. However, during the double support phase, how this wrench is shared between the two foot-ground contacts is unknown and a sharing criterion has to be used for estimating the amount of the total wrench assigned to each foot. This benchmark uses the Corrected Force Plate (CFP) method developed by the authors [5].

The obtained results are the inverse dynamic wrenches (see Fig. 4). They start at the toe off of one foot, include one double support, and finish at the heel strike of the other foot. The online results file contains the contact reactions at each foot ($\mathbf{F}_1, \mathbf{M}_1, \mathbf{F}_2, \mathbf{M}_2$) and the joint torques (τ_1, \dots, τ_{11}). Note that the index of the joint torques τ_i is the same as the angle index α_i .

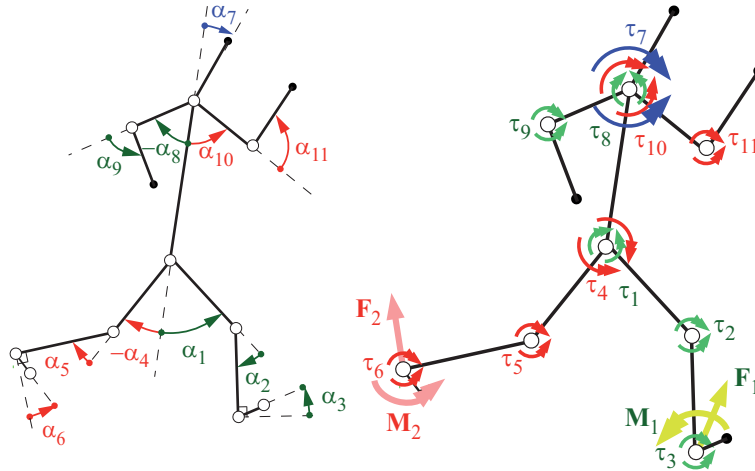


Fig. 4 Joint angles, external reactions and joint drive torques

3 Conclusions

A computational benchmark for 2D gait analysis has been presented. A multibody methodology for the dynamic analysis of human motion has been implemented. The inverse dynamics problem is addressed with the aim of calculating the musculoskeletal forces developed at the anatomical joints of the human body while performing a prescribed movement. For this purpose the CFP sharing method has been used.

In order to share all the results, the library tool provided by the Technical Committee for Multibody Dynamics of the International Federation for the Promotion of Mechanism and Machine Science (IFTOMM) is used. All the input data and also the output results have been uploaded, so that researchers can compare the obtained forces and torques using their own method for inverse dynamic analysis of gait. Moreover, the data can also be used to perform a forward dynamics simulation. Finally, visual information regarding the captured motion and the obtained 2D data is available on the website.

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