Simulation Results

Several methods have been proposed in the literature to combine the measured motion with the measured reactions in order to obtain the joint torques. Depending on the selected approach, different results can be obtained. This file explains the methodology used to obtain the IDA results.

Input data file contains the raw information recorded at the laboratory. In order to compute the IDA, force plate data and position information are filtered using singular spectrum analysis (SSA). The window length is fixed as $L = 10$ and the two main components of the decomposition are used in the signal reconstruction.

A text file containing the filtered force plate results, "ForcePlates_Filtered.dat", can be found in the miscellaneous file. The first column contains the captured time from 0 to 1,56 s with an increment of 0,01 s. Columns 2, 3, and 4 contain the filtered contact force from force plate 1 (see Figure 1), and columns 5, 6 and 7 provide the moment components of the contact wrench about the centre of force plate 1. The filtered results obtained from force plate 2 are stored in columns 8 to 13.

Moreover, for each component of the filtered independent coordinate vector, a B-spline from its time history is calculated using the MATLAB function "spaps".The absolute angle α_0 is obtained using a tolerance of $5\cdot 10^{-6}$, the relative angles are processed using a tolerance of 10^{-6}, and finally 10^{-8} is used as the tolerance for the point position P_4. Since the "spaps" function returns the B-form function of the input data, the velocities and the accelerations can be obtained using analytical spline differentiation. The processed independent coordinates are shown in "Processed_Ind_Coordinates.dat". Also in this case, the first column contains the time vector, columns 2 and 3 contain the position of the point P_4, and the remaining columns contain the angular coordinates from α_0 to α_{11}.

The joint positions are obtained by solving the position problem for the filtered independent coordinates. These positions guarantee the kinematic consistency of the model with a tolerance of $2{\cdot}10^{-15}$. Text file "Points.dat" provides this information. As previously, the first column contains the time vector. The other columns contain the position of the points P_1, P_2, ..., P_{13}: columns 2 and 3 contain the X and Z coordinate of the first point P_1 (see Figure 5, problem description file); the position of P_2 is expressed in columns 4 and 5, etc.

In this solution, the inverse dynamic analysis is carried out using only the angular coordinates and the position of the pelvis joint (P_4), not the force plate measurements. As a result a net external reaction is obtained, in this case expressed as acting at the pelvis joint. In contrast, AMTI force plate provides the three orthogonal components of the foot-ground contact force and moment acting at their respective centres. In order to make these wrenches comparable, they have been properly translated to a common point, namely the projection of the pelvis joint onto the ground.

The time interval when these wrenches are comparable starts at the toe off of one foot, including one double support, and finish at the heel strike of the other foot. Figure 8 shows the comparison of the net external reaction obtained from inverse dynamics and from the force plate data. As error indicator, the root mean square (RMS) deviation is used. Since My depends on both, F_z and the location of the centre of pressure, the RMS error related to the moment M_y is adopted as accuracy indicator of the model.

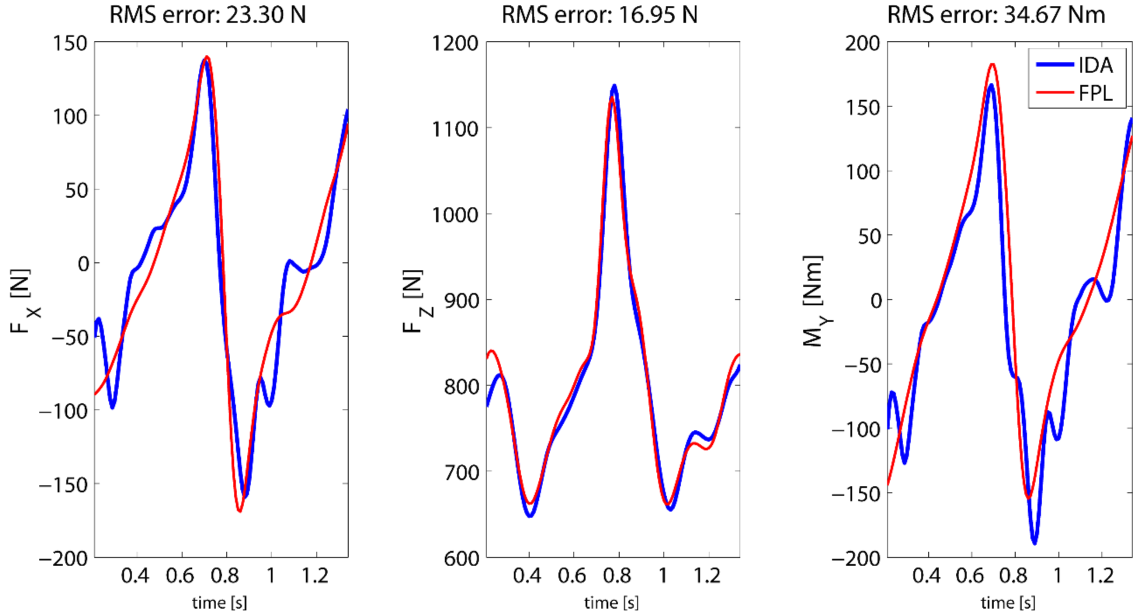

Figure 8. Comparison of the total contact wrenches obtained from inverse dynamics (IDA) and from the force plate data (FPL).

In the proposed solution, the force plates measurements are used to solve the ground reaction sharing problem during the double support phase. In this phase, both feet contact the ground, thus rendering kinematic measurements alone insufficient to determine the individual wrench at each foot. The contact wrench calculated from inverse dynamics, $\tilde{\mathbf{G}}$, must be shared between both feet along the double support phase, i.e., between the heel strike of the leading foot, time instant t_h, and the toe off of the trailing foot, time instant t_t. $\tilde{\mathbf{G}}^{gr}$, $\mathbf{G}_{FP1}^{gr}$ and $\mathbf{G}_{FP2}^{gr}$ are, respectively, the IDA wrench $\tilde{\mathbf{G}}$ and the force plate wrenches $\mathbf{G}_{FP1}$ and $\mathbf{G}_{FP2}$ (see Figure 9) translated to the projection of the lumbar joint onto the ground.

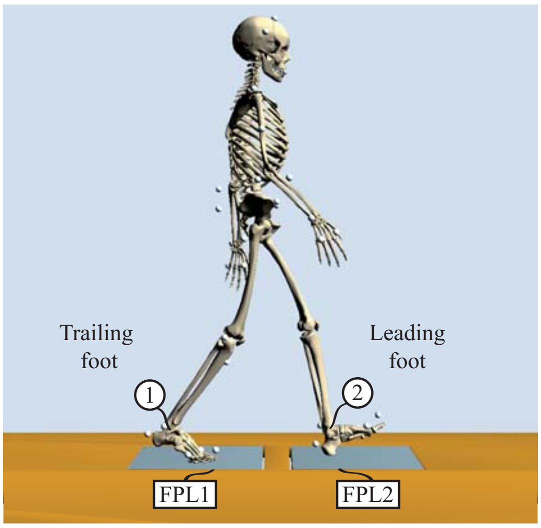

Figure 9. An instant of the double support phase.

Thus, the residual between the calculated and measured reactions, $\boldsymbol{\varepsilon} = \tilde{\mathbf{G}}^{\text{gr}} - \mathbf{G}^{\text{gr}}_{\text{FP1}} - \mathbf{G}^{\text{gr}}_{\text{FP2}}$, can be split and added to each of the force plate values to make their resultant consistent with the inverse dynamics. This residual is a 6-row vector that contains the differences between the two curves of each plot in Figure 8 (only during double support).In order to avoid discontinuities between single and double support, the correction amount applied to each foot is proportional to the relative magnitude of its measured reaction, by means of the following functions:

$$\mathbf{G}^{\text{gr}}_{1}(t) = \mathbf{G}^{\text{gr}}_{\text{FP1}}(t) + \frac{\left|\mathbf{G}^{\text{gr}}_{\text{FP1}}(t)\right|}{\left|\mathbf{G}^{\text{gr}}_{\text{FP1}}(t)\right| + \left|\mathbf{G}^{\text{gr}}_{\text{FP2}}(t)\right|}\boldsymbol{\varepsilon}(t) \qquad t_h \le t \le t_t$$
$$\mathbf{G}^{\text{gr}}_{2}(t) = \mathbf{G}^{\text{gr}}_{\text{FP2}}(t) + \frac{\left|\mathbf{G}^{\text{gr}}_{\text{FP2}}(t)\right|}{\left|\mathbf{G}^{\text{gr}}_{\text{FP1}}(t)\right| + \left|\mathbf{G}^{\text{gr}}_{\text{FP2}}(t)\right|}\boldsymbol{\varepsilon}(t) \qquad t_h \le t \le t_t$$

where $\mathbf{G}^{\text{gr}}_{1}$ and $\mathbf{G}^{\text{gr}}_{2}$ are the wrenches at the trailing and leading foot respectively translated to the projection of the hip onto the ground. After this sharing process, the wrenches $\mathbf{G}^{\text{gr}}_{1}$ and $\mathbf{G}^{\text{gr}}_{2}$ are properly translated to the corresponding ankle joints obtaining the actual wrenches $\mathbf{G}_1$ and $\mathbf{G}_2$. At this point, and using the principle of virtual power, the actual internal joint torques ($\tau_1 \ldots \tau_{11}$) are calculated[1]: a system of motor torques and external reactions is equivalent to another one as long as their corresponding generalized forces coincide.

The final results obtained using the proposed method are shown in results.txt file.

[1] *Lugris, U., Carlin, J., Luaces, A., Cuadrado, J., 2013.* “Gait Analysis System for Spinal Cord-injured Subjects Assisted by Active Orthoses and Crutches”. Journal of Multi-body Dynamics, 227 (4), pp. 363–374.