About Kinematic Consistency in the Inverse Dynamics Problem in Biomechanics

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Abstract: *The inverse dynamic analysis is used in the study of the human gait to evaluate the reaction forces transmitted between anatomical segments and to calculate the net joint moments resulting from the muscle activity in each joint. There are two approaches well defined. In the clinical field reconstruction techniques are often applied. The errors caused, mainly, by the relative movement of the skin over the bones make that the joint centres localized in two adjacent segments do not place the same position in the space. Velocities and accelerations are obtained through numerical derivation of the position. Finally, joint moment are calculated to balance the equilibrium equations. On the other hand, the engineers employ multibody models. They apply techniques to reduce the measurement errors and to obtain kinematically consistent data up to the acceleration level and calculate reaction and driving actions by means of the Lagrange multipliers. There is no agreement about which approach provides better results. The first procedure presents errors due to the skin motion which are avoid in the second method introducing errors inherent to the model. In this work, the two approaches were compared. Dynamic residuals defined to balance the Newton's equations were used as a measure of the model goodness. A discussion about the effect of the kinematically inconsistent data on the second approach was carried out. Results highlighted that the addition to the recorded motion of kinematic constrains according to a multibody model could lead to worse results in the inverse dynamic problem.*

Keywords: Biomechanics, Gait analysis Kinematic inconsistency, Dynamic residuals

I. Introduction

The musculo-skeletal system can be modeled as a multibody system which degrees of freedom depend on the number of segments considered as well as the kinematic constrains considered between them [1], [2]. Generally, at least three markers must be located on each segment in order to measure the location and orientation of the segment, considered rigid, in space. Therefore, there is no need to consider kinematic constrains in the model given that six degrees of freedom are measured for each rigid body considered in the model.

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The approach, which does not consider kinematic constrains to model joints, allowing six degrees of freedom in each segment, is the most employed in the clinics field. This procedure is commonly used in commercial codes as Vicon [3] and by many other researchers [4].[5].[6]. As the motion of each segment is reconstructed separately, without modelling joint articulations with kinematical constraints, unrealistic motions such as important joint dislocations may occur. The use of kinematic constraints overcome this problem easily [7] This approach, which reduces the number of degrees of freedom in the joints by adding kinematic constrains, is the preferred by the multibody community.

Despite widespread use, it is well recognized that inverse dynamics solutions are prone to errors. Errors can stem from a variety of sources including inaccuracies in body segmental parameters (BSP), inaccuracies in measurements, inaccuracies related to locating joint centers, etc. But the main source of error in the kinematic data obtained from marker-based motion capture system is. the skin motion artifact, also known as soft tissue artefact(STA). STA are interdependently caused by the inertial effects,the skin deformation and the deformations due to muscle contractions. Such perturbations typically contain frequencies similar to gait frequencies and consequently cannot be removed by only filtering. It has been shown that only motion about flexion axis of the hip, knees and ankles can be determined reliably. Motion about other axes at those articular joints should be regarded with much more caution as STA produces spurious effects with magnitudes comparable to the amount of motion actually occurring in those joints. Efforts have been made to improve measurement techniques to minimize STA [8] but they cannot be eliminated unless markers are applied to the bones directly or through bone-pins [9] It is particularly important to develop and apply a corrective method that compensates for skin movement artifact. The motion of the skin makers can be minimized by least square methods or redundancy as the cluster method or can be specifically modeled [10], [2]. One of the methods belonging to the first category is called Local Optimization Method (LOM). This approach is based on a least squares pose estimator, separately for each body segment. The model-determined configuration of the markers is fitted to the measured configuration in a least squares sense. This method reconstructs the motion of each segment separately without kinematic constrains. There are also methods belonging to the first category that impose kinematical constrains to avoid joints dislocations. In this case the optimization process is based on a minimization of the weighted sum of squared distances between experimental and model-determined marker positions, while ensuring kinematic consistency of the motion by applying kinematic constraints. This method is known as the Global Optimization Method (GOM). GOM is most used by the multibody community. It uses ideal joints to model biomechanical joints. A large number of models published in the specialized literature use simple joints as revolute, spherical or universal joints. Generally it is accepted that kinematic consistent data obtained with the model improve the kinematic reconstruction of the musculo-skeletal system. Reconstructed data does not present dislocated joints, but errors arising from an inadequate modeling of the joint articulation can strongly bias the estimated motion [11]. Using idealized knee joint constraints have the drawback of limiting or eliminating actual bone motions [12]. Therefore, the addition of a spherical or revolute joint constraint may result in a source of error that is being introduced to minimize a second source of error (the STA) [13]. Thus, adding joint constraints can improve the ability of skin marker-based kinematic data to represent the actual motion of the underlying bones only if the error introduced by the joint constraints is smaller than the STA error.

Data measure by the motion capture system can be processed in many different ways. Different choices should be made. For instance, whether kinematic constrains are implemented or whether methods to reduce STA errors are implemented. The selected procedure yields different inverse kinematics and consequently different inverse dynamics. It's difficult to know which procedure gives the better reconstructed data. A challenging problem in gait biomechanics is the experimental validation of the results. Most methods for STA compensation have been tested using just numerical experiments[9]. Few experimental validations have been conducted based on a comparison between the estimated motion and in vivo measured motion. Andersen et al.[13]used the data described by Benoit et al.[12] which includes simultaneously recorded skin and bone-mounted pin markers for the thigh and shank for six healthy male subjects measured during gait. Knee motion estimated with GOM using different kinematic models was compared to in vivo measurements concluding that the use of simple knee models produces errors in the analysis larger than those induced by the STA.

There are several published studies about the influence of different parameters in inverse dynamic solutions, but none of them analyze the influence of the use of simple kinematical joints. Six degree of freedom joints method presents measurement errors due principally to skin movement while including simple joints introduces errors associated to a predicted relative motion of the joints.

Dynamic residuals will be used as a measure of the goodness of the procedure. These residuals are artificially defined to balance the Newton's equations which are not usually verified due to the errors introduced through the whole procedure.

II. Material and methods

A. Experimental set-up

An experiment has been designed to obtain quantitative data of normal walking. Gait analysis was carried out on one adult male subject with no pathologies in gait using a modified Newington gait model (MoPiG) [11] as set of markers used to defined the position and orientation of the different parts of the human body, Fig. 1. The marker trajectories were measured at 100 Hz using a Vicon six-camera motion capture system. Ground reaction forces were recorded with two AMTI force plates and a sample frequency of 1000 Hz.

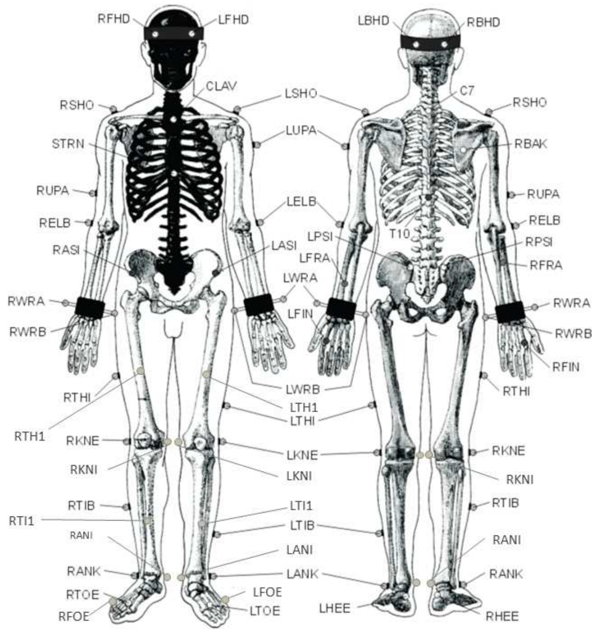

Fig. 1. MoPiG markers placement

B Kinematics

The position in the space of the musculo-skeletal system is described by means of the multibody system techniques, considering a segmentation of the human body. A formulation based on dependent cartesian coordinates and Euler parameters was used to define each segment. Motion equations defined this way are easy to implement and the formulation is free from singularities. As an inconvenience, this formulation requires a higher computational effort because of the additional constrain equations introduced by the Euler parameters. In any case, the analysis developed in the present work was independent of the formulation employed.

C Body pose reconstruction methods

Four different approaches have been implemented to reconstruct the position and orientation of the different segments of the human body during gait through the position of the markers attached to the skin.

UNO: The method is named UNO for un-optimized and is based on the Newington-Helen Hayes gait [3]. It calculates biomechanical segment lengths (distance between the joint centres) from the static trial. Rigid segments are defined frame-by-frame. Each segment is defined by an origin (generally located at the proximal joint centre) along with three orthogonal axes which are defined at every frame from the external markers. This method yields dislocations and residuals, since the constant length segment does not coincide in every frame with the distance between the joints centres, as the local position of the markers does not coincide either with those obtained in the static trial, mainly due to STA. It is important to highlight that the position obtained by means of the markers set with UNO is completely independent of the way the joints are modelled.

KC: The procedure proposed by Silva and Ambrosio [7] consists in assembling the model and using the independent coordinates obtained from the marker set as the parameters that locate and orient the model. In this procedure, independent coordinates are reconstructed in the same way than in UNO, while dependent coordinates are computed by imposing kinematic constraints. This method has been named KC, for kinematic constraint, in this work. To eliminate the dislocations existing at the joints the segments are artificially moved, thus increasing their marker residuals. Therefore, this method produces bigger residuals than the previous one but eliminates the dislocations, yielding kinematically consistent results.

LOM: The goal of this procedure is to minimize the differences between the position of the markers experimentally obtained and the position of the markers. Model-determined marker positions correspond to the positions of the markers estimated under the assumption that they were rigidly attached to the corresponding segment of the model.

GOM: In GOM, optimization of the residuals is performed simultaneously in all segments subject to kinematic constrains. A set of parameters can be defined to weight the errors associated to the markers placed on the segment.

D Inverse Kinetics

Solving equations of motion leads to a determined problem during the single-support phase because the motor torques can be derived by equating the corresponding generalized forces to those obtained with the external forces (the inertial forces, the weights and the ground reaction forces). However, during the double-support phase the problem results in an overdetermined system of equations because ground reaction forces are applied as input data instead of unknown external loads which originates the motion. The introduction of these extra measurements associated to a segment, typically the pelvis, reduces the number of unknowns. The inverse dynamics problem for the case of measured ground reaction forces can be solved by introducing residuals forces and moments. These variables correspond to external forces and moments that would have to be applied to the model to make the input data and the model compatible. It is clear that these residuals would equal zero if the mechanical model reproduces perfectly the real system and if there were not errors in the input data. Since the models are far from perfect and the input data always contain some amount of error, the vector of residuals is always unequal zero. Therefore, the magnitude of the vector of residuals gives an idea of the relevancy of the simulation, including the kinematic data, the mechanical model and the ground reaction forces measurements.

E Mechanical Model

The mechanical model is composed of two feet, two shanks, two thighs, one pelvis, one trunk, one head, two upper-arms, two forearms and two hands.

III. Results

Results section was divided in two subsections. First it was discussed whether the use of ideal kinematical constrains improves the kinematic and kinetic results. In the second subsection, a multibody model with imposed kinematic constrains was assumed. It was discussed the effect of considering kinematic consistent or inconsistent data.

Results shown were obtained for one subject and eight trials. Just one subject was analyzed because the main objective of the work was to show the influence on the kinematics and kinetics of different data manipulation using the same set of data. A statistical analysis would have partially hidden these differences in the scattering of the results. Only results for the lower limb were presented as they were the most relevant for gait analysis.

A On the use of kinematic constrains

A gait cycle has been analyzed (heel strike at 0 and 100% of the cycle) using four different approaches mentioned above. The difference between these procedures may be the imposed kinematic constrains, or the method to reconstruct the kinematics or both. The first approach, used UNO, to reconstruct position. Velocity and acceleration vectors were got by double derivation of the position vector. No kinematic constrains were imposed. The model used in this work has 90 coordinates and 90 degrees of freedom. Therefore, all the coordinates were independent.

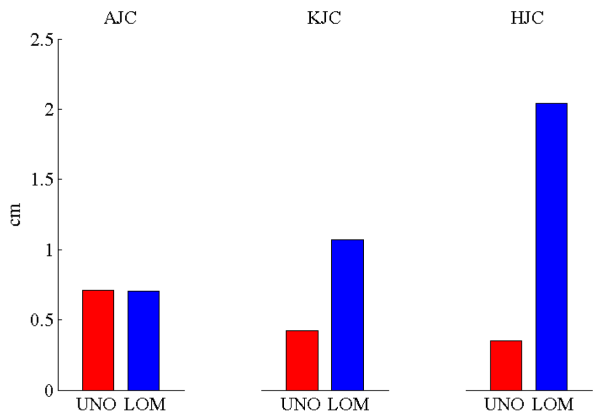

Fig. 2. Average values of dislocations at the lower limb joints (AJC: ankle. KJC: knee. HJC: hip) obtained with UNO and LOM

The second used LOM, which did not impose the kinematic constrains neither, but it reconstructed the kinematics through a minimization of the markers residuals to minimize the STA. Because kinematic constrains were not imposed, this approach also yielded joint dislocations, as it can be seen in Fig. 2. Logically, because of the optimization process applied, marker residuals were smaller than with the previous approach, as shown in Fig. 3.

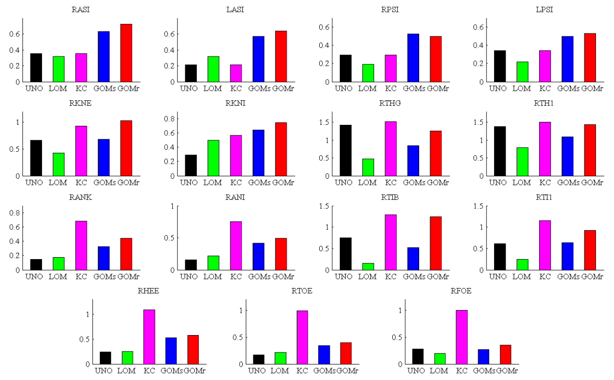

Fig. 3. Averaged values of marker residuals for the different approaches implemented in this work. Markers position shown in Fig.1

The third procedure was the KC method. It imposed kinematic constrains but it did not use any additional method to reduce STA errors. Position, velocity and acceleration vectors were obtained from constrain equations, but independent coordinates were got directly from raw data, in the same way as UNO did. Therefore, the degree of freedom coordinates were contaminated by STA errors. In this work spheric joints had been selected for all joints, and therefore, the number of degrees of freedom reduced to 48. Marker residuals were shown in Fig. 3.

The fourth method, GOM, shared with KC that kinematic constrains were imposed. But, as LOM did, it reconstructed the kinematics minimizing the marker residuals to reduce STA errors. While LOM reconstructed each segment separately, GOM optimized all segments together as kinematic constrains should be satisfied. The method was implemented in two ways yielding the two last approaches. First, modelling all the joints as spheric joints. Second, modelling the knee joint as revolute joint. In this case the number of degrees of freedom reduced to 44.

In Fig. 4 joint angles calculated using the five procedures (UNO, KC, LOM and the cases of GOM) were compared. The implemented formulations yielded the position and orientation of each segment. Once the position and orientation of each segment was calculated, joint angles were expressed as the rotation of one segment relative to another. These relative angles were expressed in the proximal body reference system.

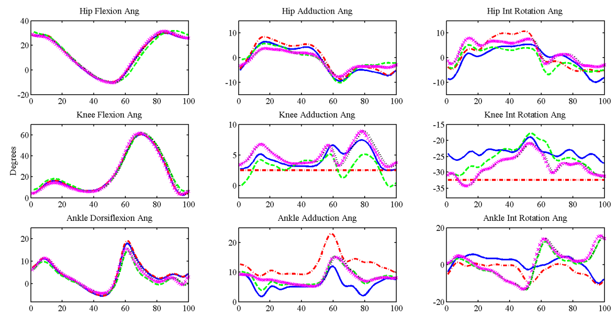

Fig. 4. Temporal evolution of joint angles. In black and dotted lined, UNO. In green and dashed line, LOM. In magenta and crosses, KC. In blue and solid line, GOM with spheric joint. In red, and dot-dashed line, GOM with revolute joint

It was observed that flexion angles were very similar while abduction-adduction and internal-external angles were more sensitive to the procedure implemented.

Inverse kinematics results using UNO and LOM were very similar in the ankle. The differences increased in knee and hip joints although time evolution was quite similar. The introduction of kinematic constrains using KC did not modify the independent coordinates evolution, as explained before. UNO and KC joints angles were identical. The same did not occur with the dependent coordinates. So, inertia forces using UNO and KC were very different, what was crucial for kinetic results, as it will be seen later in this section. GOM significantly changed the kinematics out of sagittal plane, because the position and orientation were greatly modified to avoid dislocations during the minimization of the marker residuals.

It has been shown that imposition of kinematic constrains introduced great changes in kinematic variables. The same did not occur with kinetic variables. The moments plotted in Fig. 5 were very similar no matter the procedure used, although there were slight differences.

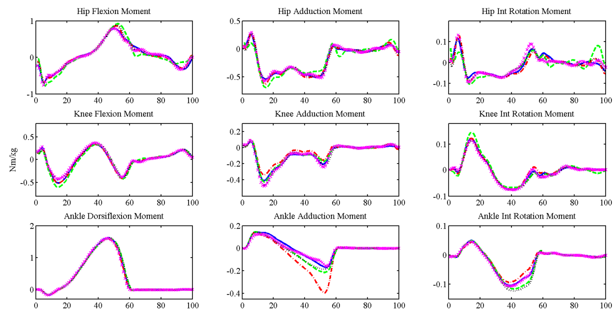

Fig. 5. Temporal evolution of joint moments. In black and dotted lined, UNO. In green and dashed line, LOM. In magenta and crosses, KC. In blue and solid line, GOM with spheric joint. In red, and dot-dashed line, GOM with revolute joint. In magenta and crosses, kc method.}

Reaction forces balance the external forces applied to the system, including the inertia forces. In inverse kinetics, generalized reaction forces include generalized driving forces, since the law motions of the independent coordinates are introduced as kinematic constrains. Both the gravitational and the plates reaction forces were independent of the procedure applied in the inverse kinematics. However, the joint angles changed, as it was shown in Fig. 4, modifying, as a consequence, the accelerations and the inertial forces. It must be recall that position, velocity and acceleration of independent coordinates of KC and UNO coincide. However, though not shown, those of the the dependent coordinates were different since the calculation procedure was different. The different position obtained in each case may affect the moments. However, the moments were very similar with both procedures (see Fig. 5), despite the substantial differences found in position, particularly in the abduction and internal rotations. This result shows that the forces driving these degrees of freedom were not very significant in the joint moment calculations.

As stated before, the ground reaction forces were implemented as external forces. Since these forces were more important than inertial forces, the changes in these last ones had low influence in the global result, as it has been noticed in the literature [4]. The joint moments showed in Fig. 5 were taken as driving moments in all cases except for the case where the knee was modelled as a revolute joint. In this case the adduction and the internal rotation joint moment at the knee were reaction moments. This consideration is crucial in the estimation of muscles forces, given that only the driving moments (and not the reaction moments) use to be implemented in the algorithms to estimate muscle forces.

Analyzing Fig. 4 and Fig 5, it was observed that kinetic results in accordance with previous studies were achieved, no matter the procedure used whereas kinematic results presented higher divergences. In other words, changes on kinematics (position, velocity and acceleration) had a minimal effect on the kinetics.

Marker residuals were widely used in the literature [14] to quantify how well the model fit the experimental results. The total error measured by the marker residuals included not only the error due to the model but also the errors contained in the measurement process, being the STA the error with more importance in the gait analysis. GOM was introduced, mainly, to reduce the STA. However, if the error introduced by the simplifications of the model was higher than the STA error, the results with UNO would be more accurate than results obtained with GOM.

According to Fig. 3, it seemed that LOM provided the lowest values of marker residuals, which could lead to conclude than LOM yielded the best kinematics. However, the estimation of marker residuals seemed not enough to evaluate the goodness of the procedure, for it was necessary to consider the joint dislocations as well [14]. Considering both results simultaneously (Fig. 2 y Fig. 3) UNO provided better results than LOM. Even GOM yielded a good combination of results (moderate marker residuals but no dislocations). KC method provided, in general,the highest marker residuals because no optimization was carried out. Instead, segments were simply moved to prevent dislocations, but keeping their orientation and this led to higher residuals in most of the markers.

The previous analysis was just a kinematic analysis. It was not discussed the validity of the approaches in a kinetic level. Therefore, the dynamic residuals were defined to carry out this analysis. The inertial forces, the weights and the ground reaction forces should be balanced. Because of the experimental and numerical errors in the procedure, three residual forces and three residual moments rose, which were represented in Fig. 6 in the five cases.

The obtained results showed that UNO was the procedure with lower values of dynamic residuals. These results were in agreements with experimental results using markers attached directly to the bones [13] and with data taken from the literature [15]}. Andersen et al. [13] reported that spherical and revolute joint did not simulate properly the knee mobility.

Regarding the analysis carried out the evaluation of the different approaches should be made from three points of view: marker residuals, dislocations and dynamic residuals. UNO provided the best dynamic residuals although joint dislocations came up with this approach. LOM produced the lowest marker residuals but high joint

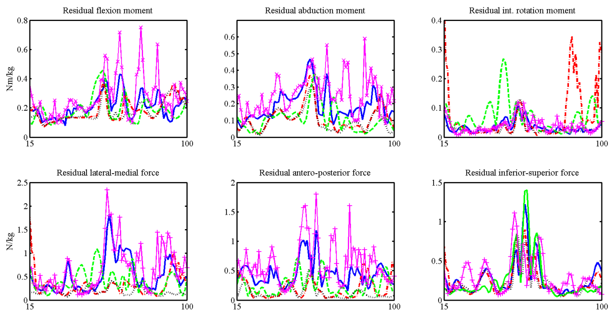

Fig. 6. Temporal evolution of dynamic residuals. In black and dotted lined, UNO. In green and dashed line, LOM. In magenta and crosses, KC. In blue and solid line, GOM with spheric joint. In red, and dot-dashed line, GOM with revolute joint. In magenta and crosses, kc method.

dislocations were presented in this method. The approaches where kinematic constrains were imposed did not produced joint dislocations but they presented big marker residuals. Regarding kinetic results, these approaches, GOM and KC, also provided high dynamic residuals. However, no significant differences appeared if only the sagittal plane was considered. It could be observed, for instance, that the changes on the flexion angles were much smaller than the range of motion.

B Kinematic consistency

The inclusion of kinematic constrains in models of the human locomotor system does not always lead to better results, as it was established in the previous section. However, it is a usual practice among the engineers that works on the motion analysis. It has been discussed in the literature that kinematic inconsistent data can produce spurious moments to compensate joint dislocations. The objective of this section is to show that the use of kinematic inconsistent data does not necessarily lead to unrealistic joint moments but to the same moments than using an unconstrained formulation, that is, UNO method. Therefore, it does not have to produce worse results than kinematic consistent data.

Three approaches were analyzed in this section for a multibody model with only spherical joints. First,GOM, in which position, velocity and acceleration are kinematically consistent. Second, an approach where the constrains of the model were not imposed. The position, velocity and acceleration obtained with this approach were kinematically inconsistent. This method was equivalent to the UNO method defined previously. Finally, an approach called partially consistent method (PCM). In this method, the position problem was solved like in UNO, but the velocity and acceleration
problems were solved by imposing the kinematic constraints of spherical joints, like in GOM. Then, it is kinematically inconsistent at the position level and consistent at the velocity and acceleration levels.

In Fig. 7 joint moments were compared for the three approaches. Results obtained with kinematically inconsistent data provided an identical kinematics to the one reconstructed by UNO. Moreover, the influence of the kinematic constrains was indirect since they affected to the kinematics. That is, kinetics results depend exclusively on the kinematic variables through the inertial forces and the moment arms. The vector of generalized reactions on the centres of masses is the same for the same kinematics variables no matter the kinematic constrains imposed as they are the the reactions at the proximal and distal extremes of the segment. They are equal due to the ground reaction forces are defined as external forces. Therefore, the definition of the ground reactions forces as external forces determines univocally the problem. Consequently, kinetic results were also identical to the ones obtained by UNO, represented in Fig. 5. The discussion in the previous section showed that generalized reactions results only depend on the kinematics. Therefore, forces and moments were the same, keeping in mind that they could be reaction or driving actions. Results obtained with a fully kinematic data consistent with the model were identical to the ones obtained with GOM, represented in Figs. 4 and 5. Dynamic residuals were those represented in Fig. 8. For this simple model, model errors seemed to be greater than STA errors, and inconsistent data yielded better results.

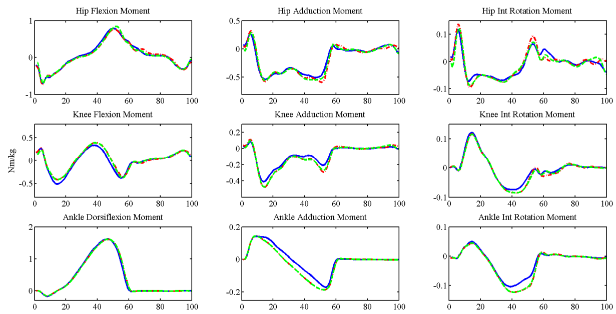

Fig. 7. Temporal evolution of joint moments. In blue and solid line, consistent kinematics, GOM. In red and dot-dashed line, inconsistent position and consistent velocities and accelerations, PCM. In green and dashed line, inconsistent kinematics

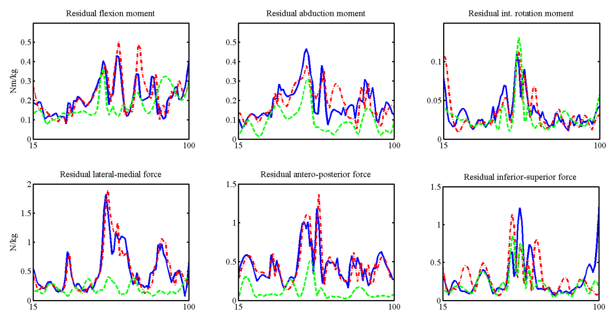

Fig. 8. Temporal evolution of dynamic residuals. In blue and solid line, consistent kinematics, GOM. In red and dot-dashed line, inconsistent position and consistent velocities and accelerations, PCM. In green and dashed line, inconsistent kinematics

IV. Conclusions

The inverse dynamics problem had been solved in this work using four different approaches to study the influence of the multibody system model in the results and, in particular, the effect of the kinematic constraints and the kinematic consistency. No significance differences occur at the joint moments whereas remarkable variations had been observed in the kinematics.

Unconstrained models with six degrees of freedom per segment present joint dislocations, mainly due to STA errors. Joint dislocations can be eliminated by imposing kinematic constraints. But this implies a substantial modification of the kinematics to avoid dislocations. Adding joint constraints can improve the kinematics and kinetics results, only if the error introduced by those constraints is smaller than the STA error. The use of simple joints (spherical or revolute) yielded worse results than using a model without kinematical constraints. More complex joint definitions could be used to improve multibody models. For example, the "anatomically" consistent kinematic

Models [16] include joint contacts and ligaments, allowing a deeper understanding of the force distribution through the different active and passive structures.

If a multibody system composed by rigid bodies interconnected by kinematic joints is used to model the musculo-skeletal system, results will not depend only on the biomechanical model but also on the kinematic data provided as input. This three dimensional data can be obtained through the reconstruction of the measured human motion, as explained for UNO. This procedure alone does not ensure that the kinematic data is consistent with the biomechanical model adopted, because the underlying kinematic constraint equations are not necessarily satisfied. When using GOM or similar procedures, positions, velocities and accelerations are consistent with the multibody model. Previous studies hold that kinematically consistent data led to results for the joints moments with better quality. It has been stated that the use of kinematically inconsistent data yields spurious joints reaction forces and net moments-of-force, associated to the constraint violations. However, this work has shown that the use of inconsistent data does not necessarily yield worse results.

Computed joint moments depend directly on positions and accelerations values and only depend indirectly on the joint constrains between links as far as they affect kinematics. When ground reaction forces are known and considered as external forces all the reactions can be determined and depend only on the external forces and the inertia forces. So, joint moments obtained using a multibody model with constrains and UNO reconstructed kinematics are identical to joints moments using UNO over a model without constrains.

Dynamic residuals had been used in this work as a tool to evaluate the goodness of each procedure. The use of kinematically consistent data with a multibody model with constrains will only yield better results that the same model with inconsistent data if the error introduced by the model is smaller than the error due to STA. However, definition of the kinematic constrains in a multibody model of the human locomotor system is absolutely necessary if a forward dynamics analysis is to be performed. In inverse dynamics analyses, kinematic constraints are not essential but can accomplish different functions. First, they could serve to reduce the number of markers in the motion capture protocol, but only up to a certain point. It must be noted that the markers set is generally redundant to make the capture protocol more robust against failures in the data acquisition. Secondly, kinematic constraints can also help to define the driving moments to be used in the muscular dynamics. If no constraints were defined, it would not be possible to distinguish between driving and reaction moments.

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