ESTIMATION OF BODY SEGMENT PARAMETERS FROM THREE-DIMENSIONAL GAIT DATA USING OPTIMIZATION

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INTRODUCTION

Body segment parameter (BSP) values are needed to perform forward and inverse dynamics analyses of gait. These parameters describe the mass, mass center, and moments of inertia of each body segment and are typically estimated from scaling rules developed from cadaver studies. However, estimated BSP values from different studies can vary by more than 40% (Pearsall and Costigan, 1999), plus there are no simple ways to determine these parameters for special populations such as children or obese adults.

Vaughan *et al*. (1982) addressed this issue by using optimization theory to tune BSP values to experimental data from running, jumping, and kicking motions. Their optimization adjusted BSP values in a planar dynamical model so as to minimize errors between the ground reaction forces and torques measured experimentally and those calculated from the model. The results showed reasonable agreement with BSP values estimated from cadaver studies, and the authors noted that further investigation of the approach was warranted.

This study extends the work of Vaughan *et al*. (1982) to the three-dimensional (3D) case using gait as the experimental motion. The two primary questions are first, given perfect experimental measurements, can accurate BSP values be determined directly from gait data via optimization, and second, can kinematic errors due to skin and soft tissue motion be "corrected" to permit accurate BSP estimation under more realistic conditions? Both questions are investigated using a computational approach.

METHODS

Full-body gait data were collected from a single subject using a video-based motion analysis system (Motion Analysis Corporation, Santa Rosa, CA) and two 6-component force platforms (AMTI, Watertown, MA). Institutional review board approval and informed consent were obtained prior to the experiments. The subject performed gait trials at a speed of approximately 1 m/s. A modified version of the Cleveland Clinic marker set was used with 46 static and 29 dynamic markers. The additional static trial markers were used to create segment coordinate systems. The positions and orientations of the joint axes in these coordinate systems were estimated from anatomical landmarks. The locations of the dynamic markers in each segment coordinate system were also calculated.

The equations of motion for a 3D, 14 segment, 27 degree-of-freedom (DOF) full-body dynamical model (Fig. 1) were derived with Kane's method using Autolev symbolic manipulation software (OnLine Dynamics, Sunnyvale, CA). The pelvis was connected to the ground via a 6 DOF joint, with the rest of the model branching out from the pelvis using various combinations of pin (1 rotational DOF) and gimbal (3 rotational DOFs) joints. Ground reaction forces and torques measured relative to the electrical center of the force plate were replaced with an equivalent set of forces and torques applied to each foot segment. The 84 BSPs in the model were estimated from data in the literature, where the principal axes of each segment were aligned with its coordinate system.

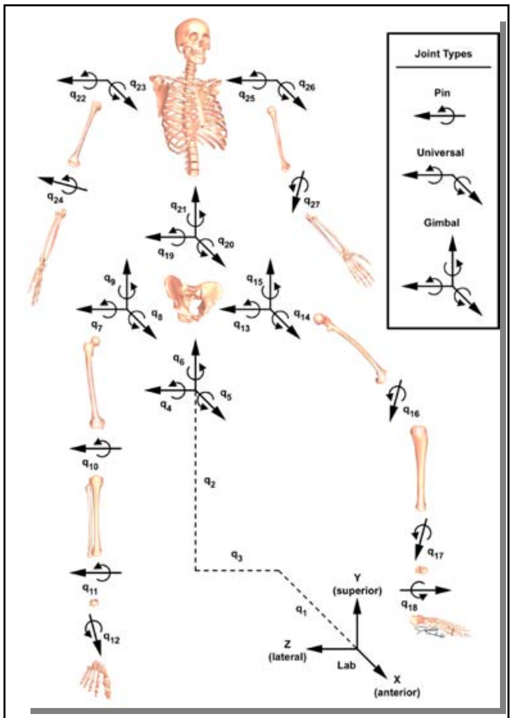

Figure 1: Three-dimensional 27 DOF dynamical model of gait.

A synthetic data set was created from the experimental gait data for theoretical analysis. For each time frame, an optimization was performed that adjusted all DOFs in the model to minimize root-mean-square (RMS) coordinate errors between the markers on the model and those measured experimentally (Lu and O'Connor, 1999). The resulting joint trajectories were filtered with generalized cross-validated splines (Woltring, 1986) and their first and second time derivatives calculated. The pelvis kinematics were then modified to satisfy the dynamics equations exactly (see below), producing a noiseless synthetic gait data set for which all model parameters and inputs were known precisely.

To develop an optimization methodology for improving BSP estimates, we also derived the 6 DOF equations of motion that result by treating the entire 27 DOF model as the "free body." The 6 pelvis generalized coordinates were treated as free DOFs and the remaining 21 generalized coordinates as prescribed DOFs based on the experimentally measured kinematics. Net muscle joint torques were internal to this system and so did not appear explicitly in the equations. However, 3 residual forces and torques acting on the pelvis were added to control the 6 DOFs and balance out the equations. For a perfect model with perfect measurements, these residual loads would be zero throughout the entire motion.

The primary hypothesis of the proposed optimization approach is that residual pelvis loads are the result of two contributing factors: inaccurate BSPs and inaccurate acceleration estimates (Cahouët *et al*., 2002). Since pelvis acceleration errors propagate to ALL body segments based on rigid body kinematics, "correction" of pelvis accelerations should improve estimation of BSPs via optimization methods. A correction scheme was therefore developed using the 6 DOF equations of motion. If subscript f refers to a free degree of freedom and subscript p to a prescribed degree of freedom, then the 6 DOF equations of motion can be written as

$$\mathbf{M}_f \ddot{\mathbf{q}}_f = \mathbf{M}_p \ddot{\mathbf{q}}_p + \mathbf{P} + \mathbf{V}(\mathbf{q}_f, \mathbf{q}_p, \dot{\mathbf{q}}_f, \dot{\mathbf{q}}_p) + \mathbf{G}(\mathbf{q}_f, \mathbf{q}_p) + \mathbf{F} \qquad (1)$$

where

$\mathbf{q}_f$ = 6 x 1 column vector of free generalized coordinates

$\mathbf{q}_p$ = 27 x 1 column vector of prescribed generalized coordinates

$\mathbf{M}_f$ = 6 x 6 mass matrix corresponding to free generalized coordinates

$\mathbf{M}_p$ = 6 x 27 mass matrix corresponding to prescribed generalized coordinates

$\mathbf{P}$ = 6 x 1 column vector of pelvis residual force and torque terms

$\mathbf{V}(\mathbf{q}_f, \mathbf{q}_p, \dot{\mathbf{q}}_f, \dot{\mathbf{q}}_p)$ = 6 x 1 column vector of velocity-dependent terms

$\mathbf{G}(\mathbf{q}_f, \mathbf{q}_p)$ = 6 x 1 column vector of gravity terms

$\mathbf{F}$ = 6 x 1 column vector of ground reaction force and torque terms

Setting **P** = 0 in Eq. (1) and solving for $\ddot{\mathbf{q}}_f$ yields the pelvis accelerations required to produce zero residual pelvis forces and torques:

$$\ddot{\mathbf{q}}_f = \mathbf{M}_f^{-1}[\mathbf{M}_p\ddot{\mathbf{q}}_p + \mathbf{V}(\mathbf{q}_f, \mathbf{q}_p, \dot{\mathbf{q}}_f, \dot{\mathbf{q}}_p) + \mathbf{G}(\mathbf{q}_f, \mathbf{q}_p) + \mathbf{F}] \quad (2)$$

To make these accelerations kinematically consistent with $\mathbf{q}_f$ and $\dot{\mathbf{q}}_f$, the calculated $\ddot{\mathbf{q}}_f$ for all time frames are numerically integrated (e.g., using the trapezoidal rule) to obtain new $\mathbf{q}_f$ trajectories. The two constants of integration are found via an optimization that adjusts the initial position and velocity of each free generalized coordinate until its new trajectory tracks the experimental one as closely as possible. Since integration attenuates errors, large "corrections" to $\ddot{\mathbf{q}}_f$ correspond to only small changes in $\mathbf{q}_f$. Once "corrected" pelvis kinematics are obtained, the resulting pelvis residual loads **P** are calculated by re-arranging Eq. (1):

$$\mathbf{P} = \mathbf{M}_f\ddot{\mathbf{q}}_f - \mathbf{M}_p\ddot{\mathbf{q}}_p - \mathbf{V}(\mathbf{q}_f, \mathbf{q}_p, \dot{\mathbf{q}}_f, \dot{\mathbf{q}}_p) - \mathbf{G}(\mathbf{q}_f, \mathbf{q}_p) - \mathbf{F} \quad (3)$$

Since the "corrected" $\mathbf{q}_f$ and $\dot{\mathbf{q}}_f$ differ from those in Eq. (2), **P** will not be zero and provides an error for evaluating the accuracy of the current BSPs. Even when no "correction" of pelvis kinematics is performed, Eq. (3) can also be solved directly using the experimental kinematics.

The entire solution process can be described as a two-level optimization, or an optimization that calls another optimization. The outer-level optimizer modifies the BSPs so as to minimize **P**, while the inner level optimizer modifies the pelvis kinematics given the current guess for the BSPs so as to minimize changes in $\mathbf{q}_f$. This solution algorithm was implemented in Matlab (The Mathworks, Natick, MA) using a nonlinear least squares optimizer for both the outer- and inner-level optimizations with all masses and moments of inertia constrained to be positive. The algorithm was evaluated using the synthetic gait data described above with and without numerical noise added to the marker coordinates (Chèze *et al.*, 1995) and with and without correction of the pelvis accelerations. The initial guess varied all BSPs randomly by ± 50% of their known values. Only 49 of 84 BSP values were optimized by assuming bilateral symmetry.

RESULTS AND DISCUSSION

The two-level optimization was able to recover the known BSP values and produce essentially zero pelvis residual loads with or without correction of pelvis accelerations when no numerical noise was added to the synthetic marker trajectories (Table 1). This indicated that the optimization algorithm was properly formulated and that gait data does, in fact, contain enough information to accurately determine BSPs given perfect experimental measurements. However, once numerical noise was added to the synthetic marker trajectories, large differences between predicated and known BSPs were observed. Though correction of pelvis kinematics reduced these errors and produced small pelvis residual loads, the correction was not accurate enough to produce realistic BSPs for all segments. This result suggests that errors in kinematic inputs are a significant limiting factor to predicting BSPs directly from gait data.

Table 1: RMS and maximum errors in body segment parameters and pelvis residual forces and torques. Maximum known BSP values are 1.40 kg m^2, 27.9 kg, and 0.220 m.

	Without Pelvis Correction		With Pelvis Correction	
Error	Without Noise	With Noise	Without Noise	With Noise
Inertia RMS (kg m^2)	2.67E-05	0.933	2.73E-05	0.382
Inertia Max(kg m^2)	5.65E-05	4.09	5.90E-05	1.84
Mass RMS (kg)	2.75E-08	2.11	3.95E-08	1.71
Mass Max (kg)	5.30E-08	5.77	7.66E-08	3.07
CoM RMS (m)	9.44E-10	0.197	1.31E-09	0.180
CoM Max (m)	4.00E-09	0.461	5.51E-09	0.559
Pelvis Force RMS (N)	9.01E-10	18.3	5.73E-09	0.229
Pelvis Force Max (N)	2.72E-09	50.1	2.20E-08	0.961
Pelvis Torque RMS (Nm)	6.98E-10	13.0	2.42E-09	0.600
Pelvis Torque Max (Nm)	1.68E-09	35.2	1.05E-08	1.53

SUMMARY

This study has proposed a two-level optimization procedure for predicting body segment parameters directly from gait data using a three-dimensional dynamical model. The outer-level optimization adjusts BSPs in the model while the inner-level optimization adjusts pelvis kinematics given the current guess for the BSPs. Optimization of noiseless synthetic data revealed that gait data contains enough information to predict BSPs accurately given perfect experimental measurements. The addition of numerical noise to the synthetic data prevented accurate estimation of BSPs, indicating that errors in acceleration estimates may be the primary limiting factor in this estimation process. Additional investigation is required to determine which, if any, BSPs are not highly sensitive to noisy kinematic data.

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