

DETERMINATION OF PATIENT-SPECIFIC FUNCTIONAL AXES THROUGH TWO-LEVEL OPTIMIZATION

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INTRODUCTION

Innovative patient-specific models and simulations would be valuable for addressing problems in orthopedics and sports medicine, as well as for evaluating and enhancing corrective surgical procedures [1]. For example, a patient-specific dynamic model may be useful for planning intended surgical parameters and predicting the outcome of high tibial osteotomy (HTO). Development of an accurate inverse dynamic model is a significant first step toward creating a predictive patient-specific forward dynamic model. The precision of inverse dynamic analyses is fundamentally associated with the accuracy of kinematic model parameters such as segment lengths, joint positions, and joint orientations.

Understandably, a model constructed of rigid links within a multi-link chain [2] and simple mechanical approximations of joints [3] will not precisely match the human anatomy and kinematics. The model should provide the best possible assessment within the bounds of the joint models selected [3]. Earlier studies describe optimization methods to discover a set of model parameters for three-dimensional (3D), 2 degree-of-freedom (DOF) models by decreasing the error between the motion of the model and experimental data [3, 4]. In this paper, we present a nested, or two-level, system identification optimization approach to determine patient-specific joint parameters that best fit an 18 DOF lower-body model to movement data.

METHODS

A generic, parametric 3D full-body kinematic model was constructed with Autolev as a 14 segment, 27 DOF linkage joined by a set of gimbal, universal, and pin joints. Comparable to Pandy's [1] model structure, three translational and three rotational DOFs express the movement of the pelvis in 3D space and the remaining 13 segments comprise four open chains branching from the pelvis segment. A static motion capture trial is used to create segment coordinate systems and define dynamic marker locations in these coordinate systems. A modified version of the Cleveland Clinic marker set is used for this purpose. The locations and orientations of the joints within the segment coordinate systems are described by 98

patient-specific model parameters for the following joints: 3 DOF hip, 1 DOF knee, 2 DOF ankle, 3 DOF back, 2 DOF shoulder, and 1 DOF elbow. The patient-specific parameters for each joint are defined in two adjacent body segments (Figure 1). For example, the knee joint axis is simultaneously established in the femur coordinate system and the tibia coordinate system.

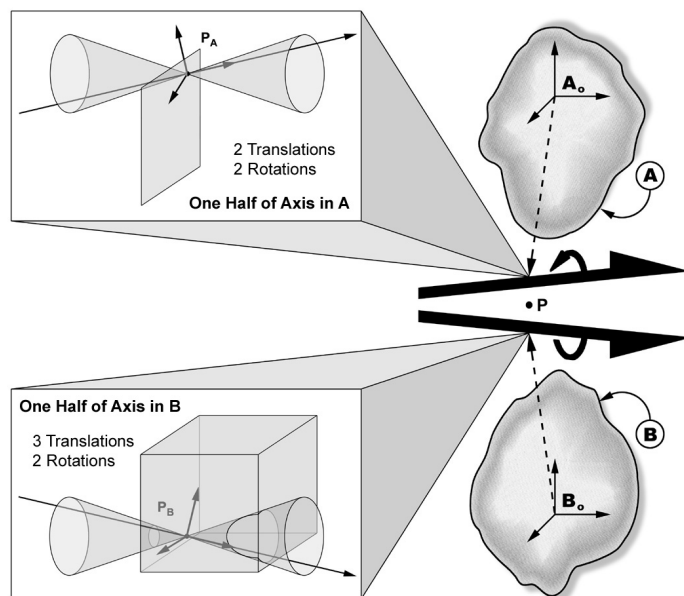


Figure 1. Schematic of a 1 DOF joint axis simultaneously defined in two adjacent body segments and the geometric constraints on the optimization of each of the 9 parameters.

Given dynamic motion capture data, the lower-level sub-optimization (Figure 2, inner boxes) minimizes the 3D marker coordinate errors between the model and the movement data using a

nonlinear least squares algorithm that adjusts the DOFs of the model at each instance in time [2]. Initially, the algorithm is seeded with exact values for the pelvis DOFs, since the marker locations directly identify the position of the pelvis coordinate system, and all remaining DOFs are seeded with values equal to zero. Given the joint motion is continuous, each optimal DOF solution at a particular time instance is used as the algorithm's seed for the subsequent time instance.

The upper-level global optimization minimizes the sum of the squares of the 3D marker coordinate errors computed by the lower-level algorithm throughout every time instance, or the entire joint motion, by modifying the patient-specific model parameters. To manage computational requirements, the upper-level optimization employs a parallel version of the particle swarm algorithm operating on a 20-processor network cluster; therefore, each is separately seeded with a random set of initial patient-specific model parameter values. The number of patient-specific model parameters adjusted throughout each optimization are as follows: hip = 6 (all translations); knee = 9 (4 rotations, 5 translations); and ankle = 12 (5 rotations, 7 translations).

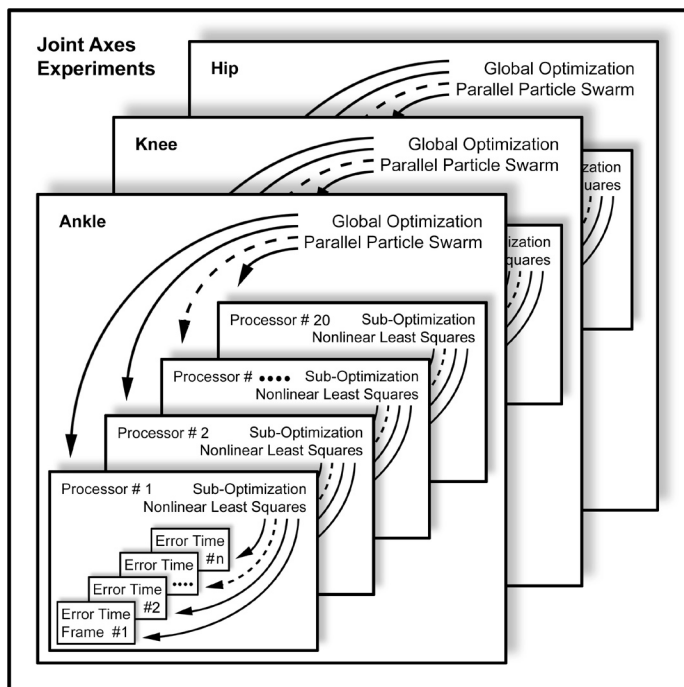


Figure 2. Two-level optimization technique minimizing the distance errors between kinematic model markers and marker trajectory data to determine functional joint axes.

To evaluate the ability of this two-level optimization approach (Figure 2) to calibrate the generic kinematic model to a particular patient, we generated synthetic movement data for the ankle, knee, and hip joints based on *in vivo* model parameters and movement data. We then evaluated the optimization's ability to recover the original model parameters used when generating the synthetic motions. For each generated motion, the distal segment moved within the physiological range-of-motion and exercised each DOF for the joint. The resulting synthetic marker trajectories without noise were recorded. To simulate skin movement artifacts, a continuous numerical noise model of the form $A \sin(\omega t + \phi)$ was used and the equation variables were randomly generated within the following bounds: amplitude A (0 to 1 cm); frequency ω (0 to 25 rad/s), and phase angle ϕ (0 to 2π) [5].

RESULTS

For synthetic motions without noise, each optimization precisely recovered the original marker trajectories and model parameters to within an arbitrarily tight convergence tolerance (i.e., $1e-12$). For synthetic motions with noise, the ability of the two-level approach to determine the original marker trajectories and model parameters is summarized in Table 1. The mean marker distance errors are approximately 0.5 cm, which is of the same order of magnitude as the selected random continuous noise model.

Synthetic Data With Noise	Hip	Knee	Ankle
Mean Marker Distance Error (cm)	$4.61e-01 \pm 1.81e-01$	$5.10e-01 \pm 1.95e-01$	$5.06e-01 \pm 1.88e-01$
Mean Rotational Parameter Error (deg)	n/a	$2.56e-01 \pm 8.20e-02$	$2.42e+00 \pm 1.03e+00$
Mean Translational Parameter Error (cm)	$1.74e-02 \pm 1.55e-02$	$8.90e-02 \pm 5.14e-02$	$3.45e-01 \pm 2.84e-01$

Table 1. Results of two-level optimization for synthetic data with random continuous numerical noise to simulate skin movement artifacts with maximum amplitude of 1 cm.

DISCUSSION

The main motivation for developing a 27 DOF patient-specific computational model and a two-level optimization method to enhance the lower-extremity portion is to predict the post-surgery peak knee adduction moment in HTO patients [6]. The accuracy of prospective dynamic optimizations made for a unique patient is determined in part by the fitness of the underlying kinematic model. If the current model cannot adequately reproduce experimental motion, the chosen joint models may be modified. The two-level optimization method satisfactorily reproduces patient-specific model parameters defining a 3D lower-extremity model that is well suited to a particular patient.

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