PERSONALIZED MUSCULOSKELETAL HUMAN MODELS FOR USE IN DYNAMIC GAIT SIMULATION FOR CLINICAL AND SPORTS APPLICATIONS

S. McGuan

Mechanical Dynamics Inc., Ann Arbor, USA

INTRODUCTION

The purpose of this project is to advance the current technology of musculoskeletal modeling as applied to gait simulation into: 1) A general clinical tool for the health care industry, 2) The evaluation of athletic performance and injury reduction, and, 3) To provide a validated base for research in muscle activation and optimal control as applied to human locomotion. A novel scaling method is introduced to automatically generate statistically valid gait simulation models for a specific human subject based on a minimal set of input parameters. In a clinical setting, physical measurements such as height, weight, joint axes alignment and joint ROM would be available, however, the joint torques necessary for driving the dynamic simulation would not be directly measurable. This paper introduces new scaling methodologies to develop the torque functions necessary to generate a statistically valid, personalized gait simulation model based on experimental data.

METHODS

To develop a scaling methodology from the immense amount of data which comprises a human gait simulation, each experiment must be categorized using a reduced set of data or parameters. To develop the reduced set of data from gait simulation experiments, personalized musculoskeletal models were built for a large, varied population sample using the ADAMS® (Mechanical Dynamics, Inc.) simulation software (see figure 1).

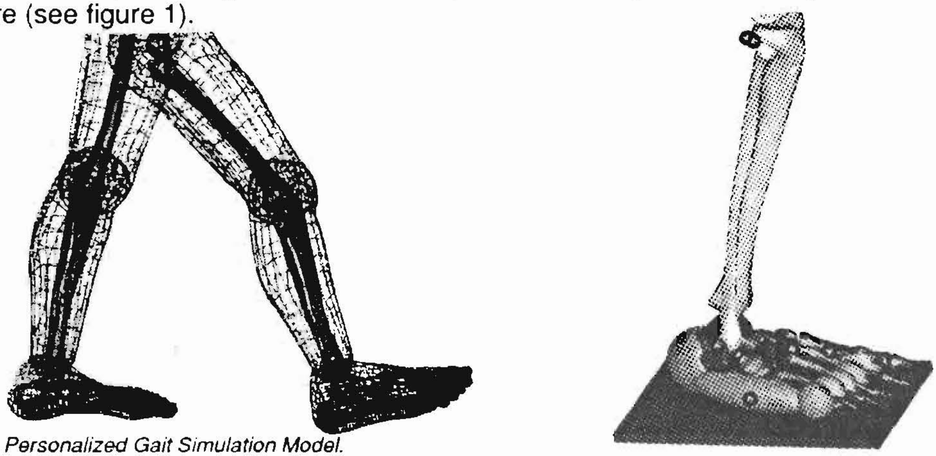


Figure 1. Personalized Gait Simulation Model.

The models used for the gait simulation included one rigid segment representing the head, arms and trunk (hat) and one lower extremity. The lower extremity model consisted of 26 parts using a lumping scheme in the foot similar to [Scott 1993]. Using various coupling constraint schemes, the motion in model is reduced to a total of 10 degrees-of-freedom (DOF) with 1 DOF at the hat, 3 DOF at the hip, 2 DOF at the knee, 1 DOF at the talocrural joint, 1 DOF at the subtalar joint, 1 DOF at the longitudinal metatarsal joint, and 1 DOF at the oblique metatarsal joint.

A two step process was used to obtain the joint torques necessary to drive the dynamic simulation to emulate the recorded motion. The portion of the gait cycle considered for this study is heel strike through full forefoot load for hat and single lower extremity.

First, motion data for each subject was used to drive the gait simulations and a hybrid inverse-dynamic/direct dynamic approach [McGuan 1995], was used to derive local joint compliances for each of the 10 DOFs in the musculoskeletal model for the gait cycle. The method involves fixing "motion agents" to the skeletal model at the locations of the motion sensors from the data source using 6 DOF springs (bushings). The motion agents will follow the experiment motion, and with this spring fixity will become motion influencers rather than motion governors, accommodating data errors from the motion source (skin motion, etc.). With the segment resolution of the data source for the model being four rigid bodies (shank, thigh, forefoot and rearfoot), and the resolution of the model being 10 DOFs, any unconstrained freedoms were secured with spring dampers. To model the interaction between the fat pads of the foot with ground, contact ellipsoids were positioned under the 5 metatarsal heads, calcaneous and hallux using tissue compliance properties from [Valient 1984]. A simulation was performed with this arrangement to obtain the 10 internal joint rotation histories for the gait cycle.

Second, the motion agents were removed from the model and torque functions were added to each of the 10 DOFs. The joint torque functions were implemented using the rotation histories from the previous simulation in a feedback controller of the form displayed in figure 2.

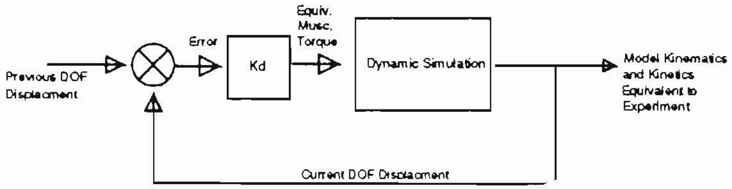
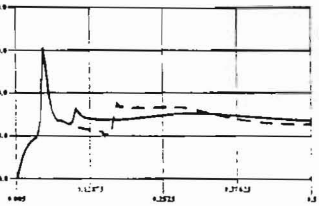


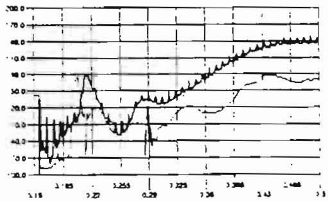
Figure 2. Feedback Controller for Torque Functions in the Dynamic Simulation.

This controller produces the torques necessary for the human model to emulate the recorded motions from experiment. The mass and inertia properties of the model segments under the influence of the internal torques will cause the model to produce ground reaction forces similar to experiment (figure 3). With the external reactions of the model correlating with the experiment in conjunction with a correlation of segment motion, it is assumed that the internal reactions will also correlate to the loads (soft tissue, articular contact forces) the experimental subject experienced.

From each experimental subject simulation, the recorded data included the clinical measurements, the non-linear joint torque histories, the system motion response and the system GRX response. The clinical measurements included the subject's height, weight, talocrural joint axis orientation and ROM, subtalar joint axis orientation and ROM, oblique metatarsal joint axis orientation and ROM, and longitudinal joint axis orientation and ROM [Michaud 1993]. The non-linear joint curves were recorded as discrete points reported for 12 time points in the gait cycle. The system motion response was recorded as the magnitude of the displacement of 6 reference points in the model recorded at each of the 12 time points in the gait cycle. The system GRX response was recorded as the value of the normal force at each of 12 time points. This entire set of data serves to classify a particular experiment.



Vertical GRX Correlation (dash - experiment).



FWD CP Travel Correlation (thickline-experiment).

Figure 3. Correlation of GRX with Experiment.

To process the data a matrix approach is used. Table 1 organizes the recorded data in a form suitable for matrix processing. The table includes the clinical measurements, the torque set (10 DOFs for 12 time points) and the response set (GRX for 12 time points and 6 motion reference locations for 12 time points).

Exp	Ht.	Wt.	Ankle Axis	Ankle ROM	SubT Axis	SubT ROM	OMJA Axis	OMJA ROM	LMJA Axis	LMJA ROM	Torq. Set	Res. Set
1												
2												
3												
..												

Table 1. Table Format used to Process Experiment Data.

Twenty five experiments were run and the results were added to the matrix. Each column was given a weighting function based on it's relative effect on the result set. The weighting functions were determined by performing parameter sensitivity analyses on the models developed for the experiments. Based on the sensitivity analyses, the height and weight were given the highest weighting functions, with the axes orientation values given the next highest and ROM given the smallest. To develop a personalized gait model from this data, clinical measurements were taken for the human subject and matched to the table. By using the weighting functions a result set and torque set can be interpolated. The torques are then adjusted using optimization techniques internal to ADAMS to fit the results of the simulation to the selected result set.

RESULTS

This scaling method was used to generate a personalized model for a specific human subject and the simulation results were compared against experiment for a subject not included in the table. The segments and joints were automatically generated and sized based on the clinical measurements. Segment mass properties were generated using an implementation of GEBOD [Baughman 1983]. Non-linear torque curves for each of the 10 DOFs were generated by fitting polynomials through the interpolated values for each of the 6 time points. The dynamic simulation was performed and the GRX for the simulation is compared to experiment in figure 4.

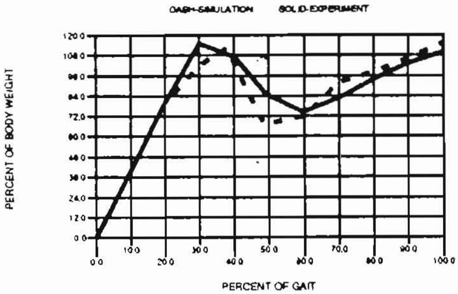


Figure 4. Comparison of Simulation from Statistical Source to Experiment.

CONCLUSION

This study was intended to develop a methodology to automatically generate statistically valid, personalized gait simulation models based on a minimal set of input parameters. The near-term practical application of a scaleable gait simulation model is as a tool in conservative foot care, where the clinician can examine the human kinematic and kinetic aspects of an orthoses or a specific sports shoe, optimizing its correctional properties to restore optimal extremity function or injury prevention.

The prediction accuracy of this model is directly related to the number of experiments and the accuracy of data collection. When sufficient number of experiments have been performed and the sensitivity of the weighting functions explored, the model can be expanded to incorporate more features such as more time points, more response variables (CP travel history), full gait cycle, both extremities, etc.

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