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AN APPROACH FOR A DETAILED ANALYTICAL MODEL OF THE HUMAN LOWER EXTREMITY DURING A DROP LANDING

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INTRODUCTION

A computer model of the human leg and foot was generated to explore the kinematic and kinetic properties of the human leg and foot during a drop landing. Experimental data from an actual drop landing was used to produce the model. A goal is to develop this modeling approach into a tool to investigate the effects of mechanical and geometric characteristics of sports shoes on acute injury such as an eversion-related injury to the lateral ligament complex.

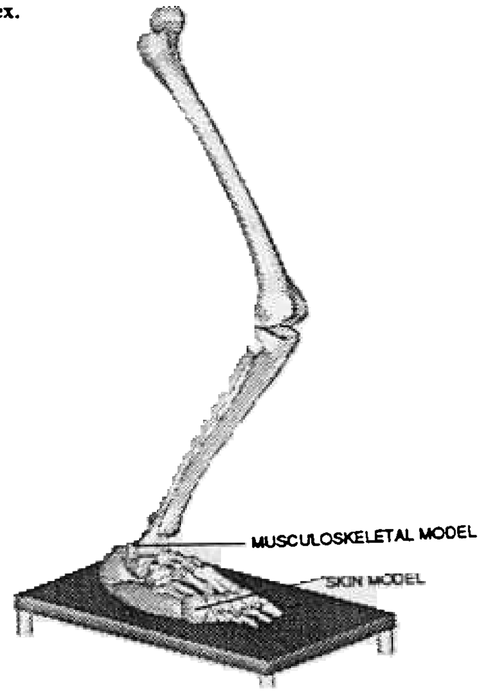

Figure 1. Musculoskeletal Model with Skin Model Overlay.

REVIEW AND THEORY

Rearfoot stability during running and general sports activities is related to foot anatomy and the kinematic changes that result from footwear, Nigg (1986). To study the effects of changes in footwear design variables, researchers have predominantly relied on laboratory analysis. Simple analytical models, Stacoff et al. (1988), Nigg (1986), Miller, et al. (1973), Jonsson (1987), have also been used, however, researchers continually stress the need to develop more detailed models to supplement and complement existing laboratory methods, Stacoff et al. (1988), Clark et al. (1984), Cavenaugh (1980), Cavenaugh (1990), Miller et al. (1973), Jonsson (1987).

As early as 1960, researchers have recognized that the human locomotor system can be characterized by a set of differential equations, Miller (1973). This characterization can be expanded to include a mechanical model of the shoe. Simple analytical models have been useful in obtaining relationships between rearfoot eversion and a changing moment arm due to varying midsole geometry and cushioning properties, Stacoff et al., (1988), Nigg (1986). Although a computer is used to find solutions to the set of differential equations characterizing the dynamics of these models, the set of equations themselves, were usually derived and assembled by hand, limiting the detail and complexity of the mechanical system described.

With the evolution of mechanical system simulation tools such as ADAMS™, it is now convenient to generate a system of non-linear (differential/algebraic) equations, representing a set of constrained six degree-of-freedom parts by working on a computer graphics analogy of the system. The system of equations are then assembled into matrix form and solved through time, Chase (1984). The simulation results are interrogated using computer animations and data graphs. This relatively new generation of software simulation tools removes the analyst from the complexity of the underlying mathematics allowing the focus to shift to model behavior and function.

Due to this increased convenience, the analytical models generated using mechanical simulation tools, will be of a higher order of sophistication and detail than of those used in the past for sport shoe evaluation, and will include many more interacting kinematic variables. For example, the model presented in this paper couples pronation/supination with full eversion/abduction/dorsiflexion, not just calcaneal eversion, to study the effects of pronation/supination on tibial rotation. In addition, the shoe model complete with flexure and cushioning properties, is capable of capturing the effects of a continuously varying moment arm during the jump landing. This cushioning surface can also be used to model the partial interaction between the shoe and obstacles, such as the landing on another player's foot. Through discretization, the foot and shoe model will better adapt to the ground surface, with or without obstacles, to provide increased kinematic accuracy of the entire human locomotor system.

PROCEDURES

Data Collection
A barefoot male subject dropped onto a Kistler™ force plate by releasing his grip from a "hang-bar." The drop height (distance from subject's toe to ground) was 14 cm. A Watsmart™ optoelectronic 3-D motion analysis system was used to collect the drop landing kinematic data for 2 seconds at 200 Hz. A

Watscope™ system was used simultaneously to collect force plate data at 600 Hz. Data collection was conducted on the subject's right lower extremity. Kinematic data were obtained using infrared markers at boney locations. A four-segment experimental model was assumed (Thigh, Shank, Rearfoot, and Forefoot) for data collection. Three-dimensional joint motions for the Hip, Knee, Ankle, and the "pseudo-joint" between Rearfoot and Forefoot were calculated using data analysis software provided with the Watsmart system. Data was collected for both a flat landing and a landing on a 3 cm obstacle under the 1st metatarsal head.

Computer Model
To simulate the lower extremity response to the drop landing, three types of computer models were constructed, a coarse model, a detailed model and a skin model (see figure 1). The coarse model was built with 4-parts to reflect the discretization employed during data collection. The degrees-of-freedom, DOFs, in this kinematic model would be driven with the experimental data produced by the Watsmart system. A detailed model of the complete musculoskeletal lower extremity was developed using 26 parts and a lumping scheme in the foot similar to Scott (1993). Mechanical joints were used to connect all parts in model except for the subtalar joint where a 3-D surface contact force was employed. A skin model was developed to provide a contact force between the musculoskeletal model and the environment (i.e., shoe, force plate, etc.)

Simulations
A model overlay technique was employed to drive the 26 parts of the detailed model with the 4 parts of the coarse model using the experimental displacement data. Spring-dampers elements were used to anchor the coarse model to the detailed model at the diode locations used in the experiment. The spring and damping rates of the connection elements were normalized to the specific accuracy of the diode, to allow for the more accurate diode locations to provide the dominant motion contributions. Viscous dampers were applied to the rest of the model to prevent any motion in the free DOFs during free-fall. The skin model was then overlayed over the detailed model to provide for foot to floor interaction. Dynamic simulations were performed with this overlay arrangement to record the relative rotational and translational displacements at the joint connections.

The coarse model was then stripped from the detailed model. Muscle-ligament forces acting at the joints were described using a controller element positioned at each DOF with the error function being based on the difference between the recorded instantaneous displacement from the previous simulation and the current simulation displacement. This controller would produce the internal muscular-ligament reactions necessary to guide the motion at each DOF in order for the segments of the model to match the segment motions in the experiment. Simulations were then performed with this dynamic model. The gains of the controller elements were iteratively adjusted using an optimization technique to match model results to experimental results (segment motion and external reaction forces).

RESULTS

Model verification was performed by comparing the ground reaction forces for model and experiment and the CP travel history. Figure 2 displays the vertical ground reaction force comparison between model and experiment. 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 or muscle forces and ligament loadings of the model will also correlate to loads the experimental subject experienced.

DISCUSSION

Simulations using this method were performed for both flat landing and obstacle landing cases. With the model validated for both cases, the height of the obstacle is increased in the simulations to cause an ankle eversion in the model. Stresses on the spring elements representing the lateral ligament complex are monitored to gage injury and rupture. With this acute injury producing mechanism isolated, research is now focused on the development of a sports shoe model to overlay onto the detailed model to stabilize and reinforce the ankle.

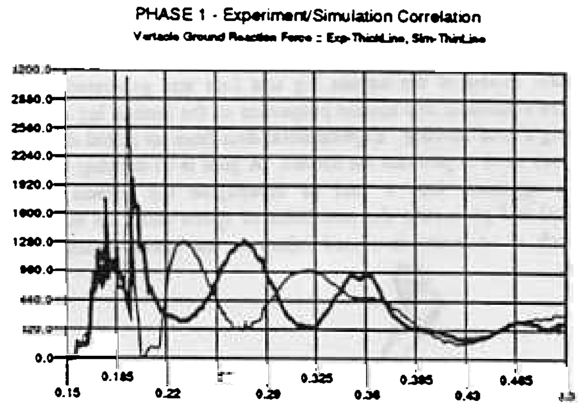

Figure 2. Experiment and Model Vertical Ground Reaction Force.

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