DYNAMIC FINITE ELEMENT ANALYSIS OF THE HUMAN FOOT COMPLEX

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INTRODUCTION

The human foot is a complex structure comprising numerous bones, joints and soft tissues, delivering a variety of biomechanical functions in standing and moving. A large number of studies including both experimental tests and finite element (FE) computer analyses have been conducted to investigate foot biomechanics [1,2]. However, most previous FE modeling involved simplified loading and boundary conditions, and analyses were static or quasi-static in nature. Little is known about the dynamic response of human foot structure during various movements.

The objective of this study is to develop a purely dynamic FE human foot model to investigate the dynamic characteristics of the human foot complex. This will lead to a better understanding of the dynamic behaviors and the internal loading conditions of the foot musculoskeletal structure especially in strenuous activities, and thereby improve clinical diagnosis, footwear design and injury prevention.

METHODS

A three-dimensional (3D) foot model (Figure 1) was constructed first from MRI images of the right foot of a healthy male subject (age: 27yrs, weight: 75kg). A two-dimensional (2D) cross section in the sagittal plane along the first ray was used to construct a plane strain model in ABAQUS (Simulia, Providence, RI). A 2D model considering the foot as a whole was built first with the purpose to choose the proper dynamic solver which is capable of handling the inertial effects on stress analysis.

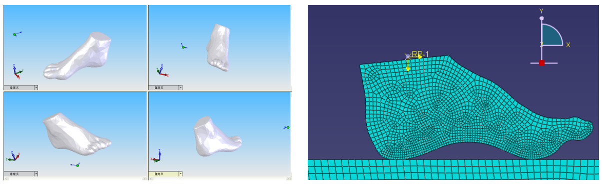

Figure 1: The 3D and 2D FE model of the human foot

A rigid flat plate was used to simulate the ground surface. Interaction between the foot and the ground was modeled as a kinematic contact with friction. Dynamic loads over a whole stance phase during normal walking were calculated using a 3D inverse dynamics analysis [3]. This included vertical and horizontal forces and a dorsi-flexion/ plantar-flexion moment applied about the middle of the talus bone as driving forces. The ground was fixed and the foot was allowed to move freely without any prescribed constraints. The simulation was conducted using the ABAQUS/EXPLICIT module, and all inertial properties were considered.

Experimental measurements were conducted to support and validate the FE modeling. The subjects were instructed to walk barefoot along a walkway to perform walking, running, vertical and long jumping motions. An eight-camera motion analysis system (Qualisys, Sweden; 250 Hz) was used to capture the 3D motion data. A six-force plate array (Kistler, Switzerland; 1000 Hz) and a 1m pressure plate (RSscan, Belgium; 250 Hz) were used to record simultaneous ground reaction and foot pressure data. An infrared marker cluster system was specially designed (similar to [4]) to capture the intricate 3D multi-segment foot motions (Figure 2).

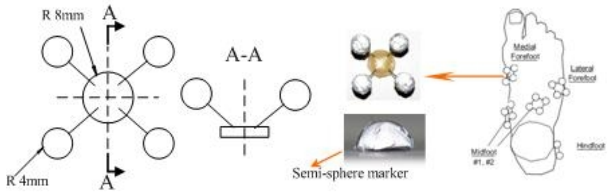

Figure 2: Maker cluster system to capture 3D foot motions

RESULTS AND DISCUSSION

The simulation results using the force data from a representative stance phase of normal walking are shown in Figure 3. Our preliminary results show that the calculated pressure distributions are higher than in static models, and are closer to measured foot stress patterns.

To test the dynamic solver and the foot-ground contact model, the foot was modeled as a whole part constrained in the sagittal plane only in this study, which would affect the simulation results. The development of a 3D dynamic FE model consisting of soft tissues, bones and cartilages is ongoing, including the investigation of the dynamic bone and soft tissue loadings in different motor tasks, the effect of non-linear material properties, and the foot dynamic behaviors under different contact boundary conditions.

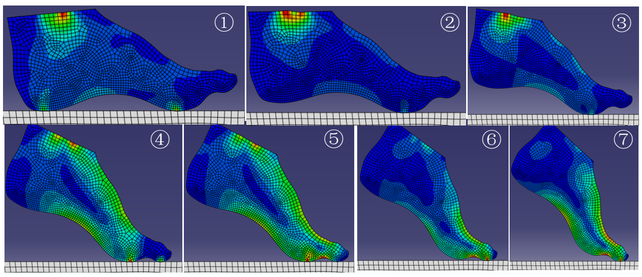

Figure 3: Dynamic simulation results in a walking gait.

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