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A quasi-dynamic nonlinear finite element model to investigate prosthetic interface stresses during walking for trans-tibial amputees

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Abstract

Background. To predict the interface pressure between residual limb and prosthetic socket for trans-tibial amputees during walking.

Methods. A quasi-dynamic finite element model was built based on the actual geometry of residual limb, internal bones and socket liner. To simulate the friction/slip boundary conditions between the skin and liner, automated surface-to-surface contact was used. Besides variable external loads and material inertia, the coupling between the large rigid displacement of knee joint and small elastic deformation of residual limb and prosthetic components were also considered.

Results. Interface pressure distribution was found to have the same profile during walking. The high pressures fall over popliteal depression, middle patella tendon, lateral tibia and medial tibia regions. Interface pressure predicted by static or quasi-dynamic analysis had the similar double-peaked waveform shape in stance phase.

Interpretation. The consideration of inertial effects and motion of knee joint cause 210% average variation of the area between the pressure curve and the horizontal line of pressure threshold between two cases, even though there is only a small change in the peak pressure. The findings in this paper show that the coupling dynamic effects of inertial loads and knee flexion must be considered to study interface pressure between residual limb and prosthetic socket during walking.

Keywords: Prosthetic socket; Finite element analysis; Interface pressure; Knee flexion; Inertial loads

1. Introduction

A prosthesis is often used to restore appearance and lost function to individuals with lower-limb amputation, and the socket is a critical component for prosthetic performance. The successful design and fitting of a prosthetic socket results in the effective transfer of forces from the socket to the residual limb such that the amputee can maintain daily activities without damaging tissue or experiencing pain.

The general characters of the residual limb such as geometry, size, and load bearing tolerance varies from each person. Moreover, the shape of the socket is not an exact replica of the residual limb, but includes appropriate rectification to optimize the interface mechanics. Consequently the design of a satisfactory socket often cause time-consuming or unnecessary complications

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for the amputees. More quantitative and objective information about the interface mechanics is needed in the process of the fitting of a prosthesis.

Finite element (FE) analysis is a technique widely used in bioengineering to determine stress and strain in complicated systems and has been identified as a useful tool for prosthetic socket design. Since Steege and Childress (1987) established the first FE models of the trans-tibial residual limb and prosthetic socket, several models have been developed to improve prosthetic design (Quesada and Skinner, 1991; Reynolds and Lord, 1992; Silver-Thron and Childress, 1997; Zhang et al., 1995; Zachariah and Sanders, 2000; Tracy et al., 2002; Lin et al., 2004). The development started from simple linear elastic models with simplified two-dimensional or symmetric geometry to the nonlinear models with more accurate geometry. The socket modification, varied external loads to simulate walking, nonlinear mechanical properties, and slip/friction boundary conditions have been addressed in different models. Regardless of their assumptions and simplifications, these analyses not only provided information on load transfer at the residual limb/socket interface and helped to design a better socket, but also showed more advantages over experimental measurements in the estimation of interface stresses.

However, all models reported so far are static or pseudo-static (Saunders and Daly, 1993) by applying static forces/moments to simulate a single or more phases of gait. Although the significance in developing dynamic models has been reckoned by researchers who developed the static models (Quesada and Skinner, 1991; Saunders and Daly, 1993; Silver-Thron and Childress, 1997; Zhang et al., 1998a,b), there is only one new model (Jia et al., 2004) that considered material inertial effects and variable external loads during gait. In their work, material inertial effects and the motion of the knee joint were considered to calculate the equivalent loads, but the change of angle of the knee joint was ignored in the FE model during ambulation. Since the geometry of FE model is one of the main factors which determine the simulation results, ignoring the change of the limb posture will affect the accuracy of interface pressure prediction.

Before establishing a full dynamic analysis of the interface biomechanics between a trans-tibial residual limb and the prosthetic socket during a whole gait cycle, the aim of this paper is to build a quasi-dynamic FE model which can predict stress distribution on the residual limb. Although the equivalent loads applied in this FE analysis were calculated by using a simplified multi-rigid dynamic model, the new FE model can consider not only variable external loads and material inertia but also the coupling between the large rigid displacement of knee joint and small elastic deformation of residual limb and prosthetic components.

2. Methods

A unilateral trans-tibia male amputee, 56 years old, 158 cm in height, and 81 kg in weight volunteered to join in this study. He had more than 5 years experience in using an endoskeletal trans-tibial prosthesis with patella-tendon-bearing socket and solid-ankle-cushion-heel foot with no skin complications.

2.1. Finite element modeling

The geometry of the residual limb surface and the bony structure was obtained from three-dimensional reconstruction of magnetic resonance images conducted on the residual limb with axial cross-sectional images at 6 mm interval. To reduce the distortion of the soft tissues in a supine lying position, an unmodified cast was wrapped on the residual limb. The bony structures and the soft tissue boundaries in magnetic resonance images were identified and segmented using MIMICS v7.10 (Materialise, Leuven, Belgium). The boundary surfaces of different components obtained were processed using SolidWorks (SolidWorks Corporation, Massachusetts, USA) to form surface models. The shape of residual limb was further sent to ShapeMaker (Seattle System, WA, USA) to implement modification using the patella-tendon-bearing socket rectification template built-in Shapemaker system. Since the liner could not be identified from the magnetic resonance images, the inner contours of the liner were designed to be same as the outer contours of the residual limb after modification, and with 4 mm offset its inner surface, the outer surface were gotten, which was identical with the inner surface of the socket (Lee et al., 2004).

Based on the actual geometries of the socket, the residual limb surface and the internal bones of the same subject, the models were automatically meshed into three-dimensional 4-node tetrahedral elements using ABAQUS v6.3 FE package (Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, RI, USA). The whole FE model consisted of 22,301 elements and 6030 nodes. The meshed geometries of residual limb, prosthetic socket and bones were shown in Fig. 1.

All materials were assumed to be isotropic, homogeneous and linearly elastic. The Young's modulus was 200 kPa for soft tissues, 10 GPa for bones and 380 kPa for prosthetic liner, and Poisson's ratio was assumed to be 0.49 for soft tissues, 0.3 for bones, and 0.39 for liner (Zachariah and Sanders, 2000; Zhang et al., 1995).

2.2. Interactions and constraints

In the FE model of residual limb and prosthetic socket, the relative relationships including interactions and constraints between each component were defined by using the commands in ABAQUS 6.3.