EFFICIENT DYNAMIC FINITE ELEMENT RIGID BODY ANALYSIS OF TJR

Jason P. Halloran (1), Sarah K. Easley (1), Janaki Penmetsa (1)
Peter J. Laz (1), Anthony J. Petrella (2), and Paul J. Rullkoetter (1)

(1) Department of Engineering
University of Denver
Denver, CO

(2) Biomechanical Testing and Analysis
DePuy, a Johnson & Johnson Company
Warsaw, IN

INTRODUCTION

Joint kinematics and contact mechanics dictate the long-term performance of current total joint replacement (TJR) devices. A volume of recent research has, therefore, focused on the prediction of joint contact stresses and areas due to articulations and kinematics at the joint interfaces as an indication of potential clinical performance. Implicit finite element (FE) methods have traditionally been used to determine contact parameters during static and quasi-static loading conditions. Dynamic rigid-body models have been created for assessment of relative kinematics and/or kinetics; however, they have generally lacked the ability to predict polyethylene contact stresses. Recently, however, explicit FE analyses have been used to develop dynamic models of TKR able to determine joint and contact mechanics during force controlled, dynamic loading conditions [1,2]. Although these explicit FE models are reasonably efficient, reported CPU time is still in the range of 8 hours to several days for a full gait cycle [1,2]. Parametric analyses or numerical wear simulation of TJR components, which both require repeated analyses, can therefore be cost prohibitive. As a result, the objective of this research was to develop efficient, explicit FE rigid-body models of TJR that will predict comparable relative kinematics and contact mechanics as a fully deformable analysis with significant timesavings.

METHODS

TKR Model

A TKR model was developed in ABAQUS™/Explicit (HKS, Pawtucket, RI) from CAD models of a current semi-constrained device. Three-dimensional, 8-noded brick finite elements were used to represent the polyethylene tibial insert and three-dimensional, rigid finite elements were used to represent the femoral component (Figure 1). A coefficient of friction between metal and polyethylene of 0.04 was chosen to be consistent with previous explicit FE models [2]. For deformable analyses, a nonlinear stress-strain model was used for the elements representing the polyethylene tibial insert [3]. Contact was defined using a penalty-based method with a weight factor. As a result, contact forces are defined as a function of the penetration distance of the master into the slave surface. The explicit dynamic analysis permits the polyethylene insert to be easily characterized as a deformable or rigid body. In order to estimate the contact area and contact pressure distribution during a rigid body analysis, softened contact capability was employed. A nonlinear relationship between contact pressure and surface overclosure (penetration) was estimated for the mesh based on the nonlinear stress-strain material data and element size. The contact prediction of the pressure-overclosure relationship was then optimized using nonlinear, unconstrained minimization. The objective function was based on the sum of the squared difference between the rigid and deformable results along the contact pressure and area curves. A simplified range of motion with compressive load was applied to the femoral component for the optimization analysis.

Boundary conditions were then applied to the tibial insert and femoral component to replicate the testing conditions during force-controlled gait simulation using the Stanmore knee simulator [4]. The input profiles include an anterior-posterior load and internal-external torque applied to the insert, and a flexion-extension angle and an axial force applied to the femoral component [4]. Simulated soft-tissue constraint present in the knee simulator was included in the FE model [4]. Anterior-posterior and internal-external kinematics were determined for both deformable and rigid body analyses. Kinematic trends and magnitudes were compared with experimental data. Predicted contact mechanics were compared between deformable and rigid body analyses. Finally, computational time was evaluated to examine the timesaving resulting from use of the rigid body with softened contact.

THR Model

A THR model was also developed in ABAQUS™/Explicit, using three-dimensional, 8-noded brick finite elements to represent the polyethylene liner, and an analytical rigid surface to represent the spherical femoral head. The friction coefficient and polyethylene material model were consistent with the TKR analysis. Again, the pressure-overclosure relationship used in the rigid body simulation was optimized for the liner mesh to recreate the contact results of a deformable polyethylene analysis. Load and motion boundary conditions were applied to the femoral head to represent stance phase gait loading conditions [5]. Predicted contact mechanics were determined and compared between deformable and rigid body analyses during this loading condition. Finally, computational time was again evaluated and compared.

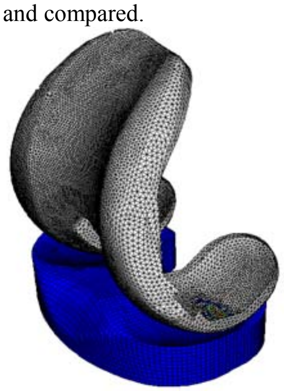

Figure 1. Finite element model of rigid femoral component contacting polyethylene tibial insert.

RESULTS

Results from the TKR analysis during gait simulation showed very good agreement between the model predicted and experimental internal-external rotation and anterior-posterior translation. Rigid body with softened contact and fully deformable analyses predicted nearly identical kinematics. Peak contact pressures were found near 45% and 55% of the gait cycle, and were approximately 20 MPa (Figure 2). The second peak resulted from the internal-external rotation creating contact more near the edge of the insert. Rigid body and fully deformable analyses predicted very similar trends for the contact pressure and area (Figure 2 and 3). Rigid body analysis under-predicted contact pressure at the second peak at 55% of the gait cycle, but otherwise matched very well. The contact pressure contours for positions throughout the cycle were compared and also closely match. Contact area for the rigid and deformable analyses differed by approximately 20 mm^2 (Figure 3). CPU time for the TKR analyses was approximately 8 hours for the full deformable analysis, yet as little as 8 minutes for the rigid body analysis. Contact pressures and areas determined during the stance phase gait cycle loading for the THR were nearly identical for the rigid and deformable analyses, yet the rigid analysis required only a 3 minutes to complete, compared to approximately 3 hours for the deformable simulation.

DISCUSSION

Joint kinematics and contact mechanics significantly influence the long-term success of total knee arthroplasty. Polyethylene stresses and strains are of interest in predicting potential for wear or damage. Hence, a great deal of recent research has focused on determining the magnitude and distributions of stresses within polyethylene components. As traditional implicit and explicit FE methods require considerable computational time, the aim of this study was to develop efficient, rigid body FE analyses capable of reproducing the predicted joint mechanics of a deformable analysis. Experimental evaluation was accomplished by comparing model-predicted relative kinematics with measured data from the Stanmore knee simulator. Excellent agreement was found between the trends and magnitudes of experimental and model predicted kinematics for both the deformable and rigid analyses. Deformable contact mechanics were very reasonably reproduced using the rigid body with softened contact approach for both the THR and TKR models. An average 98% reduction in computational time was realized using the rigid body analysis. TKR models were run that required less than ten minutes to complete, yet resulted in excellent kinematic agreement and good estimates of contact pressures and areas, especially notable given the highly nonlinear contact in the knee. Limitations of the rigid body analysis using softened contact include the fact that the nonlinear pressure-overclosure relationship must be estimated (using the material property data) for each mesh size, and that internal element stresses and strains are obviously not calculated. Thus, the softened contact rigid body analysis allows very efficient parametric study. The method presented here provides a unique approach in that both rigid and deformable analyses can be run from the same model. The dramatic reduction in computational time will allow repeated analyses, such as required for numerical wear simulation, to occur in an acceptable timeframe.

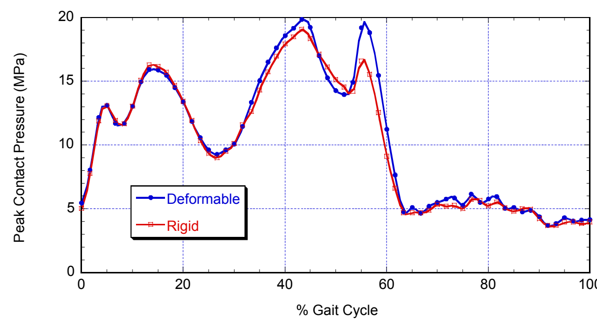

Figure 2. Predicted peak contact pressure for both rigid and deformable analyses (MPa).

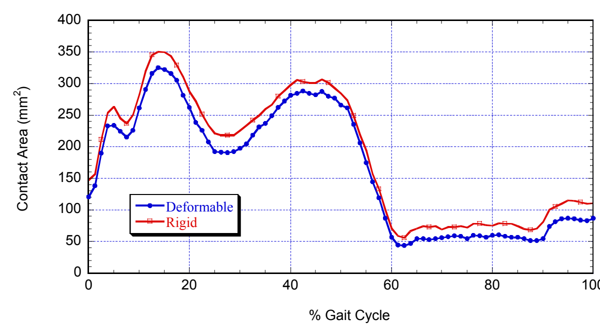

Figure 3. Predicted contact area for both rigid and deformable analyses (mm^2).

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Acknowledgement: This research was supported in part by DePuy, a Johnson & Johnson Company.