

A COMPARISON OF THE PERFORMANCE OF HEXAHEDRAL AND TETRAHEDRAL ELEMENTS IN BONE-SOFT TISSUE FINITE ELEMENT MODELS

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INTRODUCTION

Characterization of foot-ground or foot-shoe contact stresses provides significant insight into the biomechanics of the normal and pathological foot. The finite element method (FEM) is widely used in orthopaedic biomechanics for predictive simulations of joint contact stresses[1-2]. Due to the complex geometries of the anatomical structures, mesh generation accounts for most of the labor in model development. In FEM, hexahedral elements are generally preferred over tetrahedral elements because of their superior performance in terms of convergence and accuracy of solution[3,4]. This becomes more apparent as the convergence behavior of simulations are hindered by large deformation, material incompressibility, and contact with friction, mechanical features commonly seen in foot mechanics. Unfortunately, unlike tetrahedral meshing which is highly automated [5], hexahedral mesh generation is a time consuming process requiring considerable operator intervention. Despite their reputed advantages, the relative performance of tetrahedral meshes in contact models has not been well established; to our knowledge, there has not been a comprehensive study comparing the performance of hexahedral and tetrahedral elements when material and geometric nonlinearity are combined with material incompressibility and shear force loading conditions. Hence, the objective of the present study was to evaluate various types of meshes that can be used to model the interaction of a bone-soft tissue construct in contact with the rigid surface under compressive and shear loading.

METHODS

To assess the influence of the mesh type on the convergence and accuracy of the solution, a

simplified geometric representation of a bone-soft tissue construct was used (a hollow sphere of inner and outer diameters of 20 mm and 30 mm, respectively). The model consisted of three components: bone, soft tissue and floor. Bone and the floor were modeled as rigid bodies to decrease computational time and the soft tissue was modeled as an incompressible hyperelastic material with a strain energy represented by a first order Ogden material model [6]. The bone and floor were meshed using 2D rigid shell elements (triangular and quadrilateral) while soft tissue was meshed using 3D continuum tetrahedral (linear and quadratic) and hexahedral (linear) elements [7]. A mesh convergence study was performed using both the models to assess the required mesh density (number of nodes and elements) for a converging solution. Tied contact was defined between the bone and the soft tissue so as to prevent any relative motion. Surface-to-surface contact was defined between the soft tissue and the floor. Two types of simulations were conducted using: 1) frictionless contact and; 2) contact with a coefficient of friction (0.3) between the floor and the soft tissue. The floor was completely fixed in all degrees of freedom while the bone and the soft tissue were allowed to move in the vertical direction (the direction of the applied load) and also horizontally along the direction of the applied shear force where appropriate. Two loading scenarios were considered. In the first case, a constant compressive load of 300N was applied to the bone. In the second case, the compressive load was increased to 700N and in addition, a shear force of 100N was also applied to the bone. Additional simulations also evaluated the effect of relaxation of the incompressibility assumption on tetrahedral mesh performance. For this purpose the Ogden material model parameter, was changed to reflect an

effective Poisson's ratio of 0.45. In all simulations, the influence of the mesh type on the contact pressure predictions between the soft tissue and the rigid floor, and solution time was assessed. All the simulations were performed on a 16 processor computer with 64 GB RAM. Abaqus 6.10 beta [7] was used for the FE analysis.

RESULTS AND DISCUSSION

The peak pressure values, pressure distribution patterns, and the CPU times under the given loading conditions for hexahedral, linear and quadratic tetrahedral meshes are reported in Table 1. Contact pressure distributions for various conditions are shown in Figures 1, 2, and 3. Models consisting of hexahedral, linear and quadratic tetrahedral elements resulted in smooth and uniform pressure distribution in frictionless contact under compressive and shear loading conditions at full incompressibility [8]. When frictional contact was added between the soft tissue and the floor, the pressure distribution from the mesh consisting of linear tetrahedral elements was mesh dependent, as illustrated by many patches of locally elevated pressure indicating the phenomena of shear locking at full incompressibility (Figure 1b). Models consisting of hexahedral and quadratic tetrahedral elements resulted in smooth and uniform pressure distribution in frictional contact under compressive (Figure 2a, b) and shear loading conditions at full incompressibility (Figure 3a, b). In the most challenging simulation (700N compression, 100 N shear, contact with friction), both hexahedral and quadratic tetrahedral meshes resulted in similar pressure distributions.

CONCLUSIONS

Given the large amounts of time required for meshing complex anatomical structures using hexahedral elements, use of quadratic tetrahedral meshes appears to be a feasible alternative even in the setting of large-deformation hyperelastic contact. It should be noted that other FE solvers may have varying formulations to accommodate material and geometric nonlinearities and results from a test problem such as that presented here should always be examined.

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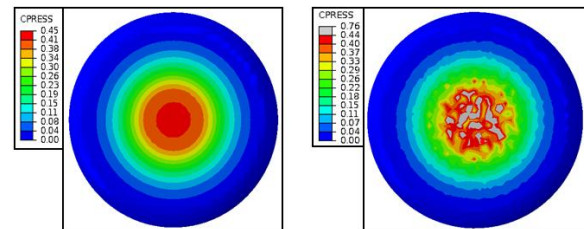


Figure 1: (a) Pressure distribution in hexahedral mesh as a result of compressive load (300 N) and contact with friction ($\mu=0.3$) at full incompressibility. (b) Corresponding pressure distribution in linear tetrahedral mesh.

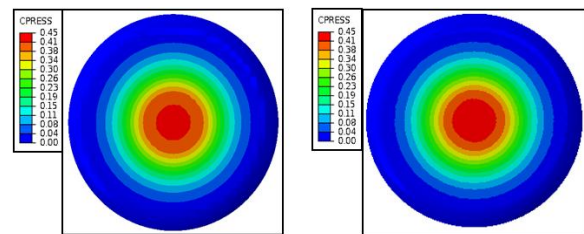


Figure 2: (a) Pressure distribution in hexahedral mesh as a result of compressive load (300 N) and contact with friction ($\mu=0.3$) at full incompressibility. (b) Corresponding pressure distribution in quadratic tetrahedral mesh.

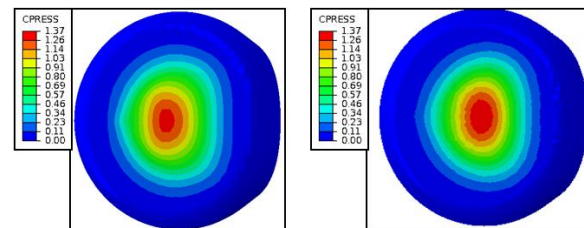


Figure 3: (a) Pressure distribution in hexahedral mesh as a result of compressive load (700N) combined with shear force (100N) and contact with friction (0.3) at full incompressibility. (b) Corresponding pressure distribution in quadratic tetrahedral mesh.

Type of Mesh	μ	ν	Load	Contact Pressure (KPa)	Time(Sec)
Hexahedral	0	0.5	300 (C)	450.5	5833
Tetrahedral (Lin)	0	0.5	300(C)	474.3	4018
Tetrahedral (Quad)	0	0.5	300(C)	462.0	8238
Hexahedral	0.3	0.5	300 (C)	440.4	13779
Tetrahedral (Lin)	0.3	0.5	300(C)	765.5	30964
Tetrahedral (Quad)	0.3	0.5	300(C)	450.4	19459
Hexahedral	0.3	0.5	700(C) + 100(S)	1303	64444
Tetrahedral (Lin)	0.3	0.5	700(C) + 100(S)	1593	75516
Tetrahedral (Quad)	0.3	0.5	700(C) + 100(S)	1371	64390

Table 1: Influence of mesh type on peak contact pressure prediction and computational time, coefficient of friction, Poisson's ratio, compressive (C) and shear (S) load, peak contact pressure and the simulation times.