INTRODUCTION:
Accurate prediction of stresses at the foot-ground or foot-shoe interface can provide insight into the biomechanics of foot pathology especially in people with diabetes and peripheral neuropathy [1]. Finite Element (FE) models of the foot comprised entirely of tetrahedral or hexahedral elements have been previously developed [2-8]. Our previous work has demonstrated that poor element selection may hinder accurate representation of normal and shear stresses under the foot [9]. This is particularly true in the setting of nonlinear tissue response, tissue incompressibility, contact with friction, and the use of conventional linear tetrahedral elements. Hexahedral elements are generally preferred over tetrahedral elements because of their superior performance in terms of accuracy and convergence [10]. However, while tetrahedral meshing can be easily automated, hexahedral meshing commonly requires user intervention and is sometimes unrealistic due to the geometric complexity of the foot. Recent advances in finite element formulations have led to the development of higher order enhanced tetrahedral elements which may serve as adequate substitute for hexahedral elements especially under large deformations. Hence the objective of the present study is to extend our previous work [9,11] by evaluating various types of meshes with different element types that can be used to model interaction of a bone-soft tissue construct in contact with a rigid floor and deformable footwear materials under physiologically realistic compressive and shear loading conditions.

METHODS:
A previously developed FE model of a bone-soft tissue construct representative of heelpad geometry was used [9, 11]. All simulations were performed using ABAQUS 6.10. The model consisted of bone, soft tissue, floor, and insole components. The bone and floor were modeled as rigid bodies while soft tissue was modeled as an incompressible hyperelastic Ogden material [4]. The insole, representative of Microcel Puff, a commonly used footwear material, was modeled as a nonlinear hyperfoam [5]. The bone and floor were meshed using 2D rigid shell elements (triangular and quadrilateral); the insole was meshed with hexahedral elements (C3D8H) and the soft tissue was meshed using one of the following elements, all of which accommodated incompressibility: hexahedral (C3D8H), linear tetrahedral (C3D4H), quadratic tetrahedral (C3D10MH) and enhanced quadratic tetrahedral (C3D10I). A mesh convergence study ensured the appropriate and equivalent element sizes across models to ensure a meaningful comparison. Tied contact was defined between bone and soft tissue to prevent any relative motion. Frictional contact (μ=0.3) was defined between the soft tissue and insole as well as between insole and rigid floor (or tissue and floor in barefoot simulations). The floor was completely fixed in all degrees of freedom while bone and 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. Compression only loads of 300 N simulated standing; to simulate nearly heel strike like condition, a compressive load of 700N was applied to the bone in addition to a shear force of 100N. Simulations were conducted to assess the influence of element type on the contact pressure and contact shear stress predictions (between the soft tissue and floor or insole) and on solution time. The simulations were performed on a 16 processor computer with 64 GB RAM [12].

RESULTS:
Figure 1 illustrates exemplar contact pressure distributions predicted by models with different loading conditions and with different element types simulating the stress within the soft tissue. During compression-only loading on both rigid and deformable surfaces, linear tetrahedral elements generated extremely noisy pressure distributions which overestimated peak pressure compared to the hexahedral elements (Fig 1a and b) because of many isolated patches with predicted high pressures (Figures 1c and d). However, the enhanced quadratic tetrahedral elements performed well under both compressive and combined compressive and shear loading (Fig 1e and f). The simulation times for the model comprising linear and quadratic tetrahedral elements were 0.66 and 2.45 times that of hexahedral elements in barefoot simulations and 0.7 and 2.2 times that of hexahedral elements in footwear simulations. All models using quadrilateral tetrahedral elements (C3D10MH) had numerical difficulties in deformable-deformable contact conditions that hindered convergence to a solution.

DISCUSSION:
Our results show that for foot and footwear simulations FE models using enhanced quadratic tetrahedral elements can perform well under both compression and combined shear and compressive loading. Linear tetrahedral elements do not provide a satisfactory simulation compared to hexahedral or enhanced quadratic tetrahedral elements. However, the average computational time required by a model using enhanced quadratic tetrahedral elements is much higher compared to that of an equivalent hexahedral mesh [11]. Given the large amounts of time required for meshing complex anatomical structures using hexahedral elements, the use of enhanced quadratic tetrahedral elements (C3D10I) appears to be a feasible alternative even in the setting of large-deformation, deformable-deformable contact, nonlinear, and incompressible tissue properties. It should be noted that other FE solvers, or different versions of the same solver, may have varying formulations to accommodate material and geometric nonlinearities and the results of a test problem similar to that presented here should be explored on a solver by solver basis.

REFERENCES: