VALIDATION OF HIP JOINT CONTACT PressURES IN A SUBJECT-SPECIFIC FINITE ELEMENT MODEL

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INTRODUCTION: A better understanding of patient-specific hip joint cartilage contact pressures may improve the diagnosis and surgical treatment of disorders and provide the basis for preoperative surgical planning. Due to the complex geometry of the hip, the finite element (FE) method offers several advantages over simplified mathematical models or experimental studies. The objective of this study was to use subject-specific modeling techniques to construct and validate a FE model of a cadaveric hip joint using experimental measures of cartilage contact pressure under physiological loading.

METHODS: All soft tissue except articular cartilage was removed from a 25 y/o male hip (bodyweight = 82 kg). A volumetric CT scan was obtained (320 mm field of view, in plane resolution = 0.625 X 0.625 mm, 0.6 mm slice thickness). A solid mineral phantom was included in the CT scan to correlate trabecular bone density with stiffness. A custom manufactured loading apparatus and in-vivo hip joint loading data [1] were used to test three physiological loading scenarios on the cadaveric hip (walking, stair climbing, and descending stairs). Pressure sensitive film (Sensor Products Inc., range 1.7–10 MPa) was cut into a rosette pattern and placed between polyethylene sheets on the femoral head. Peak loads for each scenario (141 - 261% BW) [1] were simulated by displacing the femur into the acetabulum at a loading rate of 1.5 Hz, representative of the average time reported by [1]. The films were converted to color for comparison with FE predictions.

Separate surfaces for the outer cortex, the boundary of the cortical and trabecular bone, and articular cartilage of the pelvis and femur were extracted from the CT data. An FE model was created from the surfaces, consisting of tetrahedral and hexahedral elements for trabecular bone and cartilage, respectively (Fig. 1). Cortical bone was represented using triangular shells with position-dependent thickness [2]. Cartilage was represented as a homogenous, isotropic, incompressible, neo-Hookean hyperelastic material with shear modulus, G=5.0 MPa [3]. Bone constitutive relations and material properties were based on a previous FE model of the pelvis [2]. Boundary conditions were defined to mimic those applied experimentally. All FE analyses were performed with NIKE3D. FE predicted contact pressures were transformed into a flat rosette pattern that had the same dimensions, including rosette cuts, as the experimental films.

Sensitivity studies were performed to investigate how changes in cartilage material properties and boundary conditions affected FE predictions of cartilage contact mechanics. The cartilage shear modulus was altered by ±1 SD [4] and bulk to shear modulus ratios of 10:1 (v=0.452) and 100:1 (v=0.495) were analyzed in separate models for the walking loading scenario. Bones were also assumed to be non-deformable (rigid) structures for each of the loading scenarios tested.

RESULTS: Experimental pressures ranged from 1.7 – 10 MPa (limits of film detection). FE predictions of contact pressure (Fig. 2) and contact area (Fig. 3, top left) corresponded well with experimental measurements. Alterations to the shear modulus (~±50% change) resulted in less than ±25% change in FE predictions of peak pressure, average pressure and contact area (Fig. 3, top right). Lowering the cartilage Poisson’s ratio from v=0.5 to v=0.495 (bulk to shear ratio of 100:1) did not have an appreciable effect (Fig. 3, bottom, left). A further decrease in the Poisson’s ratio to 0.452 (bulk to shear ratio of 10:1) resulted in up to a 20% change in FE predictions (Fig. 3, bottom left). Changes in FE predictions were prominent when bones were represented as rigid structures, especially during simulated walking and descending stairs (Fig. 3, bottom right).

DISCUSSION: FE predicted contact pressures and areas were in very good agreement with the experimentally measured data, both in terms of magnitude and location. Notably, the FE model predictions were relatively insensitive to deviations in cartilage shear modulus (a 50% change in the shear modulus resulted in only a 25% change in predicted contact stresses). Thus small errors in material coefficients associated with deviatoric response may be tolerated. In terms of the assumed volumetric response, FE predictions were most accurate when articular cartilage was represented as incompressible. Reducing the shear:bulk modulus ratio to 100:1 had only minor effects, while a reduction to 10:1 resulted in errors of up to 18% in predicted contact stresses. Therefore, incompressibility was an appropriate assumption for cartilage in this study, and this is consistent with the relatively rapid loading rate that was used in the experiments.

Representing the bones as rigid structures had a dramatic negative effect on the accuracy of FE predictions of pressures. This finding is in disagreement with a FE study of the knee [5]. The difference in results is likely due to the fact that the underlying boundary and loading conditions dictate whether or not bony deformation will affect FE predictions of contact stress. The modeling protocol developed herein demonstrates the feasibility of the FE method for elucidating patient-specific hip joint pressures. These validated methods will provide the basis for patient-specific modeling of the mechanics of hip dysplasia.

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Figure 1: (Left) hip FE model; (Right) close up view of joint surfaces

Figure 2: Cartilage contact pressures for all three loading scenarios (columns) with FE predictions (top row) and exp. measurements (bottom row). SC- stair climbing, DS- descending stairs, W- walking.

Figure 3: Top left) FE and exp. contact areas. Change in peak pressures, avg. pressures, and contact areas due to: top right) cartilage Poisson’s ratio, and bottom right) rigid bones. W- walking, DS – descending stairs, SC- stair climbing.