A SUBJECT-SPECIFIC FINITE ELELMENT MODEL OF THE PELVIS ACCURATELY PREDICTS CORTICAL STRAINS UNDER ACETABULAR LOADING

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INTRODUCTION: An improved understanding of the stress distribution in and around the hip may provide important information regarding the relationship between altered pelvic and acetabular geometry and the development of hip osteoarthritis, as well as point to improved diagnostic methods and analysis of surgical treatments. Because of the complex geometry of the acetabulum and pelvis, a numerical method can facilitate analysis of stress and strain distributions. Although finite element (FE) models of the pelvis have been reported [1-3], validation was not performed with experimental measurements. Past models used simplified bone geometry and homogeneous material properties. The objectives of this study were to develop and validate a FE model of the pelvis using subject-specific measurements of bone geometry, location-dependent cortical thickness and cancellous bone elastic modulus, and to assess the sensitivity of FE predictions to assumptions regarding cortical thickness and cancellous bone elastic modulus.

METHODS: A combined experimental and computational protocol was used to validate a subject-specific model of a 68 y/o female pelvis. The sacroiliac joint and all soft tissue were removed. A volumetric CT scan (512x512 acq. matrix, FOV=225mm, 354 slices, thickness=0.6mm) was obtained.

The iliac crests were submerged in a mounting pan of quick-setting cement to a predetermined depth. Ten rosette strain gages (30 channels) were attached around the acetabulum, pubis, ischium, and ilium (Fig. 1). Vertically orientated loads (0.25, 0.50, 0.75, and 1.0 BW) were applied to the acetabulum via a femoral prosthesis, attached to a linear actuator, while strain data were recorded continuously. 3D coordinates of the strain gauges and prosthesis were digitized (Immersion Corp., San Jose, CA). Data were analyzed to determine minimum and maximum principle strains as a function of gauge position and load.

Separate surfaces for the outer cortex and the boundary of the cortical and cancellous bone of the pelvis were extracted from the CT data. (Fig. 2, L). An FE model was created from the surfaces, consisting of triangular shell elements for cortical bone and tetrahedral solid elements for cancellous bone (Fig. 2, R). Acetabular cartilage was represented with shell elements at a constant thickness of 2 mm. A novel algorithm was developed to assign a spatially varying cortical shell thickness based on the spatial distance between the two polygonal surfaces.

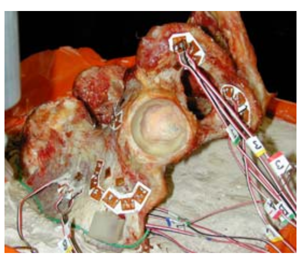

Fig 1: Strain gages and stress relief tabs attached to the cadaveric pelvis.

The femoral implant, cortical and cancellous bone were represented as isotropic hypoelastic. Cortical bone was assigned properties of E=17 GPa and ν=0.29 [2]. Relationships between CT Hounsfield unit, apparent density and elastic modulus were used to assign a density-dependent modulus for each tetrahedral element [5,6], with ν=0.20 [6]. Acetabular articular cartilage was represented as a hyperelastic Mooney-Rivlin material. Coefficients C_1 and C_2 for articular cartilage were assumed to be 4.1 MPa and 0.4 MPa respectively with ν=0.4 [4]. Boundary conditions and loads were applied to the FE model to mimic those used experimentally. Nodes superior to the cement line and nodes along the pubis-symphasis joint were defined as rigid. Contact was enforced between the femoral implant and cartilage surface while the appropriate load was applied to the implant. All analyses were performed with the implicit capabilities of LS-DYNA. FE predictions of maximum and minimum cortical principal strains were averaged over elements that were located beneath each strain gage.

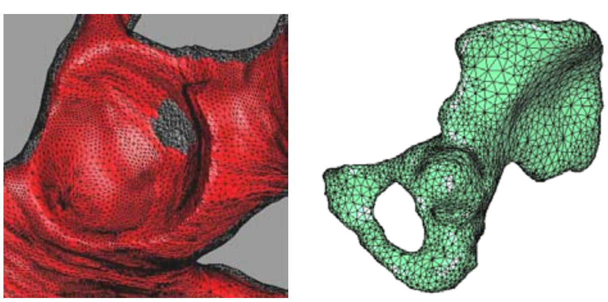

Fig. 2: Left – closeup of surfaces at acetabulum, showing cortex (black) and cortical-cancellous bone boundary (red). Note region of only cortical bone. Right - tetrahedral FE mesh.

Sensitivity studies were performed to assess the effects of cortical bone thickness and cancellous bone material properties. Specifically, models that assumed average cortical thickness, homogenous cancellous bone density or a combination of both were analyzed and compared with experimentally measured strains.

RESULTS: Cortical bone thickness ranged from 0.4-3.0 mm (mean 1.25±0.5 mm). Cancellous bone elastic moduli ranged from 20-400 MPa (mean 150±80 MPa). The subject-specific FE model predictions of principal strains showed very good correlation with experimental measurements (R^2=0.94, Fig 4). However, the y-intercept of the best-fit line was greater than 0 indicating that the FE predictions were too stiff (Fig 4). Homogenous models showed slightly less correlation with experimental measurements and reported FE predictions that were stiffer than the subject-specific model (R^2=0.86-0.88, Fig. 3). The model that assumed constant thickness with varying elastic moduli showed the stiffest results.

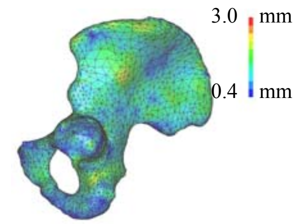

Fig. 3: Contours of position dependent cortical thickness.

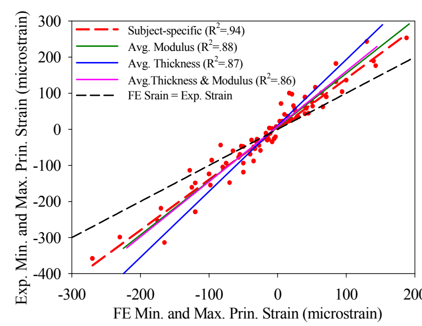

Fig. 4: FE predicted vs. experimental strains with regression lines for all models.

DISCUSSION: This research validated a subject-specific FE model of the pelvis. FE model predictions were most accurate when position dependent cortical thickness and elastic modulus were used. Although there was only a slight difference between the homogenous models and subject-specific model, it is important to note that the average cortical thickness and cancellous bone modulus were taken from the specimen itself and not from assumed values in the literature [6]. The results of this study provide the basis for future efforts to analyze patient-specific FE models of the pelvis to elucidate the biomechanics of hip dysplasia and total hip reconstruction.

REFERENCES: [1] Dalstra M, et al J Biomech 28:715-24, 1995. [2] Dalstra M, et al., J Biomech Eng 117:272-78, 1995. [3] Huiskes R, et al., Acta Orthop Scand 58:620-25, 1987. [4] Little R, et al., J Biomech Eng 34:111-19, 1986. [5] Ploeg H, et al., NAFEMS World Congress 811-22, 2001. [6] Dalstra M, et al., J Biomech 26:523-35, 1993.

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