Introducing a Fiber-Directed Anisotropic Capsule in a Total Hip Arthroplasty Dislocation Finite Element Model

Introduction
Dislocation remains a serious problem in total hip joint replacement, and joint instability now ranks number one in terms of reasons for total hip arthroplasty (THA) revisions [1]. The hip capsule, a highly intricate soft tissue complex including several major ligamentous bundles, acts to constrain motion between the acetabulum and proximal femur, while allowing for large rotational movement. The complex nature of the hip capsule requires sophisticated modeling in order to capture realistic behavior of the structure. The purpose of this study was to incorporate physiologically based anisotropic capsule representation in a dynamic total hip dislocation finite element (FE) model.

Methods
A human cadaveric hemipelvis was obtained, and was carefully dissected of all non-capsular soft tissue. Fiber directions on the exposed, intact capsule were demarcated with silastic tubes (0.6mm ID, 1.2mm OD) filled with aqueous barium contrast. These nine tubes were sutured to the outside of the capsule and were directed along major fiber directions running from the distal to proximal insertion sites. Contrast for the soft tissue was created by inflating the capsule with room air at 10.3kPa. The hemipelvis was then scanned in a 64-detector multidetector CT scanner. The CT data set was segmented (Amira 5.2) to include the marking tubes, capsule and bony structures (Fig. 1). The segmented surfaces were registered (Mathcad 14) to an existing total hip arthroplasty finite element model. The registered surfaces were meshed with TrueGrid (2.3).

The capsule was modeled using a micromechanically based anisotropic hyperelastic strain energy potential developed by Holzapfel [2], which allows for modeling a distributed collagen fiber orientation. Using the segmented fiber direction markers, the capsule was further divided into 27 independent materials, each with a separate prevailing fiber direction. Material coefficients for the capsule were inferred using previously published load-displacement data for capsule distraction [3] (Fig. 2).

The capsule was incorporated into an existing THA FE model (Fig. 1), which consists of 3 parts: Femoral component (28mm head diameter), liner (28-46mm diameters) and metal backing. Mesh densities were chosen based on convergence studies, optimized for contact analyses. A sit-to-stand kinetic motion sequence [4] was used to assess the influence of capsule integrity on dislocation resistance. Four models were run to evaluate this: (1) Hardware only FE model; (2) FE model with normal capsule geometry; (3) FE model with capsule demonstrating regional atrophy posteriorly and (4) FE model with regional capsular atrophy anteriorly. Posterior atrophy was created by selecting the posteriolateral 1/3 of the capsule, and forcing the surfaces to fit a parabolic shape function so that maximal capsule thickness change was equal to half the original capsule thickness. Anterior atrophy was similarly applied but at 180°. The FE models were run as dynamic contact simulations using Abaqus Explicit (6.9.1).

Results:
All four FE models ran to frank dislocation. Compared to hardware alone, the hip capsule increased resisting moment approximately two-fold for a sit-to-stand challenge at the limit of the range of motion (Fig. 3). Comparing the regional defect simulations, integrity of the posterior region of the capsule was far more significant in providing this resistance. Simulating posterior regional atrophy of the capsule resulted in over a 2-fold average decrease in developed resisting moment compared to the intact capsule. By contrast, the anterior atrophied capsule demonstrated only a 3% reduction over the original capsule.

Discussion:
Accurate representation of the capsule is necessary to study dislocation propensity in total hip constructs model. Previous attempts to include capsule representation have involved only isotropic models, which were unable to address the all-important effects of collagen fiber orientations. This investigation also highlights the fact that capsule defects are highly idiosyncratic: The posterior region is considerably more involved than other regions in providing resistance to dislocation for a flexion-dominated maneuver. Since the majority of post-THA dislocations are posterior, the present data accentuate the importance of capsular repair following THA, especially the posterior region following a posterior-surgical approach.

References:

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