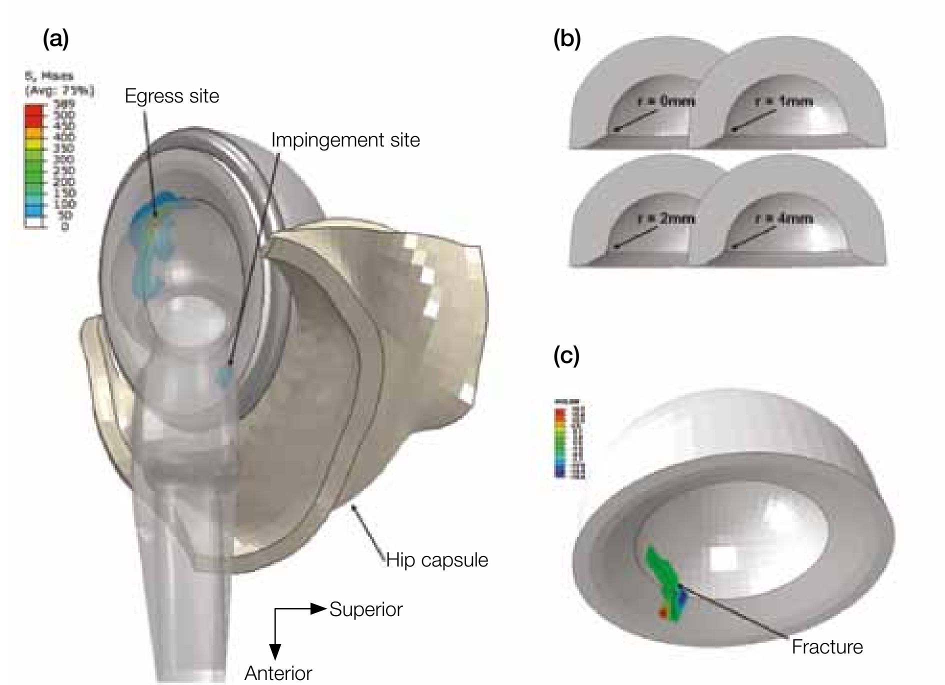
Fracture Modeling of Ceramic Liners for Total Hip Arthroplasty

Today, total hip arthroplasty (THA) is the treatment of choice to relieve joint pain and loss of mobility as a result of end-stage osteoarthritis or other severe hip pathologies. THA is one of the most successful surgical interventions in medical history. Currently, more than 250,000 cases are performed per year in the U.S., a figure expected to double in the next 20 years.

While highly successful, THAs do sometimes fail. Conventional THA bearings, consisting of a metallic femoral component articulating with a polyethylene acetabular cup, are challenged by accumulative wear debris generated over the lifespan of the implant, which can elicit adverse biological reaction. Alumina ceramics for THA were introduced nearly four decades ago to improve long-term results in younger and more active THA patients. Ceramic-on-ceramic (CoC) bearings offer several advantages over contemporary bearings, such as excellent compressive strength and lower wear. However, because of the ceramic material's brittle nature concerns persist regarding implant failure due to catastrophic fracture. In general, both components of a CoC implant are prone to fracture. Fracture of the ceramic head is a well-recognized problem historically, and extensive investigation has led to several design-specific improvements.

While it is well-established clinically that impingement between the femoral neck and liner can predispose to fracture, to date, little quantitative information exists regarding fracture propensity for liners. To help close this knowledge gap, an eXtended Finite Element Model (XFEM) of THA impingement was developed by University of Iowa and SIMULIA to investigate fracture risk and crack propagation for various cup designs and surgical orientations.



(a) Dynamic FE model of THA impingement demonstrating stress concentrations arising at both the impingement site and head egress site during head subluxation. (b) Four distinct cup designs of various edge-chamfer radii were investigated. (c) Fracture initiation and propagation corresponding to egress site during the XFEM analysis.

Method

A previously developed and physically validated nonlinear dynamic FE model of THA impingement (Figure a) was used to determine stresses developed during various impingement scenarios for a CoC implant. The FE model consisted of THA hardware (28-mm head, 46-mm liner and cup backing). The hip capsule, which acts to stabilize the joint, was assigned a fiber-based anisotropic hyperelastic constitutive model (Holzapfel-Gasser-Ogden).

Four separate models were created, by varying the cup-lip fillet radius between 0 mm and 4 mm at a constant cup inclination of 40° (Figure b), to simulate different edge profiles in contemporary THA use. Four additional models were generated to investigate surgical orientation, by varying the cup inclination between 30° and 60°, each with a constant 10° of anteversion.

Boundary conditions for driving the impingement model consisted of an input sequence of prescribed joint rotation and loading, determined from optical motion capture of subjects performing a stooping motion.

These impingement models were executed in Abaqus/Explicit. Stresses occurring during the simulations were passed (node-based) to the XFEM model of liner fracture in Abaqus/Standard. The XFEM submodel contained two separate enrichment regions, corresponding to the impingement and egress sites. Damage initiation criteria were specified at 300MPa maximum principal stress, with literature-based mixed mode (power-law) damage evolution. A separate analysis assumed a pre-existing flawed liner with correspondingly reduced fracture parameters.

Results

Fracture initiation was tracked at both the egress and impingement sites. Fractures, when they occurred, typically developed at the egress site (Figure c). Fracture initiation was demonstrated to be sensitive to both cup orientation and cup edge radius, with fracture risk increased for sharper edges at higher values of cup inclination. Substantially higher occurrence of fracture was observed for the (assumed flawed) reduced fracture criteria analyses.

The use of XFEM has proven to be a valuable technique to investigate crack initiation and propagation in ceramic THA. This technique can be used in THA design and surgical planning analysis to reduce ceramic THA fracture risk.

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