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Subject specific finite element modeling of periprosthetic femoral fracture using element deactivation to simulate bone failure

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ABSTRACT

Subject-specific finite element (FE) modeling methodology could predict peri-prosthetic femoral fracture (PFF) for cementless hip arthoplasty in the early postoperative period. This study develops methodology for subject-specific finite element modeling by using the element deactivation technique to simulate bone failure and validate with experimental testing, thereby predicting peri-prosthetic femoral fracture in the early postoperative period. Material assignments for biphasic and triphasic models were undertaken. Failure modeling with the element deactivation feature available in ABAQUS 6.9 was used to simulate a crack initiation and propagation in the bony tissue based upon a threshold of fracture strain. The crack mode for the biphasic models was very similar to the experimental testing crack mode, with a similar shape and path of the crack. The fracture load is sensitive to the friction coefficient at the implant–bony interface. The development of a novel technique to simulate bone failure by element deactivation of subject-specific finite element models could aid prediction of fracture load in addition to fracture risk characterization for PFF.

1. Introduction

Postoperative peri-prosthetic femoral fractures following total hip arthroplasty are difficult to treat and are strongly associated with increased postoperative complications [1–3] and poor functional outcomes [4]. The prevalence of postoperative peri-prosthetic femoral fracture ranges from 0.1% to 2.1%, with a rate of 4% reported in a revision setting by the Mayo Joint Registry [5]. The apparent increase in its prevalence has been attributed to the growing population of patients with existing hip arthroplasties, increasing pool of elderly patients at risk of falls, and the increasing number of young active patients at risk of high-energy trauma events [5]. Despite a higher fracture risk being linked with cementless fixation, especially in the early postoperative period [6], the recent Australian National Joint Replacement Registry Report (2010) indicates a growing trend in the use of cementless prostheses as compared to cemented or hybrid prosthesis [7]. Risk factors for peri-prosthetic femoral fractures include subject-specific or procedure-specific factors [8].

Subject-specific finite element models developed from computed tomography (CT) data are a powerful tool to investigate bone strength in different simulated clinical settings non-destructively [9–11]. Three-dimensional finite element modeling can be a better predictor of femoral strength than quantitative CT and dual energy X-ray absorptiometry [12]. Finite element analysis (FEA) techniques allow exploration of various anatomical and clinical parameters that may contribute to bone fracture [13–15], thus understanding the influence of boundary and loading conditions [9,10,13]. For this reason, subject-specific FE models of bones are able to help predict fracture risk for a bone segment under any generic loading condition (including muscles). Nevertheless, this requires development of generalized models which implement bone tissue failure and structural collapse criteria [9]. A model that adopts both criteria based on stress parameters may not be able to provide definitive results unless the FE results are validated against the data from experimental tests [16,17].

Previous studies have also adopted modeling strategies that utilized a specific strength criterion to assess bone failure based on stress parameters and compared the results with strain-based criterion [9,18,19]. However, recent advances in bone biomechanics have demonstrated that strain-based criteria are more effective than stress-based criteria in describing yield or bone failure. These previous studies have only included native femoral geometry and have been predominantly used to predict native femoral neck fracture. As peri-prosthetic femoral fracture occurs around an implant, the modeling of both the implant and the surrounding bone is essential. When

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the implant is introduced, unique challenges are presented resulting from the modeling of contact, at a boundary where there is a large stiffness discontinuity.

2. Methods

2.1. Experimental testing

A matched pair of cadaveric femur donors was sourced from the International Institute for the Advancement of Medicine (IIAM Corporate, Jessup, PA, USA) with prior ethics approval. The femurs were subjected to X-ray and then CT evaluation to ensure that they were free of pathology. After templating, the femurs were sectioned and potted in a polymethylmethacrylate (PMMA) potting medium, 30 mm distal to the expected position of the distal tip of the prosthesis for the template size. Each femur was cleaned of all soft tissue.

Prostheses manufactured by Stryker Orthopaedics (Mahwah, NJ, USA), the ABG II-plasma and the ABG II-standard size 4, were implanted in the left and right femur after a neck osteotomy. AGB II-plasma is an experimental ABG II femoral stem with a high friction plasma-sprayed titanium proximal in-growth surface with hydroxyapatite coating and proximal scales compared to the ABG II-standard with a proximal hydroxyapatite coating on a grit-blasted titanium surface with proximal scales.

To replicate the anatomic loading of femoral stems a mechanical testing jig was prepared to orient the bone 9 in the sagittal plane and 10 in the coronal plane as per ISO 7206-4, 2010 specifications. An MTS 858 mechanical testing system and simulation apparatus (MTS Systems Corporation, Eden Prairie, MN, USA) was used to load the femurs to failure with the implants in situ.

2.2. Construction of a subject-specific finite element model

The CT scan of a left-sided femur was conducted for creation of the finite element model in the DICOM (Digital Imaging and Communications in Medicine) format. Simpleware Scan IP v4.3 (Simpleware Ltd., Exeter, United Kingdom) was used to segment, smoothen and export the proximal femoral geometry.

The CT protocol is summarized in Table 1.

Table 1
CT protocol details.[a]

Scanning mode	Helical
Slice thickness	1 mm from femoral head to little trochanter 5 mm in the diaphysis
Pitch	1.3 from femoral head to little trochanter 1.5 in the diaphysis
Reconstruction spacing	1.3 mm from femoral head to little trochanter 5 mm in the diaphysis
Pixel dimension	0.59 mm
Tube current	160 mA
Voltage	120 kVp

[a] Peak voltage and tube current levels are typical of clinical examinations. The femurs were immersed in water to prevent beam-hardening effects.

The volume of interest was isolated whereas the volume not representing proximal femoral bone was removed by utilizing the grayscale within the voxels. A threshold value of grayscale below which the voxel could be assigned to bone or soft tissue and therefore space allowed floodfill segmentation operation to approximately segment the bone from the surroundings. Cavity fill was used to fill rough areas. A second segmentation threshold was set up to remove the bone marrow. To unite the marrow volume, a Morphological Close was carried out. To remove the bone marrow volume, a Boolean operation was performed to subtract the marrow volume from the proximal femoral bone volume.

Once the correct geometry was isolated, the voxel mesh with irregular edges was smoothed and transformed into a geometric mesh. A voxel based mesh, with a jagged surface would be inappropriate for contact modeling as it could cause stress concentrations and solution convergence. To smooth and transform the mesh, a Gaussian filter was adopted.

The femur model alone was exported to the ScanCAD module in Simpleware where a single-cut neck osteotomy was simulated by introducing a CAD primitive and performing a Boolean operation. CAD models of the definitive ABG II prostheses in the .stl format, with some minor geometrical simplifications (for example, removal of small cut-outs in the proximal region), were provided by Stryker Orthopaedics. The removal of the small cutouts simplified the mesh generation and contact modeling.

An ABGII femoral stem was virtually inserted into bone canal to simulate the surgical preparation as in the experimental testing, as seen in Fig. 1. Boolean operations were applied to simulate the removal of the cancellous tissue by broaches and the distal reaming step around the distal stem, as surgically required for the insertion of

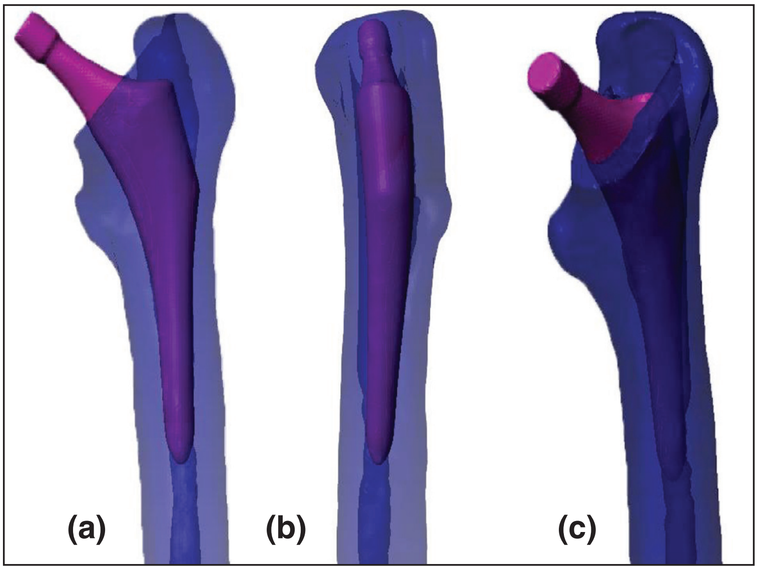

Fig. 1. Anterior (a), lateral (b) and 3D (c) views of the model in ScanCAD.