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Specimen-specific modeling of hip fracture pattern and repair

Azhar A. Ali[a], Luca Cristofolini[b], Enrico Schileo[c], Haixiang Hu[a], Fulvia Taddei[c], Raymond H. Kim[a,d], Paul J. Rullkoetter[a], Peter J. Laz[a,*]

[a] *Center for Orthopaedic Biomechanics, University of Denver, Denver, CO 80208, USA*
[b] *Department of Industrial Engineering, School of Engineering and Architecture, University of Bologna, Bologna, Italy*
[c] *Laboratorio di Tecnologia Medica, Istituto Ortopedico Rizzoli, Bologna, Italy*
[d] *Colorado Joint Replacement, Porter Adventist Hospital, Denver, CO, USA*

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ABSTRACT

Hip fracture remains a major health problem for the elderly. Clinical studies have assessed fracture risk based on bone quality in the aging population and cadaveric testing has quantified bone strength and fracture loads. Prior modeling has primarily focused on quantifying the strain distribution in bone as an indicator of fracture risk. Recent advances in the extended finite element method (XFEM) enable prediction of the initiation and propagation of cracks without requiring a priori knowledge of the crack path. Accordingly, the objectives of this study were to predict femoral fracture in specimen-specific models using the XFEM approach, to perform one-to-one comparisons of predicted and in vitro fracture patterns, and to develop a framework to assess the mechanics and load transfer in the fractured femur when it is repaired with an osteosynthesis implant. Five specimen-specific femur models were developed from in vitro experiments under a simulated stance loading condition. Predicted fracture patterns closely matched the in vitro patterns; however, predictions of fracture load differed by approximately 50% due to sensitivity to local material properties. Specimen-specific intertrochanteric fractures were induced by subjecting the femur models to a sideways fall and repaired with a contemporary implant. Under a post-surgical stance loading, model-predicted load sharing between the implant and bone across the fracture surface varied from 59%:41% to 89%:11%, underscoring the importance of considering anatomic and fracture variability in the evaluation of implants. XFEM modeling shows potential as a macro-level analysis enabling fracture investigations of clinical cohorts, including at-risk groups, and the design of robust implants.

1. Introduction

Hip fracture remains a significant public health concern as a result of the high incidence and consequence. Approximately 1.6 million hip fractures occurred worldwide in the year 2000 (Johnell and Kanis, 2006) with approximately 281,000 hospitalizations due to hip fracture in the United States in 2007 (Hall et al., 2010). Mortality rates at 1 year following hip fracture were approximately 22% for men and 14% for women in 2005 (Brauer et al., 2009). Approximately 90% of these fractures are the result of a fall (Cummings and Melton, 2002), with many occurring in the intertrochanteric region of the femur. This type of fracture is typically repaired with an intramedullary osteosynthesis device to provide stability to the reduced fracture. While implant design and the overall procedure is generally successful, surgical revisions are required in up to 12.6% of the cases due to implant failure or delayed fracture healing (Raunest et al., 2001).

Many studies have investigated factors that influence hip fracture, specifically patient anatomy, bone quality and loading. In vivo studies have identified clinical measures associated with osteoporosis and fracture risk (Fritscher et al., 2009; Kaptoge et al., 2008; Krug et al., 2005). Experimental cadaveric testing has been performed to assess fracture load and characterize bone strength on whole bones (Cristofolini et al., 2010; Keyak, 2000) and on small samples (Morgan and Keaveny, 2001; Morgan et al., 2003). For both types of testing, specimen-specific computational models have been developed to parallel the experiments. Specimen-specific models are typically created from computed tomography (CT) or microCT scans which enable a detailed representation of the anatomy of the bone and its material properties (Keyak and Falkinstein, 2003; Schileo et al., 2008a; Ural et al., 2013a). The validation of models by showing good agreement with in vitro data (Schileo et al., 2007; Trabelsi et al., 2011; Eberle et al., 2013; Dall'Ara et al., 2013) provides confidence in the techniques that will enable their application more broadly to patients in the clinic.

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* Correspondence to: Center for Orthopaedic Biomechanics, Mechanical and Materials Engineering, University of Denver, 2390 S. York St. USA.
Tel.: +1 303 871 3614; fax: +1 303 871 4450.
E-mail address: plaz@du.edu (P.J. Laz).

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Combined experimental and modeling studies have investigated the femur under stance and fall loading conditions in both the intact natural (Cristofolini et al., 2010; Keyak, 2000) and fracture repaired condition (Eberle et al., 2010). Both the experimental and modeling data contain a significant amount of variability, likely attributed to intersubject variability in bone properties (Taddei et al., 2006a; Laz et al., 2007; Wille et al., 2012; Eberle et al., 2013).

Computational studies have identified regions of high minimum and maximum principal strain (Bryan et al., 2009; Taddei et al., 2006b), which are related to the fracture location and risk. Recently, studies have utilized a variety of FE-based techniques to advance the modeling of bone fracture including: cohesive zone elements to model a crack at microstructural and macro levels (Ural et al., 2013a,b), homogenized continuum-level voxel models (Dall'Ara et al.,2013), continuum damage mechanics methods using bone remodeling and element deletion (Hambli et al., 2013a, 2012; Hambli, 2013b), and the extended finite element method (XFEM) which models crack initiation and propagation independent of the mesh (Belytschko and Black, 1999). By predicting the damage accumulation and fracture pattern, these fracture-based approaches implemented within finite element analysis show promise in providing more mechanistic predictions of bone fracture.

As a complement to the standard finite element method, XFEM introduces a Heaviside function that allows discontinuities in an element by adding enriching degrees of freedom to the element formulation (Belytschko and Black, 1999). A specialized displacement function is evaluated for enriched elements by considering a max principal stress/strain damage initiation criterion to model fracture onset and an energy-based damage evolution criterion to model fracture propagation, which includes the redistribution of strain ahead of the crack tip as the crack grows. The XFEM approach has been implemented in the Abaqus finite element software (Dassault Systems, Providence, RI). In benchmarking, numerical results from XFEM have compared well to experiments (Song et al., 2007) and for complex geometries including material non-linearity (Gracie et al., 2008; Huynh and Belytschko, 2009). In orthopaedic biomechanics, XFEM has been applied to investigate the fracture of ceramic hip liners (Elkins et al., 2013) and demonstrated in a proximal femur under impact loading (Liu et al., 2010). The approach is similar to using cohesive zone elements with the notable difference that the XFEM approach does not require a priori knowledge of the crack path.

Computational models evaluating fracture repair have characterized the implant stresses and bone strain distribution using idealized fracture planes (Eberle et al., 2010). However, fracture patterns, influenced by anatomy and bone quality, vary greatly between subjects. By creating subject-specific fractured models, the XFEM modeling approach can be utilized as a platform to evaluate the performance of implant designs and the effects of component alignment considering intersubject variability. Mechanical stimuli across the fracture are known to be important in the healing process, although the ideal conditions are not well understood (Doblaré et al., 2004). The computational platform can predict bone strains near the fracture and load sharing between the implant and bone fracture surface in the repaired construct, which influence the local conditions for healing. Given its image-based, computational nature, the approach can be employed to investigate patient cohorts, including those in at-risk populations, and utilized in design-phase evaluations of implants, including assessments of their robustness to patient and surgical variability sources.

Accordingly, the objectives of this study were to predict femoral fracture in specimen-specific models using the XFEM approach, to perform one-to-one comparisons of predicted and in vitro fracture patterns, and to develop a framework to assess the mechanics and load transfer in the fractured femur when it is repaired with an osteosynthesis implant. Initially, specimen-specific femur models of in vitro experiments were developed under a stance loading condition to validate the approach. Then, to consider fracture repair, a sideways fall loading condition was applied to the specimen-specific femur models to induce an intertrochanteric fracture, which was repaired with a contemporary intramedullary osteosynthesis device. Simulating post-surgical conditions, implant stresses, bone strains and load sharing between the implant and fracture were evaluated under stance loading.

2. Methods

In vitro testing was performed on five cadaveric femurs (3 male, 2 female, mean age of 75.2 (range 71–82), mean height of 173 cm (range 166–178 cm) and mean weight of 69.6 kg (range 43–91 kg)) per an established testing protocol (Cristofolini et al., 2010). Prior to mechanical testing, specimens were CT-scanned (HiSpeed, GE Co., USA) immersed in water with peak voltage and tube current levels typical of clinical examinations, together with a phantom containing known densities (European Spine Phantom (Kalender, 1992)). In the experimental setup, strain gage rosettes were placed on the anterior, posterior, medial, and lateral femoral head, neck, trochanteric and metaphyseal regions of each femur. The femurs were oriented and loaded to simulate stance (Fig. 1). The femur was aligned by rotating the long axis of the femur to 8° adduction in the frontal plane. The distal femur was potted in bone cement fixing the femoral shaft in all degrees of freedom (Table 2). Initially, an elastic loading condition, consisting of an applied inferior-superior load equivalent to 75% of body weight, was applied to evaluate bone stiffness. The structural stiffness was computed as the slope of the load-cell force vs. machine-actuator deflection curve (linear regression between 10% and 90% of the full load). Strain gage rosette measurements were used to measure the maximum and minimum principal strains in local regions of the femur (Fig. 2). Subsequently, loading was ramped until failure of the specimen while high speed photography at up to 18,000 frames/s captured the fracture progression (Cristofolini et al., 2007; Juszczyk et al., 2011). Applied displacement rates were nominally 2 mm/s and 20 mm/s (Table 2) resulting in strain rates on the order of 5000 and 50,000 microstrain/s in the most stressed regions and fractures occurring in 2 s and 0.2 s, respectively.

Finite element (FE) models were developed for each of the cadaveric femurs. Bone geometry was reconstructed from the CT scans using ScanIP (Simpleware, Exeter, UK). Scans had a pixel size of approximately 0.5 mm and a slice thickness of 0.6 mm. A mesh was created to represent each femur consisting of approximately

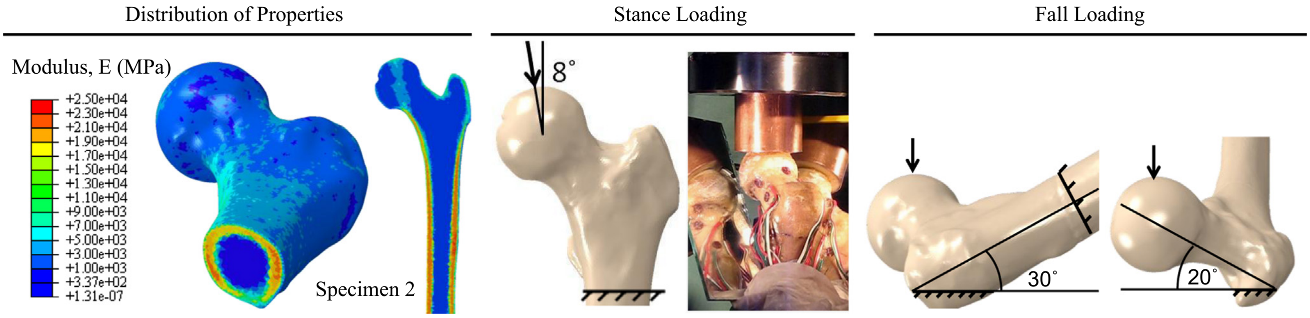

Fig. 1. Bone geometry showing distribution of material properties with applied loading conditions simulating stance (Cristofolini et al., 2010) and sideways fall (Keyak, 2000) loading conditions. (Please see the web version of the article to interpret the material property distribution in color).