# Experimental Validation of Computational Finite Element Models for Prophylactic Intramedullary Nail Fixation of Metastatic Femur Lesions

Zachary Koroneos, Hwabok Wee, Parker Fox, Scott Tucker, Edward Fox, Gregory Lewis
Penn State College of Medicine – Department of Orthopaedics and Rehabilitation
Email: zqk5040@psu.edu; Disclosures: Zachary Koroneos (N), Hwabok Wee (N), Parker Fox (N), Scott Tucker (N), Edward Fox (N), Gregory Lewis (N)

**INTRODUCTION:** Metastatic bone lesions occur frequently in the proximal femur, including the subtrochanteric intramedullary (IM) region. IM nail reconstruction is the most commonly employed strategy for prophylactic fixation to prevent completed pathologic fractures in this region.[1,2] Complication rates as high as 36% have been reported for prophylactic IM nailing, and include completed fractures and mechanical failure.[1,3] Various nailing constructs and techniques are available, but their effectiveness may vary, and endoprosthetic replacement may instead be required depending on lesion location and size.[4,5] Computational finite element (FE) models can provide insights into which scenarios IM nailing can prevent completed fractures, and the effects of implant variables such as use of distal locking screws. The purpose of this work was to experimentally validate FE models that simulate prophylactic intramedullary nailing.

**METHODS:** Three-dimensional computational models of the femur were generated based on the osseous anatomy obtained from manual segmentation of the NIH Visible Human Project (VHP) male data set. Additional modeling based on the female subject is in process. Virtual spherical subtrochanteric lesions were created to have 50%, 75%, and 90% cortical involvement of the thinnest region (Fig. 1A). FE model components were meshed with quadratic tetrahedral elements with approximately 500,000 elements total using Abaqus/CAE (Dassault Systémes), and the corresponding physical models for experimental tests were 3D printed using carbon-fiber reinforced polymer filament on an extrusion printer. Experimental validation tests were performed for both compressive loading up to 1000 N (for three lesion sizes; Fig. C-D) and offset torsional loading up to 400 N (≈ 10 N·m of torsion; for the 75% lesion; Fig. E-F) with three prophylactic fixation conditions (non-operative, IM nailing, IM nailing with distal screws). The geometry of the IM nail was based on the Gamma3 Long Nail (Stryker). Bone materials were simulated as linear elastic anisotropic, based on in-house mechanical tests of 3D printed material for cortical ($E_{11}$ = 7.54 GPa, $E_{22}$ = 2.1 GPa, $E_{33}$ = 8.1 GPa, Poisson's ratio, $\nu$ = 0.3) and cancellous (E = 25 MPa, $\nu$ = 0.3) bone. All implants were modeled as linear elastic isotropic titanium (E = 110 GPa, $\nu$ = 0.3). Axial strains from compression tests were measured with linear strain gauges, and principal strains from torsion tests were measured with triaxial rosettes around the lesion site. Strains, as well as construct stiffness, were compared between experimental measurements and computational results (n=3 per lesion size, with repeated measures across implant conditions).

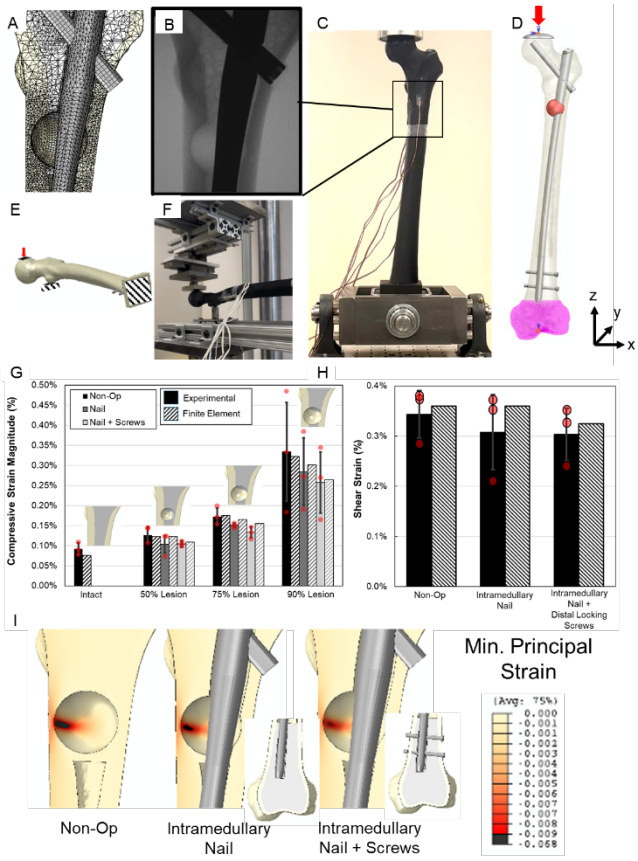


Figure: A simulated subtrochanteric lesion with 90% cortical involvement with intramedullary nail fixation, showing (A) finite element model, and (B) a radiograph of a corresponding 3D printed bone sample (B). Biomechanical experiments and corresponding FE model setups for (C,D) compressive loading simulating the stance phase of gait and (E,F) offset torsion were conducted. FE and experimental result comparisons for (G) compressive strains measured along the shaft axis for 1000 N of compressive loading for all three lesion types and fixation models, and (H) maximum principal strain comparisons for 400 N of offset torsional loading of the 75% cortical involvement lesion for all three fixation models. (I) FE results show limited effects of IM nail in contour plot of minimum principal strain at the endosteal surface (cross-section) under compressive loading at 1000 N.

**RESULTS:** FE and experimental models demonstrated greater strain magnitudes with increasing lesion size, and subtle strain reductions with the addition of an IM nail and distal locking screws under compressive loading (Fig. G). FE models showed good agreement with mean experimental data when comparing strains at the lesion for both compressive (mean difference: 8.28% ± 6.2%) (Fig. G) and torsional (mean difference: 9.7% ± 5.3) (Fig. H) loading across all models. Stiffnesses were also similar between FE and experimental models for both compressive (mean difference: 7.4% ± 6.5%) and torsional (mean difference: 4.7% ± 1.4%) loading. IM nailing with distal locking screws produced the lowest strains for both loading types, however, strain improvements were less than 0.1% strain (Fig. I).

**DISCUSSION:** The effects of prophylactic IM nailing with and without distal locking screws were more pronounced when the size of the lesion was greater (Fig. G-I). However, the strain reduction due to IM nailing (compared to non-op.) was relatively small (< 0.1%) for both FE and experimental tests. Cortical bone yield strains have been reported as 0.67% and 0.98% for tensile and compressive strains.[6] This may indicate that more rigid fixation than IM nailing may be required for reliable prophylactic stabilization of subtrochanteric lesions. Ongoing efforts include sensitivity analyses, and parametric studies of different proximal femur lesions. Limitations of this study include simplified lesions, loading assumptions that remained within the linear elastic region of the physical material, and small validation sample size.

**SIGNIFICANCE/CLINICAL RELEVANCE:** This study provides the first set of experimentally validated computational models of metastatic femurs with subtrochanteric lesions and prophylactic IM nail fixation. These models can support surgical decision-making by clarifying when IM nailing is insufficient, and guiding implant selection for subtrochanteric metastatic lesions.

**References:**

1. Tanaka T. et al. ,. World J Surg Oncol. 2016;14:4–9.
2. Ganz R. et al.,, Arch Orthop Trauma Surg. 1984;103:73–80.
3. Alvi HM. et al., Clin Orthop Relat Res. 2013;471:706–714.
4. Pasha A. et al., Iowa Orthop J. 2022;42:249–254.
5. Chin H-C. et al., Clin Orthop Relat Res. 1989;248:231:239.
6. Morgan EF. et al., Annu Rev Biomed Eng. 2018;20:119–143.