Utilizing MRI-Based Finite Element Modeling to Assess the Influence of Geometry and Material Distribution on Atypical Femoral Fracture

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INTRODUCTION: Atypical femoral fracture (AFF) is a fracture that occurs in the subtrochanteric and midshaft of the femur. AFF has been associated with the long-term use of bisphosphonate which may influence the material properties of the femur. Geometrical features of the femur have also been identified as a risk for AFF. However, the relative contribution of these factors to AFF has not been identified. As a result, the aim of this study is to assess the influence of femoral geometrical and material properties on AFF using a magnetic resonance imaging (MRI)-based finite element (FE) modeling approach.

METHODS: Six freshly frozen human cadaveric femurs from female donors (60 to 89 years old) were scanned via MRI at a 341 μm isotropic voxel size. The anterior/posterior and lateral/medial images of the femurs were taken along with a calibration tool to measure the geometrical features of the femurs. Ten geometrical features of femurs were measured via MATLAB including femur neck thickness (FNT), femur total length (FTL), femur head diameter (FHD), neck shaft angle (NSA), mid-shaft diameter (MSD), absolute offset (OSA), vertical offset (OSV), greater trochanter height (GTH), anterior bowing angle (ABA), and lateral bowing angle (LBA) (Fig. 1a). The 2D iterative closet point algorithm was utilized to ensure the markers' location consistency among the samples. The MRI images were processed using Simpleware ScanIP (Synopsys) and were cropped to include the entire range of possible locations of AFF in the models. Following this, the FE meshes composed of tetrahedra were generated (~700k elements), which were imported into the FE analysis software Abaqus (Dassault Systemes Simulia Corp). Fracture process was modeled by the cohesive extended finite element method (XFEM). The femurs were subjected to stance loading under displacement control loading. Two different models were generated per femur incorporating (i) heterogeneous material properties that reflect the bone volume fraction distribution, and (ii) homogeneous material properties with 100% bone volume fraction throughout the model. The 100% bone volume fraction was assigned an elastic modulus of 15,000 MPa, ultimate strength of 109.5 MPa, and critical energy release rate of 1.196 N/mm based on the literature [1-3]. In heterogeneous models, the elastic modulus was assumed to vary linearly with bone volume fraction [1]. Ultimate strength was taken as directly proportional and fracture toughness was taken as inversely proportional to elastic modulus [4, 5]. The correlation between the load-displacement data from the simulations and the femoral geometrical properties were calculated. In addition, mechanical properties including stiffness, ultimate load, and ultimate displacement in homogeneous and heterogeneous models were compared.

RESULTS: In homogeneous models, the ultimate load and stiffness showed a significant negative correlation with OSA (Fig. 1b, 1d) and the ultimate load showed a significant positive correlation with OSV (Fig. 1c). A decreasing trend in ultimate load with ABA and ultimate displacement with NSA was also observed ($p<0.08$). The crack initiation and propagation were captured in the AFF region of all models (Fig. 2a). Mechanical properties obtained from the three femur models (Femur A, B, C) were compared with the femur model (Femur D) which had the lowest mechanical properties. The stiffness in homogeneous models of Femur A, B and C increased by 34.6%, 38.6%, and 55.4%, respectively compared to the homogeneous model of Femur D (Table 1, Fig. 2b). These differences were only due to the differences in geometrical properties of the femurs as the homogeneous models all have the same material properties. A similar trend was observed in the ultimate load and to a moderate extent in the ultimate displacement (Table 1). The stiffness, ultimate load, and ultimate displacement were altered further when heterogeneous material properties representing bone volume fraction were incorporated in the models (Table 1, Fig. 2b). Incorporation of the bone volume fraction information influenced the percent difference in mechanical properties among femurs in a femur-specific manner compared to the homogeneous models (Table 1).

DISCUSSION: This research introduced a modeling strategy that integrated MRI and fracture mechanics-based finite element modeling to assess the influence of geometrical and material distribution on AFF. Despite identical material properties in femurs, the differences in stiffness, ultimate load, and ultimate displacement among femurs underscore the influence of femur geometry on AFF. Alterations in the distribution of material properties through bone volume fraction also altered the mechanical response of the femurs. These results indicate that both the femur geometry and material properties may contribute to the occurrence of AFF and the relative influence of these factors may be patient-specific. Future studies will incorporate a larger dataset to delineate the specific relationships among the mechanical properties and the assessed geometrical and material properties.

SIGNIFICANCE/CLINICAL RELEVANCE: MRI-based FE modeling can noninvasively assess the contribution of material and geometrical properties of the femur to AFF and help reduce the occurrence of AFF by identifying patients at risk of AFF.

REFERENCES: [1] Rajapakse et al., Radiology 283, 2017 [2] McCalden et al., J Bone Joint Surg Am 75, 1993 [3] Zioupos et al., Bone 22, 1998 [4] Gustaffson et al., J Mech Behav Biomed Mater 113, 2021 [5] Granke et al., J Bone Miner Res 30, 2015.

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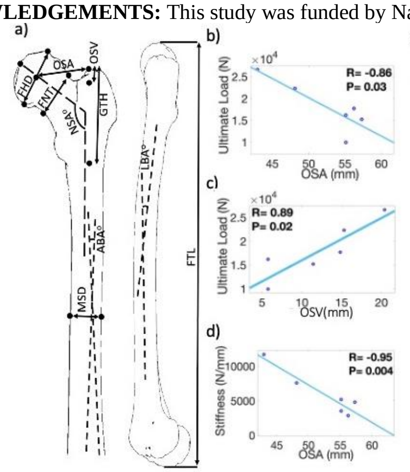

Figure 1: (a) Femur geometrical properties with measuring landmarks. Correlation of (b) ultimate load and OSA (c) ultimate load and OSV, and (d) stiffness and OSA.

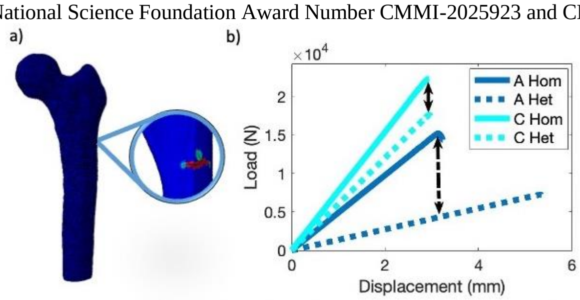

Figure 2: a) Crack initiation in a sample FE model (b) Comparison of load vs displacement plots between two sample homogeneous (Hom) and heterogeneous (Het) models.

Table 1. Percent difference in mechanical properties in homogeneous and heterogeneous models of Femur A,B,C compared to Femur D which has the lowest mechanical properties

	Material	Femur A	Femur B	Femur C
Stiffness (N/mm)	Hom	34.6%	38.6%	55.4%
	Het	11.8%	59.2%	63.7%
Ultimate load (N)	Hom	26.6%	32.0%	53.5%
	Het	19.2%	73.4%	81.5%
Ultimate Displacement (mm)	Hom	11.9%	12.0%	4.5%
	Het	8.4%	34.8%	49.2%