Biomechanical Analysis of the Femoral Neck System (FNS) for Femoral Neck Fracture (FNF) Fixation

Wei Zeng[1], Mengyin Xu[1], Yuewei Lin[2]
[1]New York Institute of Technology, Old Westbury, NY, [2]Brookhaven National Lab, Upton, NY
wzeng03@nyit.edu; ywlin@bnl.gov

Disclosures: N for all authors

Femoral neck fractures (FNFs) occur between the femoral head and intertrochanteric line and are among the most common orthopedic injuries. This study aims to develop an advanced computational approach combining finite element analysis (FEA) and machine learning (ML) to assess the biomechanical performance of the Femoral Neck System (FNS), a minimally invasive implant for FNF fixation. A series of FEA models were built to simulate the femur-implant system and evaluate the effects of different fracture morphologies on mechanical behavior, with ML used to extend predictions across untested fracture variations.

INTRODUCTION: FNFs account for over 50% of proximal femoral fractures [1] and are often classified by Pauwels angle, which reflects the fracture's verticality and shear risk. Pauwels Type III fractures [2], with angles exceeding 50°, present the highest mechanical challenge due to increased shear forces. However, the original Pauwels classification is based on 2D X-ray imaging and lacks precision in capturing 3D morphological variability [3]. This study investigates the mechanical influence of varying Pauwels Type III morphologies on FNS fixation, focusing on how fracture orientation affects implant performance.

METHODS: FEA models of femur-FNS constructs were developed using geometry from the Visible Human Male (VHM) dataset [4]. Meshing was performed in HyperMesh, and boundary conditions, material properties, and contact definitions were implemented in Abaqus, following procedures and parameters from our previous studies [2]. A physiological load of 1650 N (approximately 2.5× body weight) was applied to simulate single-leg stance [3]. Thirteen FEA models representing different fracture angles were created, and their outputs—von Mises stress on implant and maximum principal strain (MPS) on bone—were analyzed using the 95th percentile metric to reduce the influence of numerical artifacts [5]. These FEA results were then used to train a Random Forest regression ML model [6] to predict mechanical responses for new fracture orientations. The dataset was split into 80% training and 20% testing to ensure robustness.

RESULTS SECTION: FEA revealed that fracture morphology affected implant biomechanics to some extent. Most models showed peak strain between 1.3% and 2%, with implant stresses remaining below the Ti-6Al-4V yield strength (885 MPa). One outlier (CW 20°) displaying abnormally high strain (5.8%) - caused by local mesh distortion and contact artifacts—was excluded from ML training. ML predictions for previously unseen fracture angles (e.g., −22°, −17°, −6°, 2°, 12°, 16°, 22°) demonstrated alignment with FEA trends, validating the model's predictive capability and extending its applicability across a broader morphological spectrum.

DISCUSSION: This study demonstrates the utility of combining FEA and ML to evaluate and predict the biomechanical performance of FNS fixation in FNFs with varying fracture morphologies. The findings confirm that variations in fracture angle can meaningfully alter strain and stress distributions within both the bone and implant. ML proved effective in extending analysis beyond the original FEA cases, offering rapid, data-driven insights into untested scenarios. Ongoing work will expand the model library to include other fixation systems and refine ML algorithms for broader clinical applicability.

SIGNIFICANCE/CLINICAL RELEVANCE: This work provides biomechanical evidence supporting the use of the FNS in treating complex femoral neck fractures, particularly in younger patients where femoral head preservation is critical. By quantifying how fracture orientation impacts implant stress and bone strain, the combined FEA-ML approach offers a powerful tool for pre-surgical planning and implant selection. These insights may help reduce complications such as non-union or implant failure and contribute to improved surgical outcomes. The methodology also establishes a framework for future implant design optimization and personalized orthopedic treatment planning.

REFERENCES: [1] Ridzwan MIZ, et al. (2018) J Orthop Res 36(3): 993–1001; [2] Zeng, et al. (2020) Comput Methods Programs Biomed 196: 105714; [3] Wang, et al. (2021) Injury 52(11): 3227–3238; [4] Andreassen, et al. (2023) Sci Data 10(1): 34; [5] Zeng W, et al. (2023) Front Bioeng Biotechnol 11:1153692; [6] Shehata, et al. (2023) Forces Mech 10: 100151.

ACKNOWLEDGEMENTS: This work was supported in part by the 2023 and 2025 Institutional Support of Research and Creativity (ISRC) program, funded by New York Institute of Technology, and the 2025 Visiting Faculty program at the Brookhaven National Lab, funded by the U.S. Department of Energy.

IMAGES AND TABLES:

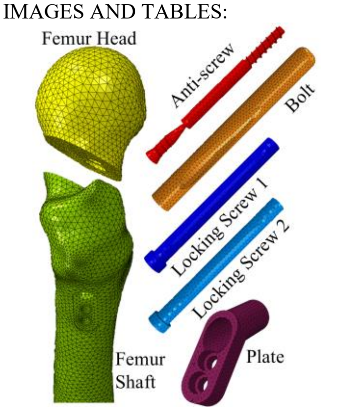


Fig. 1. FE model morphology and assembly: meshed fractured femur and individual components of the FNS device.

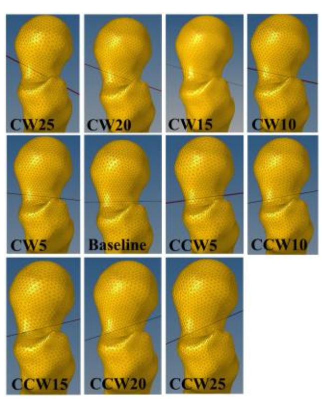
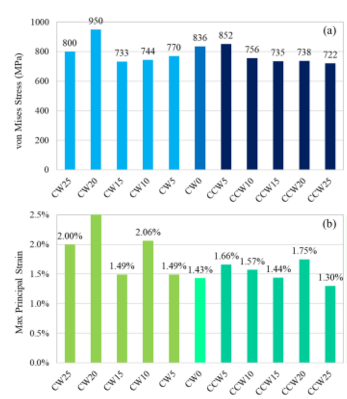


Fig. 2. Fractured femur models with varying oblique angles: baseline (0°) and twelve variations from −25° to +25° in 5° increments (CW and CCW).



Angle [°]	Disp	Stress [MPa]	MPS [%]
-22	0.213	738	0.52
-17	0.193	768	0.54
-6	0.211	825	0.52
2	0.216	792	0.51
12	0.179	753	0.52
16	0.005	789	0.53
22	-0.251	876	0.55

Fig. 3. Comparison of results: (a) peak von Mises stress on the implant (FEA), (b) maximum principal strain (MPS) on the femur (FEA), and (c) ML-predicted displacement at the femoral head, implant stress, and femoral strain.