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Comparative biomechanical evaluation of medial support plating in Pauwels type III femoral neck fractures: A finite element analysis

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ABSTRACT

Objectives: This study aims to evaluate the biomechanical contribution of medial support plating compared to isolated screws and to determine the impact of plate design (one-third tubular *vs.* mini-plate) and distal screw configuration (unicortical *vs.* bicortical) on construct stability.

Materials and methods: Five finite element models were analyzed in this study: three cannulated screws (CS) alone (control), and CS augmented with either a one-third tubular plate or a 2.4-mm mini-plate. For the plated models, the distal fragment was fixed using either unicortical or bicortical screws to isolate the effect of cortical purchase. A 1,400 N axial load was applied to simulate the single-leg stance phase of gait. Fracture micromotion, femoral head displacement, and von Mises stress distribution were recorded.

Results: Medial support plating substantially improved construct stability compared to screws alone, reducing femoral head displacement and fracture gap movement. Notably, no significant biomechanical differences were observed between unicortical and bicortical fixation configurations for either plate type. Both the one-third tubular plate and the 2.4-mm mini-plate provided equivalent rigidity. Although mini-plates exhibited higher internal stress concentrations, values remained below the yield strength of the material.

Conclusion: Bicortical fixation provided no additional mechanical advantage over unicortical fixation in improving construct stability or reducing implant stress. Therefore, the primary determinant of stability is the medial buttress effect itself; once this is established, neither the plate profile nor the screw length significantly alters the biomechanical outcome, suggesting that unicortical fixation with low-profile plates provides sufficient mechanical stability.

Keywords: Femoral neck fracture, finite element analysis, medial support plating, Pauwels type 3.

Femoral neck fractures are becoming increasingly common due to the aging population, currently accounting for approximately 3.58% of all systemic fractures and nearly 50% of hip fractures.[1] However, the epidemiology in young adults differs significantly; unlike the low-energy falls seen in the elderly, these fractures typically result from high-energy trauma.[2-4] Since young patients possess good bone stock, the primary treatment goals are femoral head preservation and stable internal fixation rather than arthroplasty. Based on the inclination angle of the fracture line, Pauwels classified femoral neck fractures into three types: type I (< 30°), type II (30-50°), and type III (> 50°).[5,6] As the angle of the fracture line increases, maintaining the biomechanical stability against vertical shear forces becomes more challenging from a surgical perspective.[7] Consequently, the technical complexity of surgery is associated with an increased risk of poor clinical outcomes.[8]

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Although different studies report varying statistics, 25 to 55% of displaced femoral neck fractures are associated with adverse outcomes, such as avascular necrosis of the femoral head, nonunion, or malunion.[9,10] Numerous treatment methods have been proposed for displaced femoral neck fractures in young adults; however, a consensus on the optimal approach has yet to be established. Currently, the most commonly used method involves fixation with three cannulated screws placed from the femoral neck into the femoral head in a specific configuration.[11] However, in Pauwels type III fractures, this technique often proves inadequate due to the high shear forces imposed by the steep fracture angle.[12,13] Indicators of failure include screw backout, varus displacement, nonunion, and avascular necrosis of the femoral head.[7,14] To address these complications, the addition of a medial support plate has gained traction and has increasingly been featured in the literature as a viable adjunct in the treatment of displaced Pauwels type III fractures.[15]

A recent study has demonstrated that the addition of a medial support plate significantly improves treatment outcomes.[16] The approach employs a plate that functions as a buttress to resist shear forces.[17-20] In this model, either a one-third tubular plate or a low-profile mini-plate is applied medially to support the fracture. As research into medial plating progresses, the optimal technique for plate application has emerged as a subject of growing interest. In particular, the choice between unicortical and bicortical screw fixation has become a focal point of ongoing debate in the literature.[16] Despite the proven benefits of medial plating, the optimal fixation technique remains controversial. A critical unanswered question for surgeons is the configuration of the distal screws fixing the plate to the femoral shaft. While bicortical screw fixation is traditionally associated with greater pull-out strength in diaphyseal fractures, applying this principle to the proximal femur carries distinct risks. Drilling bicortically in the medial femoral neck region increases the risk of iatrogenic injury to neurovascular structures and potential intra-articular penetration. Therefore, determining whether bicortical fixation offers a meaningful mechanical advantage over the safer unicortical technique is clinically vital.

Currently, there is no consensus in the literature regarding the necessity of bicortical fixation for medial support plates, and no study has specifically isolated the biomechanical contribution of distal screw length in this context. To address this gap, in the present study, we aimed to utilize finite element analysis (FEA) to compare the biomechanical stability of three cannulated screws augmented with either a one-third tubular plate or a 2.4 mm mini-plate and, specifically, to evaluate whether bicortical fixation of the distal fragment provides superior stability compared to unicortical fixation in order to assist surgeons in balancing mechanical stability with surgical safety.

MATERIALS AND METHODS

This study was conducted at Ankara University, Faculty of Medicine Department of Orthopedics and Traumatology between January 2025 and April 2025. The study design was reviewed and approved as exempt from formal ethical review (Ethics Committee Reference No: I-01-71-25) as it involved computer-based biomechanical simulations with no human participants. The study was conducted in accordance with the principles of the Declaration of Helsinki.

The femoral model used in this study was generated using computed tomography (CT) data obtained from a medium-sized synthetic femur (Sawbones®; Pacific Research Laboratories, Inc., WA, USA) specimen. Computed tomography scans were acquired using a Toshiba Aquilion Prime 128-slice spiral CT scanner (Toshiba Medical Systems Corp., Tokyo, Japan) with a slice thickness of 0.5 mm. The Digital Imaging and Communications in Medicine (DiCOM)-based CT data were imported into 3DSlicer software and segmented according to appropriate Hounsfield Unit thresholds to reconstruct the three-dimensional (3D) geometry.

Reverse engineering and 3D computer-aided design (CAD) modeling were performed using Rhinoceros 3D software (Robert McNeel & Associates, Seattle, WA, USA). The preparation of solid models for analysis, generation of optimized mesh structures, and convergence checks were performed using ALTAIR HyperMesh software (ALTAIR, Troy, MI, USA). Finite element analysis was conducted using the ALTAIR OptiStruct® solver (ALTAIR, Troy, MI, USA). The plates, cortical screws, and cannulated screws were digitally modeled using Rhinoceros 3D software based on standardized industrial parametric dimensions.

In this study, five different fixation configurations were analyzed (Figure 1). Model A consisted of three 6.5 mm cannulated lag screws. Model B included the same three cannulated lag screws combined with a one-third tubular plate

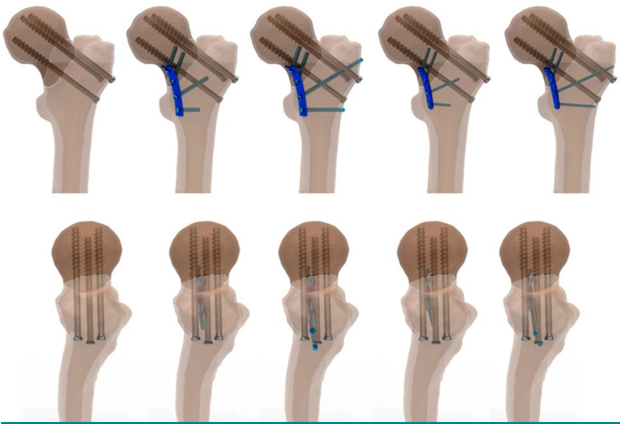

FIGURE 1. Five different finite element models used in the study: Model A (three cannulated lag screws), Model B (one-third tubular plate with unicortical distal fixation), Model C (one-third tubular plate with bicortical distal fixation), Model D (2.4 mm mini-plate with unicortical distal fixation), and Model E (2.4 mm mini-plate with bicortical distal fixation). Top row: Anterior views. Bottom row: Lateral views (from left to right in both rows: Model A to Model E, respectively).

containing four holes; in this setup, both the distal and proximal screws were unicortical, with the proximal screws measuring 20 mm and 25 mm in length. Model C also used a one-third tubular plate with four holes, but the distal screws were bicortical, while the proximal screws remained unicortical. Model D incorporated three 6.5-mm cannulated lag screws along with a 2.4-mm mini-plate with four holes, where both distal and proximal screws were unicortical. Finally, Model E employed the same configuration as Model D, except that the distal screws were bicortical. All components used in the study were modeled from high-strength, biocompatible Ti-6Al-4V alloy.

Model construction

During the initial phase, a Pauwels type III femoral neck fracture line was created at a 70° angle on the anatomical region of the 3D femur model (Figure 2). In all models, three cannulated lag screws, common to each configuration, were inserted parallel to the femoral neck axis in a triangular configuration to stabilize the fracture. The models differed only by the type of medial plate and the length of the distal screws (unicortical versus bicortical).

Development of mathematical models

Mathematical models were generated by dividing geometric models into a mesh. After

FIGURE 2. Generation of a 70-degree Pauwels type 3 fracture line on the femoral neck.

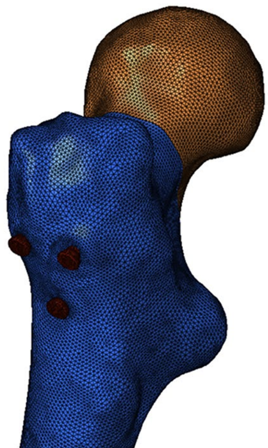

FIGURE 3. Mesh model showing surface and solid meshing of the femoral and implant structures.

modeling in Rhinoceros 3D, meshing and analysis preparation were performed using HyperMesh. Triangular (tria) surface mesh elements sized between 0.5 to 1 mm were employed to ensure high mesh quality. Surface meshes were constructed using triangular elements, and solid meshes were created using tetrahedral elements for volumetric representation (Figure 3). These mathematical models were subsequently transferred to the OptiStruct® solver for analysis.

Material definitions

Linear elastic material properties were used for all components, defined by their respective elastic modulus (E) and Poisson's ratio (ν). All materials were assumed to be homogeneous, linear, and isotropic, consistent with recent high-impact FEA protocols established for femoral neck fracture

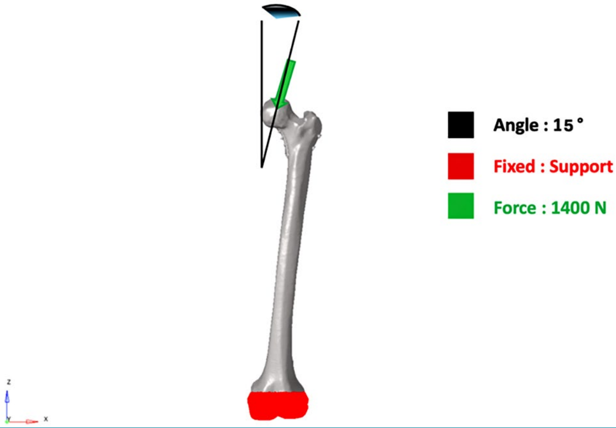

FIGURE 4. Finite element model setup illustrating loading and boundary conditions. The green arrow indicates the 1,400 N axial load applied to the femoral head, simulating the single-leg stance phase of gait. The black lines denote the 15° adduction angle in the coronal plane. The red region at the distal femur represents the fixed boundary condition where all degrees of freedom were fully constrained.

analysis.[21-23] The material properties used in the simulations were as follows; cortical bone: E = 16,700 MPa; ν = 0.3, trabecular bone: E = 157 MPa; ν = 0.3, titanium: E = 113,800 MPa, ν = 0.3.

Loading scenarios and boundary conditions

An axial load of 1,400 N was applied to the proximal spherical surface of the femoral head, corresponding approximately to twice the body weight of a 70 kg individual. A 15° angle between the femoral shaft and vertical axis was set in the coronal plane to replicate the physiological loading conditions during the single-leg stance phase of gait (Figure 4). Boundary conditions were applied by fully constraining all degrees of freedom at the distal end of the femur. Under these loading and boundary conditions, nonlinear static analyses were conducted for each model.

As summarized in Table I, the FEA models were constructed with high mesh density. The number of nodes and elements in each model was optimized to ensure reliable representation of stress distribution and load transfer across the fracture site.

System integration and interfacial contact conditions

To achieve accurate simulation outcomes, interfacial contact definitions were applied between all interacting components. Frictional contact definitions included a coefficient of 0.46 for bone-to-bone interfaces and 0.30 for implant-to-bone interfaces. In the fracture zone, frictional contact was applied only along the fracture line between the separated bone surfaces. Interfaces between cortical and trabecular bone were modeled as fully bonded.

TABLE I
Node and element counts for the developed finite element models

	Total # of Nodes	Total # of Elements
Model 1	256195	970617
Model 2	255943	971364
Model 3	254750	975420

Statistical analysis

Quantitative data obtained from the finite element simulations, including peak von Mises stress distributions in the femur and implants, femoral head displacement, and fracture gap movement, were analyzed descriptively. Comparative trends across the five fixation configurations (Models A through E) were assessed numerically to evaluate the biomechanical impact of plate design and screw purchase. As this study was based on deterministic computational modeling with standardized material properties and boundary conditions, and did not involve repeated experimental trials or human/animal subjects, no formal statistical significance testing (e.g., *p*-values) was performed.

RESULTS

Under the specified loading conditions, the following outcomes were observed:

1. Axial displacement of the femoral head (Figure 5):

In all models, femoral head displacement occurred in the inferomedial direction. The greatest displacement was observed in Model A (15.48 mm), which lacked medial support. In the tubular plate group (Models B and C), the displacement was reduced to 14.58 mm, and in the mini-plate group (Models D and E) to 14.48 mm. No meaningful biomechanical difference in displacement was observed between the tubular plate configurations (Models B and C), nor between the mini-plate configurations (Models D and E). The overall difference between the tubular and mini-plate groups was less than 1%, indicating that both plating methods provided equivalent resistance to axial movement.

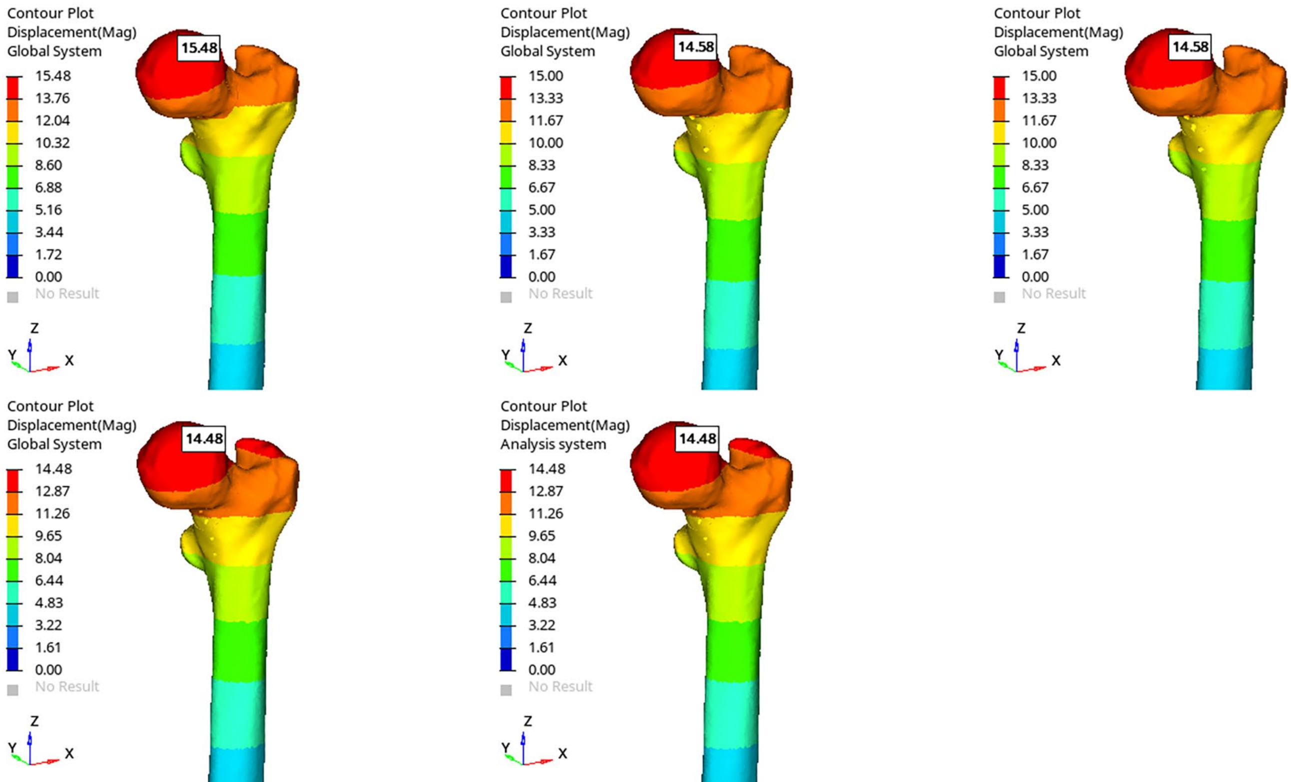

FIGURE 5. Axial displacement of the femoral head in each model.

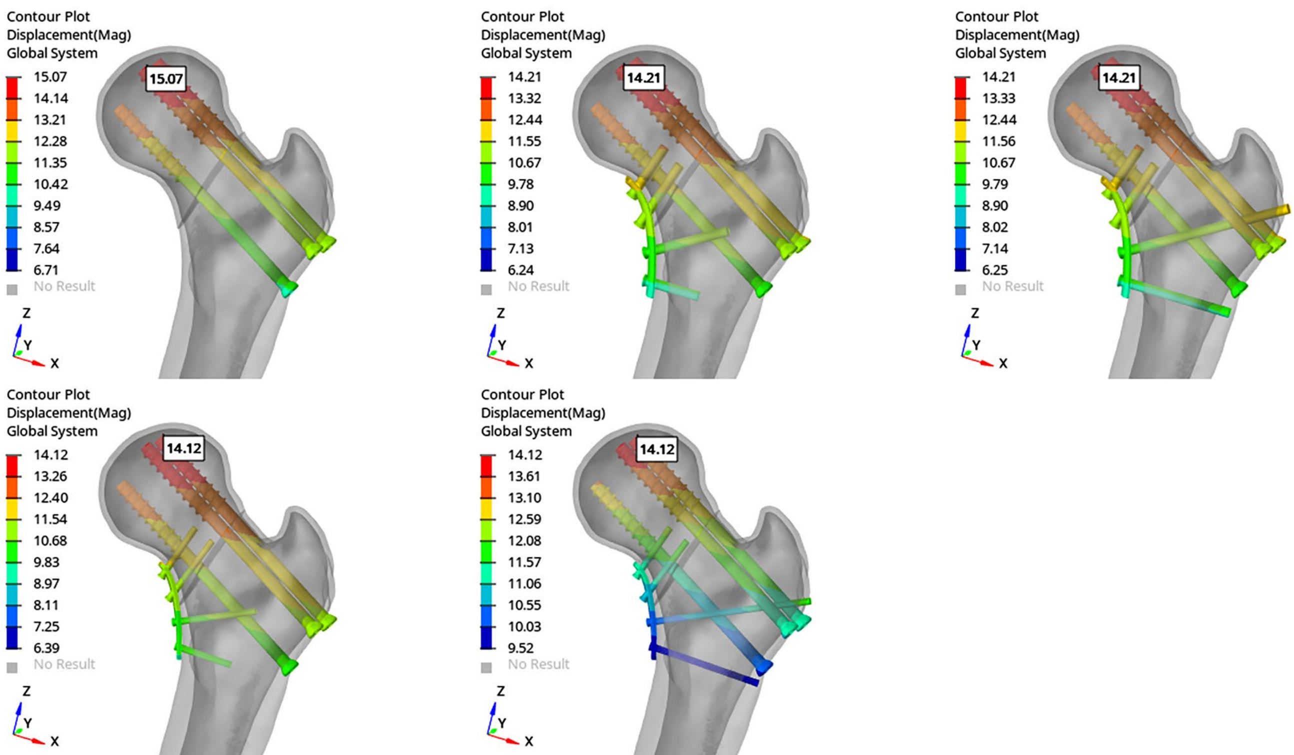

FIGURE 6. Maximum displacement in internal fixation components.

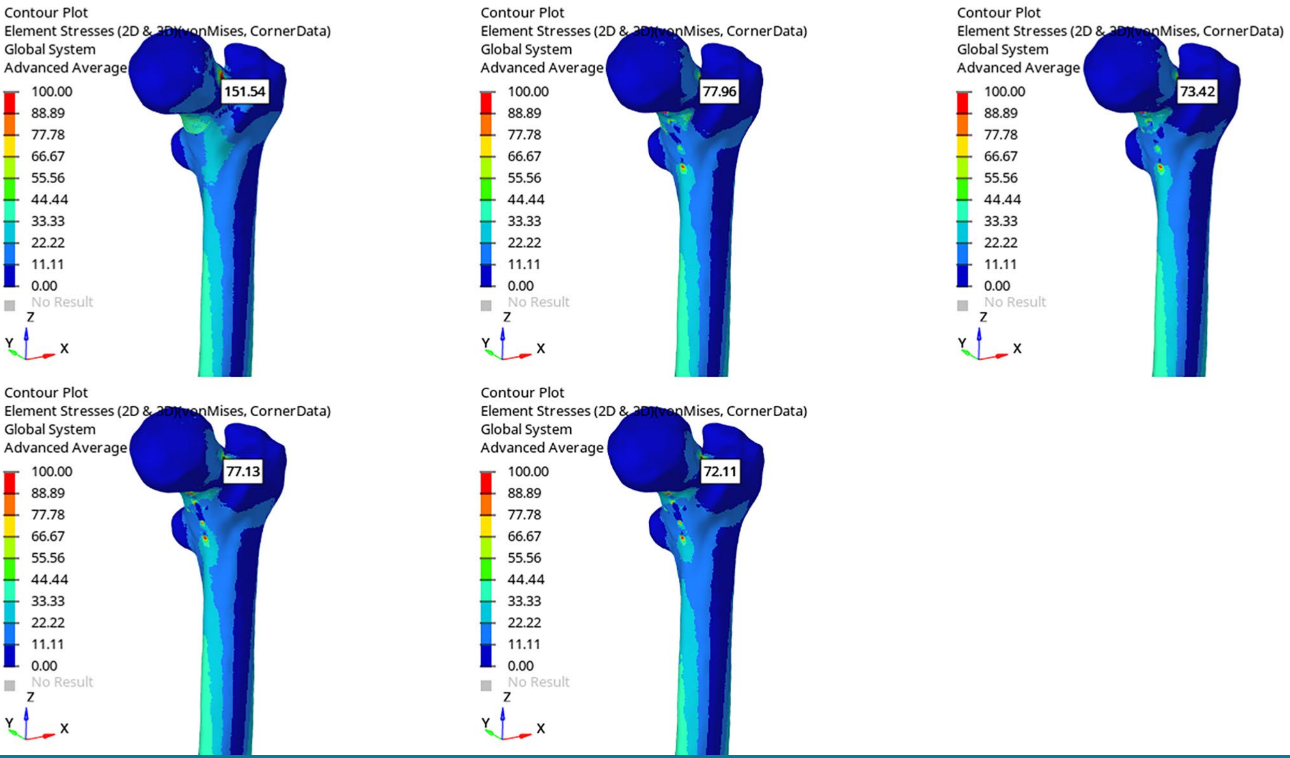

FIGURE 7. Stress concentration distribution in the femoral bone.

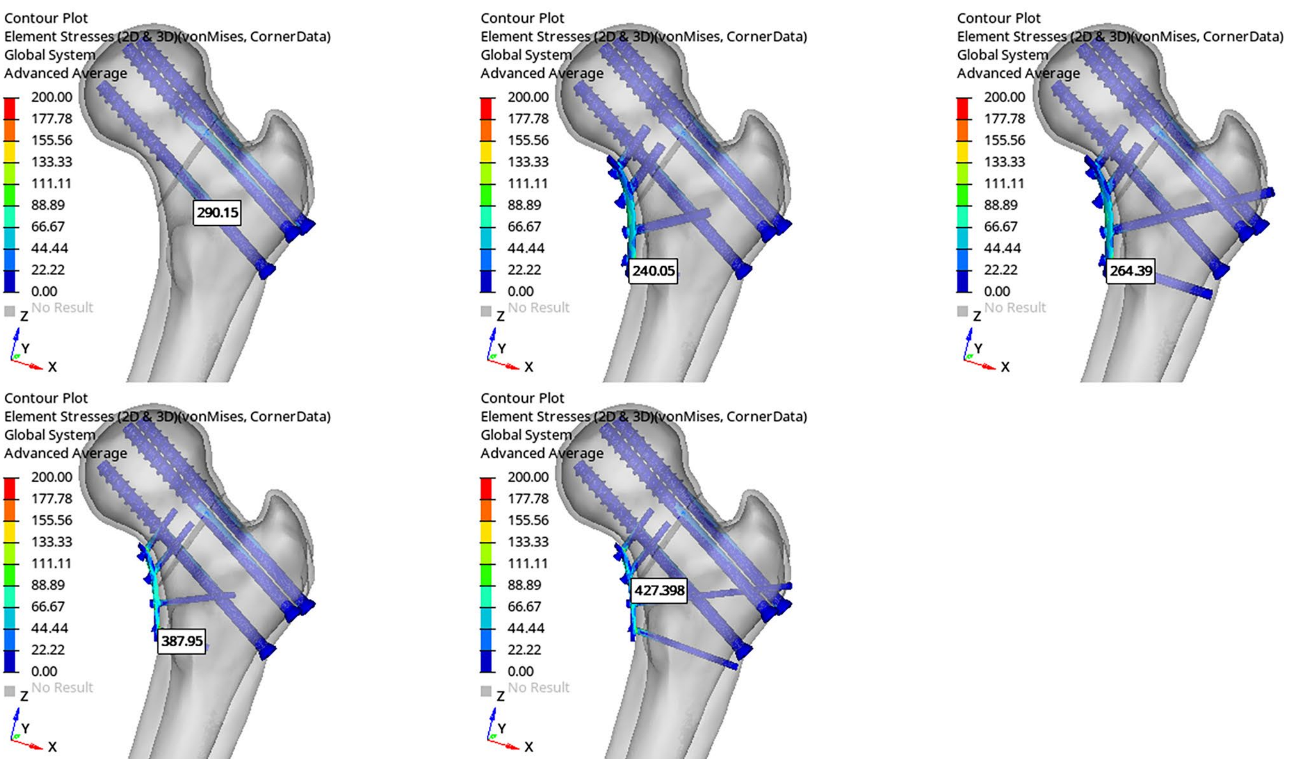

FIGURE 8. Stress distribution in internal fixation devices.

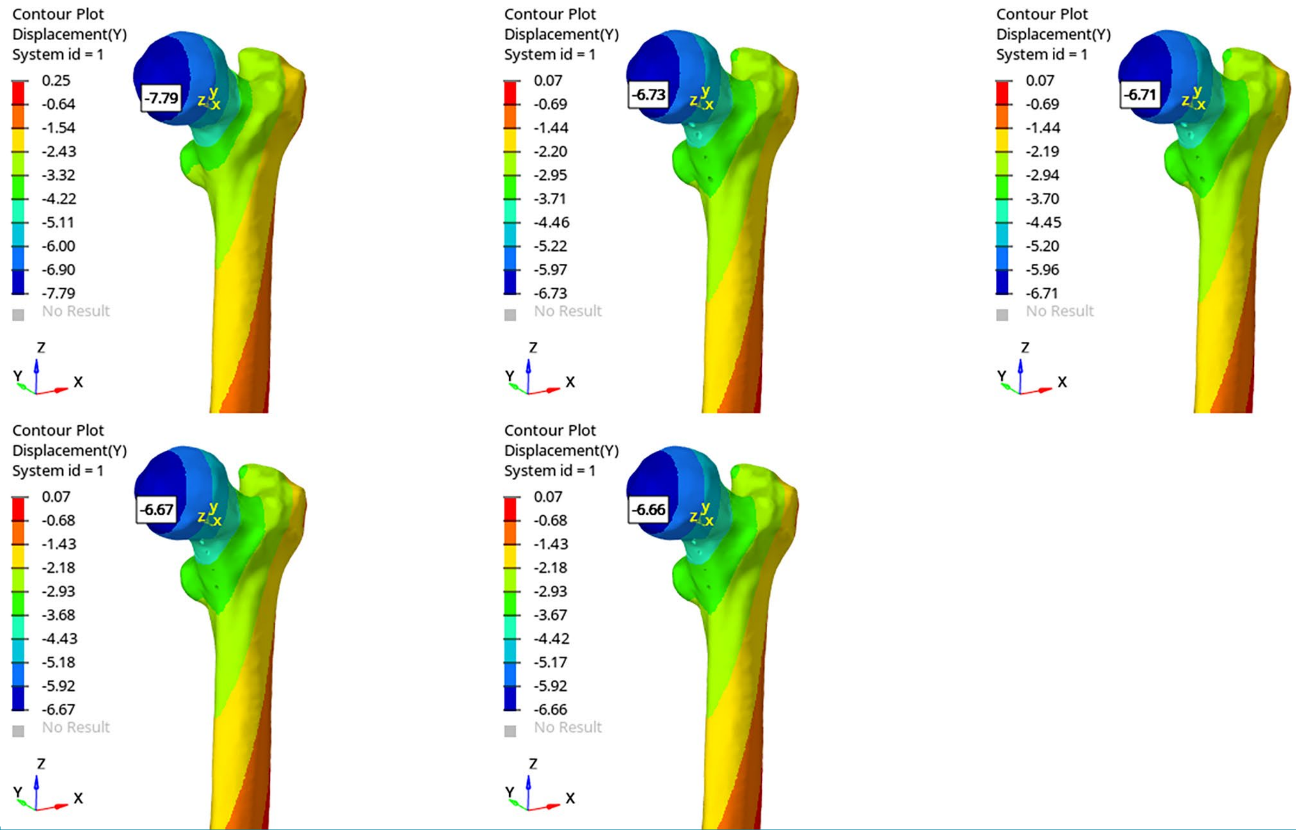

FIGURE 9. Maximum displacement across the fracture line.

2. Displacement of fixation constructs (Figure 6):

The maximum construct displacement was consistently observed at the proximal ends of the cannulated lag screws. Model A exhibited the highest value (15.07 mm), while displacements in the tubular plate group (Models B and C) were 14.21 mm, and in the mini-plate group (Models D and E) 14.12 mm. Displacement values were nearly identical between the tubular plate models (B and C), as well as between the mini-plate models (D and E). The reduction in displacement from Model A to the plated groups was approximately 6%.

TABLE II
Summary of measured biomechanical parameters

	Model A (CCS)	Model B (CCS + 1/3TP, unicortical)	Model C (CCS + 1/3TP, bicortical)	Model D (CCS + MP, unicortical)	Model E (CCS + MP, bicortical)
Maximum axial displacement at the femoral head (mm)	15.48	14.58	14.58	14.48	14.48
Maximum displacement observed in the fixations (mm)	15.07	14.21	14.21	14.12	14.12
Maximum Von Mises stress observed in the femur (MPa)	151.54	77.96	73.42	77.13	72.11
Maximum Von Mises stress observed in the fixations (MPa)	290.15	240.05	264.39	387.95	427.40
Maximum displacement along the axis of the fracture line (mm)	7.79	6.73	6.71	6.67	6.66

CCS, cannulated compression screws; 1/3TP, one-third tubular plate; MP, mini plate. Values represent maximum observed displacements or von Mises stress values under a 1,400 N axial load with a 15° loading angle. All stress values are reported in megapascals (MPa), and displacements are in millimeters (mm).

3. Von mises stress in the femur (Figure 7):

Across all models, maximum von Mises stress occurred on the anterior aspect of the proximal fragment, adjacent to the fracture line. In Model A, peak stress was 151.54 MPa. In the plated models, this was reduced to 77.96 MPa (Model B) and 73.42 MPa (Model C), and similarly to 77.13 MPa (Model D) and 72.11 MPa (Model E). This represents an approximate 50% reduction in peak bone stress. High stress concentrations were also noted at screw entry points. The use of medial support substantially decreased local stress levels regardless of plate or screw type.

4. Von mises stress in the internal fixation components (Figure 8):

In the evaluation of internal fixation components, stress distributions varied across the different models. In Model A, where no medial plate was used, the highest stress concentration was observed on the body of the lowest-positioned cannulated lag screw (290.15 MPa). In contrast, in the plated models, peak stresses were shifted to the plates themselves. Among the tubular plate models, Model B (unicortical) exhibited a peak stress of 240.05 MPa, while Model C (bicortical) reached 264.39 MPa.

In the mini-plate group, stress levels were higher due to the smaller cross-sectional area of the implant: Model D (unicortical) recorded 387.95 MPa, and Model E (bicortical) demonstrated 427.40 MPa. Crucially, although the mini-plates experienced higher stress concentrations, all measured values remained well within the safe elastic range of the Ti-6Al-4V alloy (Yield strength ~830 MPa). This confirms that despite the increased stress relative to tubular plates, none of the components were at risk of material failure under physiological loading.

5. Maximum displacement along the fracture line (Figure 9):

Model A demonstrated the largest fracture gap movement (7.79 mm). In the tubular plate group, displacement decreased to 6.73 mm (Model B) and 6.71 mm (Model C). The mini-plate group showed slightly lower values: 6.67 mm (Model D) and 6.66 mm (Model E). The use of monocortical versus bicortical screws had a negligible effect, approximately a 0.1% difference, suggesting that bicortical screw fixation offered no mechanical advantage over unicortical fixation under the tested conditions.

A summary of all measured biomechanical parameters across the five models is presented in Table II.

DISCUSSION

In the present study, we evaluated the biomechanical contribution of medial support plating compared to isolated screws and to determine the impact of plate design and distal screw configuration on construct stability. The main finding of this study was that the addition of a medial buttress plate substantially improved stability compared to cannulated screws alone. Consequently, the specific configuration of the plate construct appeared to be of secondary importance. We observed that the theoretical mechanical advantage of bicortical fixation became negligible once medial support was established. Both the one-third tubular plate and the 2.4-mm mini-plate provided equivalent rigidity regardless of whether unicortical or bicortical screws were utilized.

Numerous studies in the current literature have explored fixation strategies for Pauwels type III femoral neck fractures, highlighting the complexity and clinical importance of this injury pattern.[11] The primary cause of fixation failure in Pauwels type III fractures is the excessive vertical shear force which creates a strong tendency for varus collapse. Özer et al.[24] emphasized that this shearing stress significantly increases the risk of screw back-out and femoral neck shortening. While cannulated screws function as a tension band, they are often biomechanically insufficient to counteract these vertical loads alone. This limitation was quantitatively demonstrated by Fan et al.,[25] who observed that isolated screw configurations resulted in significantly higher stress concentrations compared to buttress plating constructs. Similarly, it has been reported in comparative biomechanical studies that screw-only fixation allows for excessive interfragmentary motion.[26,27] Our results corroborate these findings as the control model utilizing three cannulated screws exhibited the highest femoral head displacement and fracture gap micromotion. This finding confirms that without the buttress effect provided by a plate, the construct fails to neutralize the toggle effect at the fracture site.

To address the instability caused by vertical shear forces, the addition of a medial buttress plate functions as a mechanical shield. This construct works by converting the detrimental shearing forces into compressive stresses at the fracture interface. Giordano et al.[28] highlighted this "shear shielding" mechanism and reported that medial augmentation provided superior stability against varus collapse in synthetic bone models. Furthermore, detailed FEA by Li J et al.[27] revealed that anatomical medial plates provide essential structural support to the calcar region. This support effectively limits the micromotion that typically leads to nonunion. Consistent with these principles, our study found that the addition of a medial plate reduced the von Mises stress on the femoral neck by approximately 50% compared to isolated screws. This substantial reduction confirms that the plate effectively shields the fracture site from excessive stress and creates a more favorable biomechanical environment for healing.

In the search for optimal stability, various fixed-angle devices such as the Dynamic Hip Screw (DHS), proximal femoral nails, and the recently popularized Femoral Neck System (FNS) have been advocated. Zeng et al.[29] demonstrated in a comparative FEA that while intramedullary nails offered robust fixation, but they were associated with extensive bone removal. Similarly, although the DHS provides controlled collapse, Jiang et al.[30] observed that it could offer insufficient resistance to rotation in high-shear fractures compared to medial buttress plating. Recently, the FNS has gained attention for combining the benefits of a bolt and an anti-rotation screw. Gao et al.[31] reported superior clinical outcomes and faster healing with this system compared to cannulated screws in young patients with Pauwels type III fractures. While the FNS shows promise, Nan et al.[32] biomechanically demonstrated that cannulated screws augmented with a medial plate offer stability comparable to the FNS construct. However, the application of such fixed-angle devices requires precise technique. Zhu et al.[33] emphasized that the biomechanical efficiency of the FNS was highly sensitive to implant positioning. In light of these findings, medial plating represents a valuable strategy that directly addresses the mechanical demands of the medial column.

A significant finding of this study pertains to the screw configuration within the distal fragment. In the current study, we observed no meaningful biomechanical difference between unicortical and bicortical screw fixation when augmented with a medial buttress plate. This supports the observations of Liu et al.,[34] who reported that screw length was secondary to the buttress effect itself. The underlying biomechanical reason is that the cortical bone possesses the primary load-bearing properties. As noted by Augat and Schorlemmer[35] the key factor for stability is the engagement of the dense cortical layer rather than the depth of screw penetration into the cancellous bone. Consequently, the theoretical advantage of bicortical purchase becomes redundant in the presence of a rigid medial plate. This observation is reinforced by Muratoglu et al.,[36] who demonstrated that penetrating the far cortex could induce microstructural damage, potentially compromising local bone integrity. Since our results indicate that unicortical screws provide equivalent stability to bicortical screws in plated models, there is no biomechanical imperative to pursue bicortical fixation, implying that the additional surgical step of engaging the far cortex is unnecessary.

In evaluating von Mises stress on internal fixation components, the mini-plate group exhibited the highest stress magnitudes (387-427 MPa), suggesting that these lower-profile plates carry a greater portion of the mechanical load due to their reduced cross-sectional area. However, it is crucial to emphasize that these peak stresses remained well within the safe elastic range of the Ti-6Al-4V alloy. Given that the yield strength of this material exceeds 800 MPa as documented in material science literature, the observed stress levels do not compromise implant durability under physiological loading.[37,38] This biomechanical safety aligns with the broader trend in trauma surgery supporting anatomic plating alternatives to heavier implants, as highlighted by Oken et al.[39] Consequently, the theoretical concern regarding the mechanical failure of mini-plates appears unfounded in this context, provided the material properties are sufficient to withstand the physiological demands.

Despite the valuable findings, this study has several limitations inherent to FEA. First, it is a computational analysis without cadaveric validation. However, unlike cadaveric studies which are subject to specimen variability in bone density and quality, this FEA model allowed for the isolation of distal screw configuration as the sole variable under identical conditions. Second, the model assumed homogeneous, isotropic bone properties. While real bone exhibits anisotropic behavior, this simplified approach allows for the isolation of mechanical variables and remains the standard method in recent high-impact biomechanical investigations.[21-23] Third, screw and plate fixations were modeled with frictional contact without preload, potentially underestimating actual surgical stability. Finally, the loading condition simulated a single static phase of gait, excluding cyclic fatigue. Future research incorporating cadaveric testing and clinical outcomes would help validate these findings.[28,31,34]

In conclusion, our study results demonstrate that medial support plating substantially improves the biomechanical performance of constructs used in Pauwels type III femoral neck fractures. Notably, bicortical fixation of the distal fragment offers no biomechanical advantage over unicortical fixation. Both one-third tubular plates and 2.4 mm mini-plates provide comparable reductions in displacement and stress. Taken together, we conclude that the primary determinant of stability is the medial buttress effect itself; once this is established, surgeons can confidently utilize unicortical screws or low-profile plates to achieve sufficient mechanical stability.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions: M.K.: Contributed to conceptualization, methodology, and supervision; M.K.: Was responsible for data curation, investigation and formal analysis; M.B.E.: Contributed to methodology, investigation, and writing of the original draft; E.Ş.: Was involved in visualization, resources, and writing-review and editing; H.K.: Contributed to software, validation, and supervision.

Conflict of Interest: The authors declared no conflicts of interest with respect to the authorship and/or publication of this article.

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