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Biomechanical evaluation of femoral neck system versus non-sliding fixation in the treatment of young patients with Pauwels type III femoral neck fractures: a finite element analysis

Yang Gao^{1†}, Zhiyuan Lou^{1†}, Peng Jia^{2†}, Xiaohu Chang¹, Xiaoteng Li³ and Xin Tang^{1*}

Abstract

Objective This study aimed to compare the biomechanical performance of the femoral neck system (FNS) and four cannulated screws (FCS) on treating young patients with Pauwels type III femoral neck fractures.

Methods The model of a young Pauwels type III femoral neck fracture with 70° inclination, FNS, and FCS were established, and the fixations were set up. Under an axial load of 2100 N, the finite element analysis was performed, and the shear force distribution, von Mises stress (VMS), and displacement of each group of models were recorded to analyze the biomechanical effects.

Results The FNS group exhibited localized shear stress, with a peak value of 181.96 MPa, whereas the FCS group displayed a more dispersed shear stress distribution. In the FCS group, the maximum shear stress values were 71.21 MPa, 66.65 MPa, 59.22 MPa, and 84.23 MPa for the upper anterior parallel, upper posterior parallel, transverse, and lower parallel screws, respectively. The maximum shear stress observed in the femur were 113.98 MPa in the FNS group and 89.39 MPa in the FCS group. VMS in the FNS group was predominantly concentrated at the plate-screw junction, reaching a peak of 326.24 MPa, whereas in the FCS group, it was primarily localized near the fracture site in the mid-screw region, with a maximum value of 166.77 MPa. In the femur, VMS was concentrated at the stress application site on the femoral head, with peak values of 197.54 MPa and 154.85 MPa in the FNS and FCS groups, respectively. The greatest displacement of the internal fixators was observed at the screw heads and the two upper parallel screws, measuring 3.36 mm in the FNS group and 3.28 mm in the FCS group. The maximum displacement of the femur occurred at the stress application site on the femoral head, measuring 3.41 mm and 3.33 mm in the FNS and FCS groups, respectively.

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Conclusion Comparative finite element analysis demonstrates superior biomechanical stability of FCS over FNS, indicating its greater suitability for managing young Pauwels type III femoral neck fractures.

Clinical trial number Not applicable.

Keywords Biomechanics, Femoral neck fractures, Femoral neck system, Four cannulated screws, Finite element analysis

Introduction

Femoral neck fractures are a common type of injury in clinical practice, constituting approximately 3.6% of all fractures and 50% of hip fractures [1, 2]. In young individuals, these fractures predominantly result from high-energy trauma, with surgical intervention serving as the primary treatment approach [3–5]. Reported reoperation rates for femoral neck fractures in this population reach 18.0%, while the incidences of avascular necrosis and nonunion stand at 14.3% and 9.3%, respectively [6]. Unstable fracture patterns further elevate the risk of these complications [7]. Despite advancements in surgical techniques, managing femoral neck fractures in young individuals remains complex, often regarded as an unresolved challenge in orthopedic practice [8]. The predominant internal fixation techniques for femoral neck fractures in clinical practice include three cannulated screws (3CS) and dynamic hip screws (DHS), with 3CS being the preferred approach for younger patients [9, 10]. However, research indicates that 3CS fixation for Pauwels type III fractures (Pauwels angle $> 50^\circ$) is linked to a high failure rate, femoral neck shortening, varus deformity, nonunion, and osteonecrosis. These complications primarily stem from the steep inclination of the fracture line, which reduces the contact surface at the fracture ends, thereby increasing shear stress and varus forces along the fracture plane, ultimately compromising stability. The biomechanical challenges inherent to this fracture pattern further complicate fixation [11–13]. Numerous studies highlight the necessity of a more structurally sound fixation strategy to mitigate the adverse mechanical conditions associated with Pauwels type III fractures [12, 14, 15].

In 2017, a minimally invasive internal fixation method, the FNS, which combines the advantages of angular stability and minimal invasiveness, was introduced for treating femoral neck fractures in clinical practice. Structurally, it comprises a bolt, anti-rotation screws, and a locking plate equipped with locking head screws (Fig. 1). The bolt and plate maintain a fixed 130° angular stability, while the angle configuration between the anti-rotation screws and the bolt enhances resistance to rotational forces. Additionally, the bolt incorporates a 20-mm sliding compression mechanism to optimize fracture fixation. Biomechanical studies have demonstrated superior

mechanical performance of the FNS compared to the conventional 3CS system [16–20].

In 2014, Gümüştas et al. [21] conducted a biomechanical analysis comparing FCS and 3CS for managing artificial Pauwels type III femoral neck fractures. Their findings demonstrated that FCS exhibited superior mechanical stability over 3CS in treating unstable femoral neck fractures, offering enhanced structural support. In 2022, Xu et al. [22] investigated the clinical outcomes of non-sliding fixation (FCS) for unstable femoral neck fractures, evaluating its efficacy relative to 3CS. Their study revealed a significantly lower incidence of femoral neck shortening in displaced fractures within the FCS group, alongside a higher Harris hip score compared to the 3CS group.

However, there are currently no reported biomechanical studies comparing FNS and FCS. Therefore, this experiment uses the finite element analysis method to investigate the differences in biomechanical stability between FNS and FCS in the treatment of Pauwels type III femoral neck fractures, providing a theoretical basis for their clinical application.

Materials and methods

Three-dimensional modeling and fixation of femoral neck fractures

The study involved the recruitment of a healthy 25-year-old male volunteer (weight: 70 kg, height: 175 cm) with no history of hip joint or systemic diseases. Computed tomography (CT) of the femur was performed using a Siemens CT scanner with a slice thickness of 1 mm. The acquired CT images, stored in DICOM format, were processed in MIMICS (version 21.0; Materialise NV) for three-dimensional reconstruction [23]. Bone density thresholds were determined based on Hounsfield unit (HU) values, with readings below 700 indicating cancellous bone and those exceeding 700 representing cortical bone [24].

To differentiate bone structures, an HU threshold range of 226–3071 was applied. The region-growing function in MIMICS was utilized to segment cancellous and cortical bone, generating a three-dimensional femoral model that accurately represented its geometric structure.

The reconstructed model was exported in STL format and refined in Geomagic Wrap 2017, where smoothing, meshing, noise reduction, and surface fitting were



Fig. 1 ①Anti-rotation Screw; ②Bolt; ③Plate

performed on the cortical and cancellous bone models. Subsequently, the processed data were saved in WRP format and imported into SolidWorks 2017 for the final assembly of the two bone models [25, 26].

A simulation of Pauwels type III femoral neck fractures ($> 50^\circ$) was constructed by generating a plane intersecting the femoral neck center at a 70° inclination relative to the horizontal axis, utilizing SolidWorks 2017. The precise geometric specifications of FCS and FNS were applied to position these fixators within the fracture model (Fig. 2).

Material parameters

Material properties

For modeling purposes, the materials were considered continuous, isotropic, and homogeneous with linear elastic behavior. Based on existing literature, the estimated Young's moduli for cortical bone, trabecular bone, and internal fixation devices were 16,800 MPa, 840 MPa, and 110,000 MPa, respectively, while their Poisson's ratios were 0.3, 0.2, and 0.3, respectively [27].

Contact settings

In ANSYS Workbench, defining the interaction between multiple geometric models requires configuring contact relationships according to actual physical interactions. The contact between trabecular and cortical bone

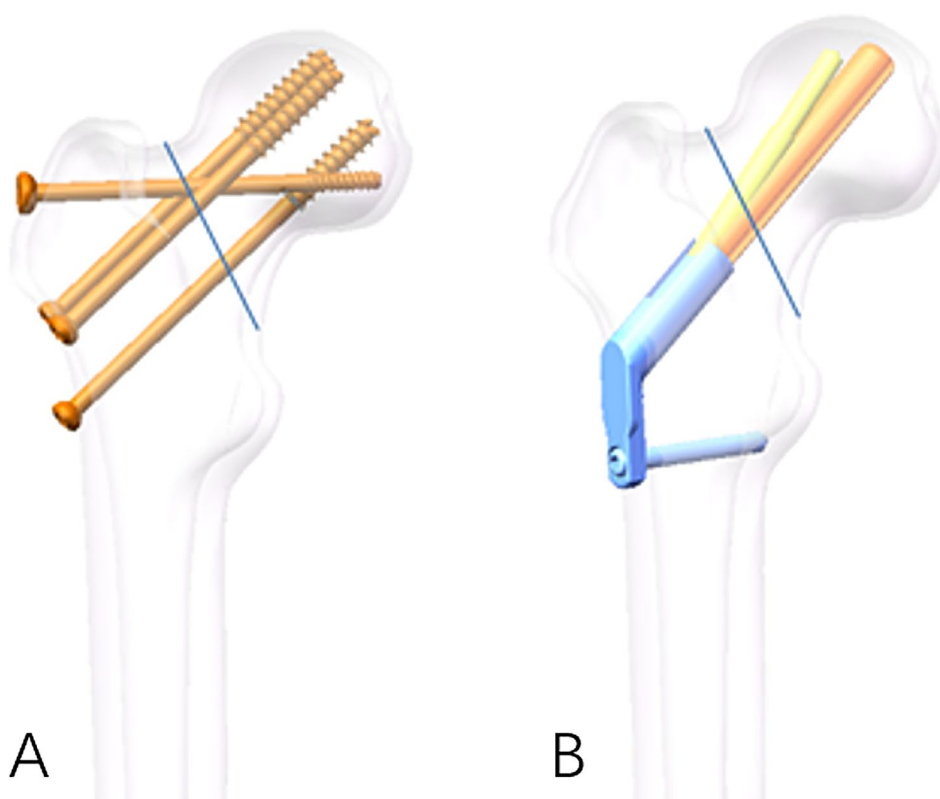


Fig. 2 A. FCS group. B. FNS group



Fig. 3 Hybrid meshing of femur model

Table 1 Details of the three assembly units and the total number of nodes

	FCS	FNS
Node	244,839	216,787
Unit	140,609	129,802

was designated as bonded, as was the interface between internal fixation devices and bone. Fracture surfaces were assigned a frictional contact condition with a coefficient of 0.46 [25].

Mesh division

A hybrid mesh strategy was employed to enhance computational accuracy in modeling the femoral neck, incorporating multiple mesh types for optimized structural representation (Fig. 3). Four-node tetrahedral elements were applied with a minimum effective size of 1.5 mm, enabling a finer resolution by increasing the number of nodes and elements, thereby improving the precision of biomechanical analysis. The total count of nodes and elements for the internal fixation devices was detailed in Table 1. Additionally, skewness was assessed to evaluate mesh quality (Fig. 4).

Boundary conditions and load force settings

For computational analysis, the distal femur was fully constrained to ensure stability (Fig. 5A). As reported by Van Houcke et al., the load exerted on a single-leg

stance was approximately three times the body weight [25]. Accordingly, in the finite element model, a force of 2100 N—corresponding to three times the subject's body weight—was applied at the center of the femoral head (Fig. 5B).

Evaluation criteria

Finite element analysis was employed to assess shear forces acting on the femur and internal fixation devices, as well as the distribution and peak values of von Mises stress (VMS) within both structures [28]. Additionally, the displacement distribution and maximum displacement of the femur and internal fixation components were quantified to evaluate mechanical stability.

Results

Shear stress distribution and peak values

In the FCS group, shear stress was primarily concentrated near the interface between the internal fixation device and the fracture site (Fig. 6). The maximum shear stress recorded for the upper anterior and posterior parallel screws was 71.21 MPa and 66.65 MPa, respectively, while the transverse and lower parallel screws exhibited values of 59.22 MPa and 84.23 MPa, respectively. In contrast, the FNS group displayed shear stress accumulation at the junction of the plate and screws, with a peak value of 181.96 MPa (Fig. 7). Furthermore, the highest shear stress measured in the femur reached 89.39 MPa in the FCS group and 113.98 MPa in the FNS group (Fig. 8).

VMS distribution and peak values

In the FCS group, VMS was primarily concentrated around the fracture site at the center of the four screws, reaching a peak of 166.77 MPa (Fig. 9A). In contrast, the FNS group exhibited VMS accumulation near the fracture site at the main screw, with a peak value of 326.24 MPa (Fig. 9B). Within the femur, VMS localized at the load-bearing region of the femoral head, with peak stress values of 154.85 MPa in the FCS group (Fig. 9C) and 197.54 MPa in the FNS group (Fig. 9D).

Displacement distribution and peak values

The assessment of internal fixation devices revealed that the greatest displacement in the FCS group was observed at the heads of the two upper parallel screws (3.28 mm), whereas in the FNS group, it was concentrated at the top of the bolt (3.36 mm). For the femur, the highest displacement in both groups occurred at the stress application point on the femoral head, with recorded values of 3.33 mm in the FCS group and 3.41 mm in the FNS group (Fig. 10).

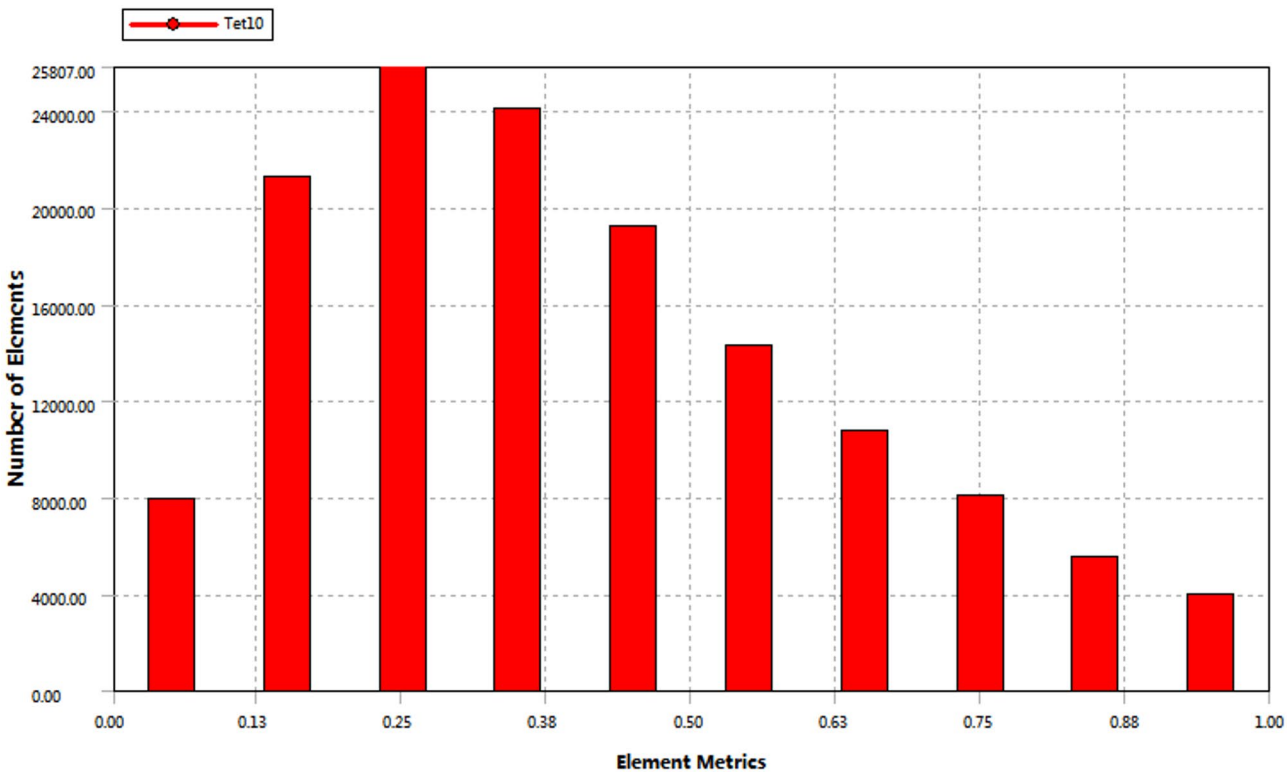


Fig. 4 Mesh Metric: Skewness (0 is the best, 1 is the worst)

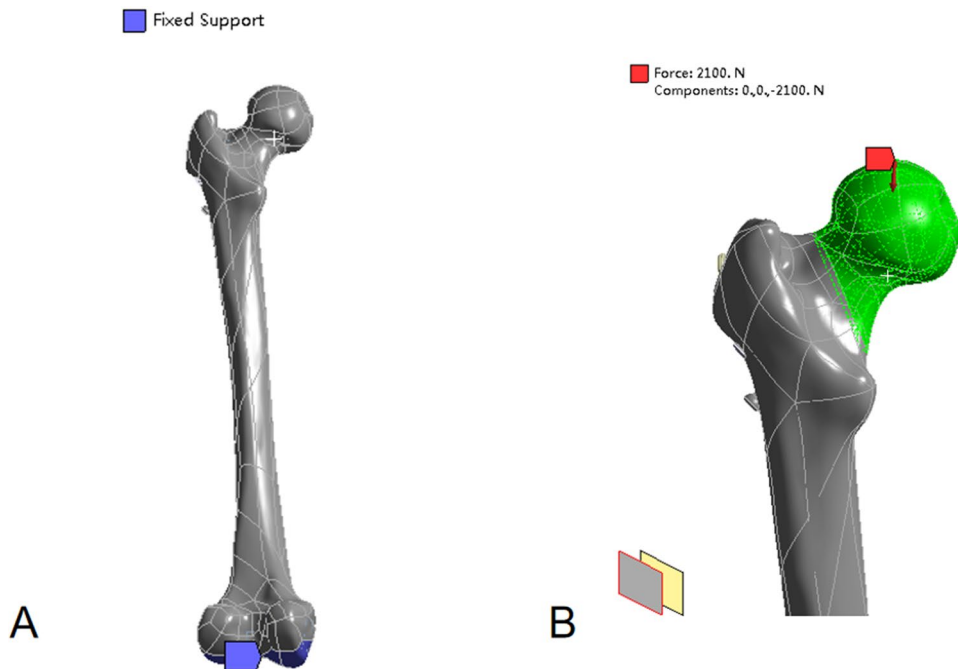


Fig. 5 **A.** Distal femoral fixation **B.** Loading (Arrow:2100 N)

Discussion

The selection of an internal fixation method for femoral neck fractures remains a complex and debated issue. Managing femoral neck fractures in young patients

presents significant challenges due to the elevated risk of postoperative complications, including avascular necrosis of the femoral head, nonunion, and femoral neck shortening. An optimal fixation device must provide mechanical

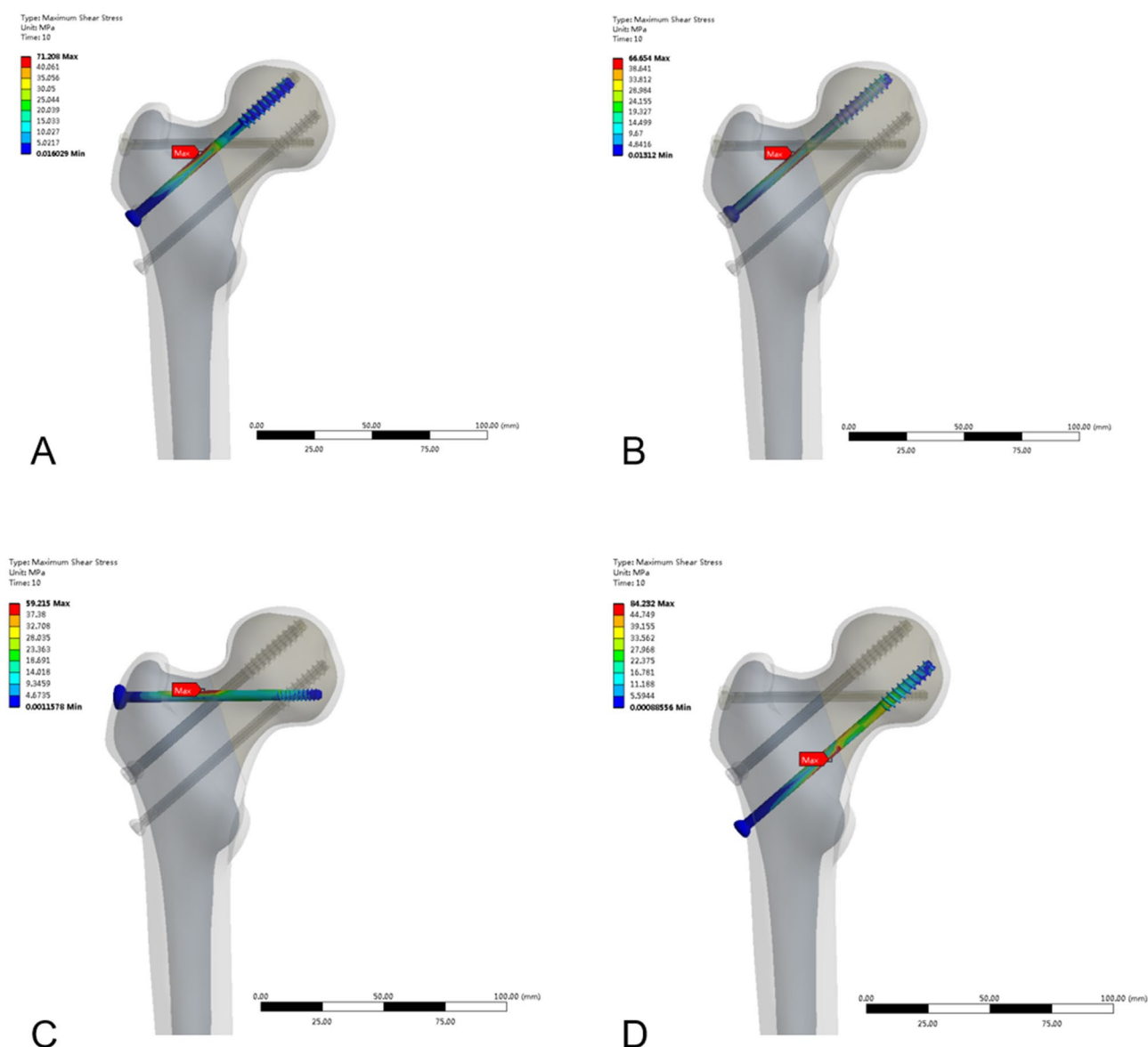


Fig. 6 The shear stress distribution within the FCS group. The measured stress values are as follows: the upper anterior parallel screws exhibit 71.21 MPa (A), the upper posterior parallel screws register 66.65 MPa (B), the transverse parallel screws demonstrate 59.22 MPa (C), and the lower parallel screws sustain the highest stress at 84.23 MPa (D)

stability while minimizing femoral neck shortening, as well as preventing femoral head tilting and rotation [16, 29, 30]. Given the high shear forces and severe instability characteristic of Pauwels type III femoral neck fractures, the choice of an effective fixation technique plays a key role in achieving successful healing. In clinical practice, 3CS has been widely used for femoral neck fractures but is frequently associated with complications such as screw loosening and femoral neck shortening [31–33]. To address these limitations, some researchers advocate for FCS, which incorporates a transverse screw in addition to 3CS to counteract the high shear forces in Pauwels type III fractures [21]. FCS has also been characterized

as a non-sliding fixation system, as the incorporation of a transverse screw helps mitigate the risk of screw backout and femoral neck shortening [22].

The FNS is engineered to enhance biomechanical stability while aligning with biological principles that support fracture healing through initial compression at the fracture site [16]. The compressive load on the femoral head is resolved into axial compressive stress along the femoral neck's centerline and shear stress directed downward along the fracture plane. Compressive stress significantly accelerates fracture healing, and the FNS permits a maximum controlled sliding distance of 20 mm, ensuring sustained interfragmentary compression. The cylindrical

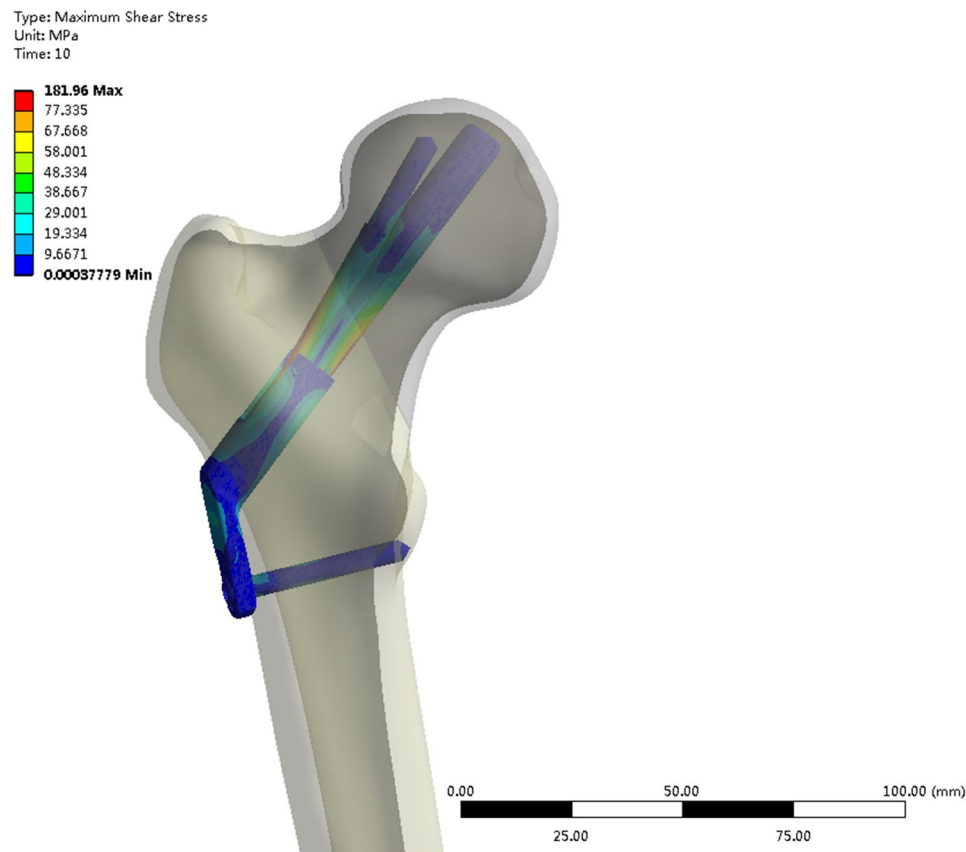


Fig. 7 Shear stress of FNS group (Maximum stress 181.96 MPa)

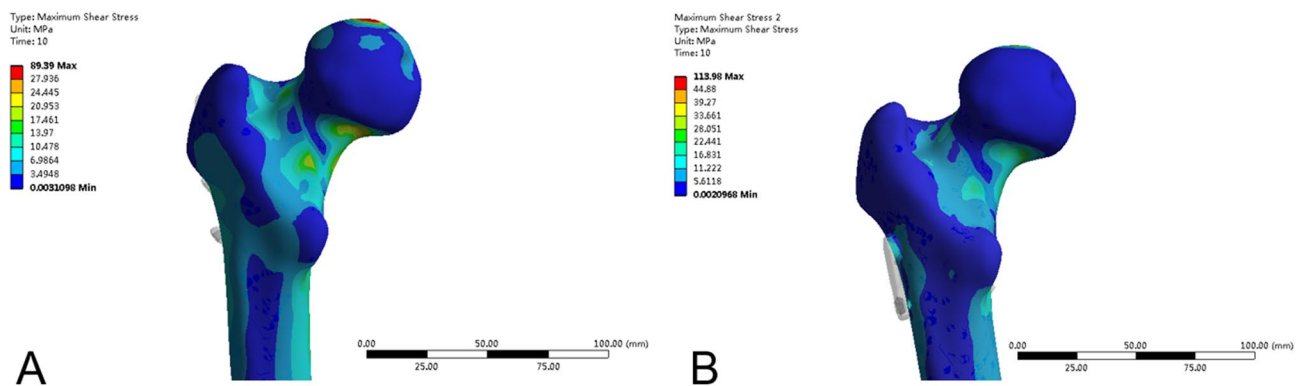


Fig. 8 Shear stress of femur. **A** is FCS group 89.39 MPa. **B** is FNS group 113.98 MPa

bolt design provides structural reinforcement, optimizing load distribution. Positioned at a 7.5° angle relative to the anti-rotation screw, the bolt effectively prevents femoral head rotation.

To the best of current knowledge, this study represents the first comparative analysis of the therapeutic efficacy of FCS and FNS in Pauwels type III femoral neck fractures. Finite element analysis was employed to develop a model of a Pauwels type III femoral neck fracture with a 70° inclination. To enhance computational precision, a hybrid mesh strategy was implemented for femoral neck

modeling, incorporating a greater number of nodes and elements to refine biomechanical analysis. Additionally, shear stress distributions of both internal fixation systems were assessed to evaluate their shear resistance. In the FNS group, shear stress was primarily concentrated at the thread root of the anti-rotation screw and the plate-bolt junction, reaching a peak of 181.96 MPa. Conversely, in the FCS group, stress distribution was more evenly spread across the four screws due to multi-plane fixation, with the highest shear stress observed at the lower parallel screw at 84.23 MPa. The peak shear

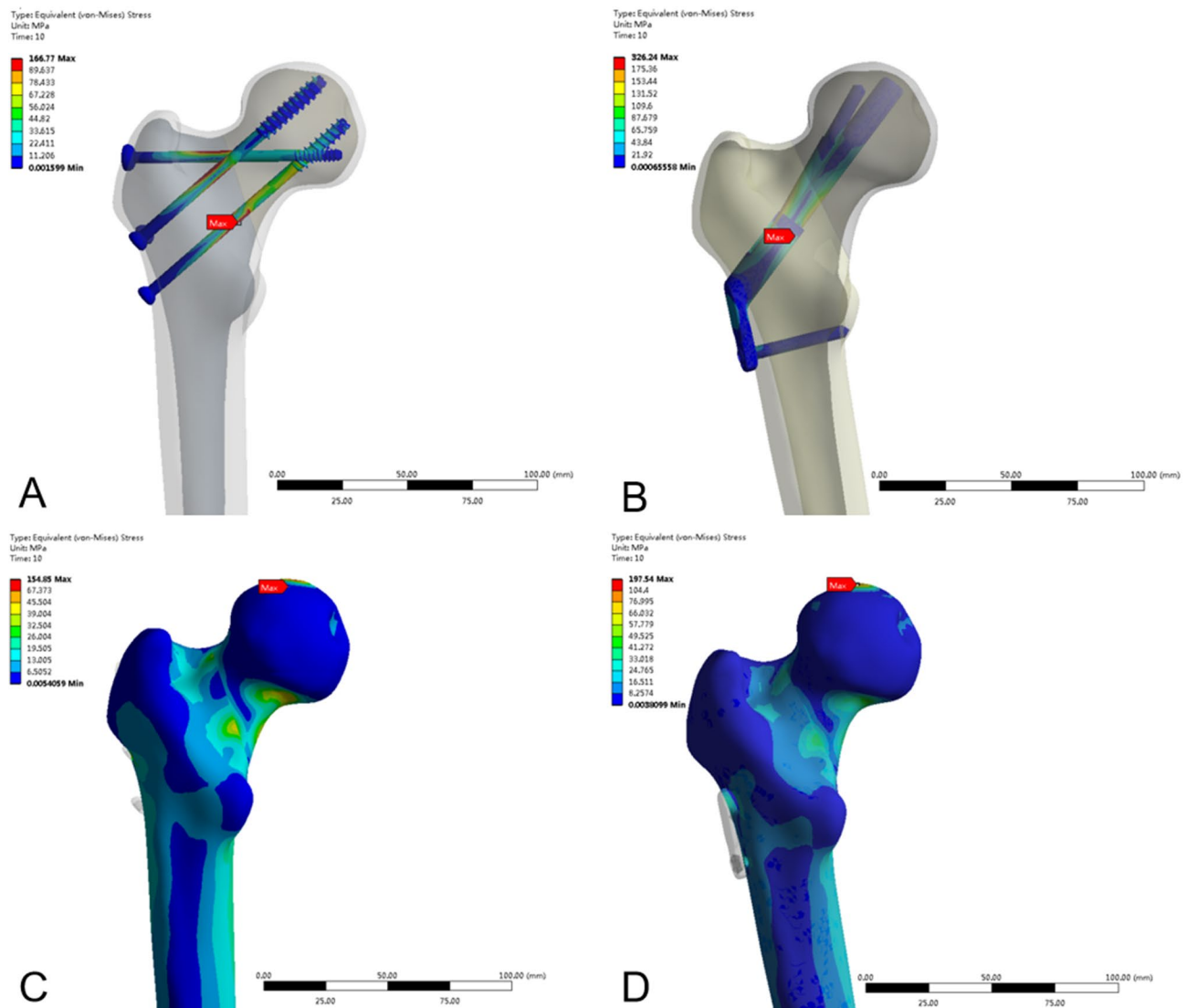


Fig. 9 Peak Values of VMS. **A** is FCS 166.77 MPa. **B** is FNS 326.24 MPa. **C** is femur 154.85 MPa (FCS group). **D** is femur 197.54 MPa (FNS group)

stress in the FNS group was 2.16 times that of the FCS group. Moreover, the maximum shear stress in the femur reached 89.39 MPa in the FCS group and 113.98 MPa in the FNS group, indicating greater femoral stability in the FCS group. The transverse screw bore 21% of the maximum shear stress, directly influencing femoral stability. The peak von Mises stress (VMS) in the FNS group was twice that in the FCS group. In the FNS group, VMS was concentrated at the plate-bolt junction, with a peak value of 326.24 MPa, whereas in the FCS group, it was localized near the fracture site at the screw's center, reaching 166.77 MPa. Regardless of shear stress or VMS, the maximum stress values were consistently higher in the FNS group than in the FCS group. Theoretically, higher stress magnitude and concentration increase the risk of internal fixation device failure. However, no instances of internal

fixation breakage have been documented in clinical studies on FNS to date.

Regarding femoral displacement, the maximum displacement in both the FNS and FCS groups occurred at the stress application site on the femoral head, with peak values of 3.41 mm and 3.33 mm, respectively. For internal fixators, the greatest displacement was observed at the bolt head in the FNS group and at the two upper parallel screws in the FCS group, with peak values of 3.34 mm and 3.28 mm, respectively. Karl Stoffel et al. [16] found that the FNS demonstrated higher axial stiffness (748.9 ± 211.4 N/mm) compared to 3CS (584.1 ± 156.6 N/mm), suggesting that FNS is approximately 1.28 times stiffer than 3CS. This increased stiffness implies that under identical loading conditions, the FNS would experience less displacement than the 3CS construct. However, in this study, maximum displacement in the FCS

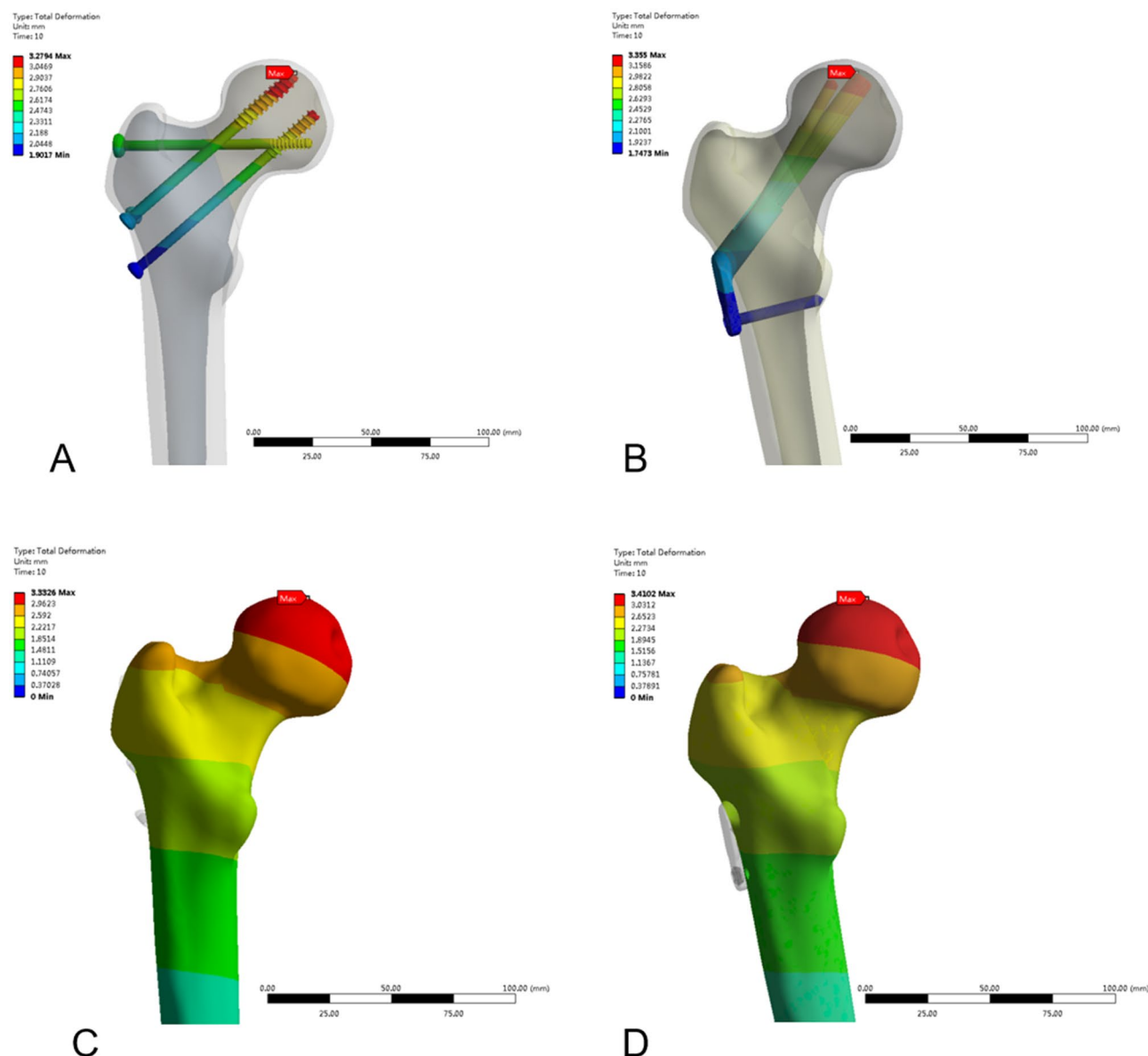


Fig. 10 Maximum displacement. **A.** FCS internal fixation. **B.** FNS internal fixation. **C.** Femur (FCS group) **D.** Femur (FNS group)

group was lower than that in the FNS group. This reduction may be attributed to the transverse screw in FCS, which distributes stress more effectively and minimizes screw displacement. This is similar to how the medial buttress plates can enhance the stability of the 3CS [34]. In clinical practice, for unstable femoral neck fractures—especially when the subtrochanteric screw cannot be used—alternative fixation methods such as a proximal femoral locking plate, a version of the FNS that does not require a subtrochanteric screw, or a combination of DHS with an anti-rotation screw can be employed. The distal portion of medial proximal femoral support acts primarily as a supportive extension, transmitting reduced force compared to the proximal segment where the major

load transfer occurs from the femoral head through the implant, allowing load sharing, helping preserve bone integrity and reducing the risk of cortical bone resorption [35].

Limitations

This study presents several limitations. First, for modeling and computational efficiency, the finite element analysis does not incorporate the influence of muscles, joint capsules, or ligaments. Second, the simulation is restricted to the immediate mechanical environment of single-leg standing, without accounting for biomechanical changes occurring during fracture healing and their potential impact on stabilization. Third, the fracture

model utilized in this study represents a single-plane linear injury with complete anatomical reduction, whereas fractures encountered in clinical settings are often more complex. Consequently, further validation through clinical studies is necessary to substantiate the finite element analysis results.

Conclusion

Comparative finite element analysis demonstrates superior biomechanical stability of FCS over FNS, indicating its greater suitability for managing Pauwels type III femoral neck fractures.

Abbreviations

FNS	femoral neck system
FCS	Four cannulated screws
VMS	Von Mises stress
3CS	Three cannulated screws
DHS	Dynamic hip screws
HU	Hounsfield unit

Author contributions

YG, ZYL and PJ conceived the study and wrote the manuscript. XHC reconstructed the models and performed the finite element analysis. XTL contributed to the data collection and interpretation of the results. XT is responsible for manuscript review and guidance.

Funding

Not applicable.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Research involving human participants have been performed in accordance with the Declaration of Helsinki and has been approved by the Ethics Committee of First Affiliated Hospital of Dalian Medical University with the ethical registration ID PJ-KS-KY-2024-761. For the human participant informed consent to participate in the study was obtained from the participant. Consent was obtained for all forms of personally identifiable data.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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