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Biomechanical difference analysis of new and classic intramedullary nail devices in the treatment of basal femoral neck fractures: finite element analysis

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Abstract

Objective There is currently a lack of in-depth comparative evaluation regarding the biomechanical properties of novel intramedullary nail devices in the treatment of basal femoral neck fractures (BFNF). This study aims to utilize finite element analysis to compare the performance differences of two novel devices with traditional PFNA and Inter-Tan nails in the fixation of BFNF.

Methods Based on a validated finite element model, this study constructed an accurate BFNF model and implanted four different intramedullary nail devices: PFNA, InterTan nail, PFBN (proximal femoral biomimetic nail), and NIS (novel intramedullary system). Under a vertical load of 2100N, the displacement and Von Mises stress (VMS) distribution of each group of models were evaluated through simulation testing.

Results Under a load of 2100N, the PFBN device exhibited the best performance in terms of displacement and peak stress, while PFNA performed poorly. The peak displacement of the NIS device was lower than that of PFNA and Inter-Tan nails, while the peak stress of the InterTan nail was lower than that of PFNA and NIS.

Conclusion The PFBN device demonstrates stronger load-bearing and shear-resistant properties in the treatment of BFNF, and the NIS device also shows significant improvement in stability. Therefore, both the PFBN and NIS devices are reliable internal fixation techniques for the treatment of CFIFs, with potential clinical application prospects.

Keywords Basal femoral neck fractures, Intramedullary nail devices, Proximal femoral bionic nails, New intramedullary systems, Finite element analysis

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Introduction

The basocervical femoral neck fracture (BFNF) is located between the femoral neck and the intertrochanteric region, accounting for approximately 1.8% to 7.7% of all hip fractures [1–3]. Compared with intertrochanteric fractures, BFNF exhibits a larger fracture angle and transmits higher forces and torques through the bone. Therefore, it can be considered a more unstable fracture compared to intertrochanteric fractures [4]. For the treatment of BFNE, it is recommended to perform firm internal fixation of the fracture as early as possible, which can facilitate early recovery of patients and avoid the occurrence of bedridden complications such as bedsores, pneumonia, and deep vein thrombosis [5]. It is reported that the failure rate of BFNF fixation may be up to 15–40% [6]. The stability of the internal fixation device is one of the essential measures to ensure successful bone healing and avoid postoperative complications. Therefore, how to better treat patients with unstable femoral neck fractures remains a challenge for trauma orthopedists.

Until now, various internal fixation devices have been developed for the surgical treatment of BFNE, such as dynamic hip screws (DHS), cannulated cancellous screws (CCS), and proximal femoral nail anti-rotation (PFNA) [7]. However, it cannot be ignored that the use of CS is prone to complications such as femoral neck shortening, screw pullout, and excision [8]. Compared with CS, the dynamic hip screw with anti-rotation screws can play a better role in anti-rotation and shear resistance, but it will cause greater trauma [9]. The long moment of external medullary internal fixation devices can easily cause stress concentration, ultimately leading to fixation failure.

Röderer et al. have explored the application of proximal femoral nail anti-rotation (PFNA) in unstable femoral neck fractures and found that PFNA is comparable to dynamic hip screw blade (DHS) in stability, indicating that intramedullary nail fixation technology has potential in the treatment of UFNFs [10]. However, PFNA only contains a helical blade, which makes it more prone to proximal screw cutout, proximal femoral shortening, and reduction of proximal femoral varus angle [11]. In the treatment of unstable hip fractures in elderly patients, PFNA has a mechanical failure rate of 7.5%, including a range of complications such as an implant cutout rate of 5.4–13%, a varus collapse rate of 2.5%, and an internal fixation failure rate of 1% [12, 13]. On the other hand, Rupprecht et al. showed that compared to CSs and DHS, the InterTan nail exhibited higher efficacy in the treatment of Pauwels type III femoral neck fractures [14]. According to previous studies, intramedullary nail devices (IMNs) offer the benefits of rigid and secure fixation, allowing early mobilization, ensuring minimally invasive exposure,

and reducing surgical time and blood loss [15]. Traditional intramedullary nail devices are biomechanically superior to extramedullary internal fixation devices, but there are few biomechanical studies on the treatment of BFNF with different types of intramedullary nail devices, which can provide reasonable suggestions for clinicians in clinical diagnosis and treatment.

Given the above background, the core objective of this study is to conduct an in-depth comparative analysis of the biomechanical properties of proximal femoral bionic nails (PFBN), new intramedullary systems (NIS), InterTan nails, and proximal femoral nail anti-rotation (PFNA) in the treatment of BFNF. Finite element analysis, as a numerical analysis method that uses mathematical approximations to simulate real physical systems, has been widely used in the biomechanical evaluation and prognosis prediction of various diseases and injury types, intramedullary nail device fixation, and surgical techniques [16]. By accurately setting finite element parameters such as material properties and boundary conditions, this method can not only achieve accurate estimation of overall displacement but also quantitatively simulate the stress distribution between surgical internal fixation devices and bones. This finite element study aims to provide more reasonable treatment options and plans for BFNF patients by evaluating the maximum stress (VMS) and displacement of bone and implants.

Method

3D model of femoral and nail devices

This study aims to delve into the biomechanical characteristics of different intramedullary nail devices in fixing femoral neck fractures in healthy individuals under high-energy injury scenarios. Given that previous literature has clearly indicated that basal femoral neck fractures account for a certain proportion of high-energy trauma cases [17]. This study specifically selects a 58-year-old male volunteer weighing 68 kg as the research subject. The volunteer must meet the following inclusion criteria: excellent physical health, without any history of hip joint or systemic diseases, to ensure that potential confounding factors such as osteoporosis can be excluded from the experimental process, thereby guaranteeing the scientific rigor and accuracy of the study.

This study will utilize the Siemens Medical Solutions (Forchheim, Germany) Sensation 64 spiral CT scanner to perform high-precision scanning of the volunteer's left femur. The slice distance for the scan is set at 0.625 mm, ensuring high-resolution and accuracy of the data, and the raw data will be stored in DICOM (Digital Imaging and Communications in Medicine) format.

Subsequently, we will utilize Materialise's (Leuven, Belgium) Mimics21.0 software to process the raw CT scan

data and construct a 3D model of the femur. Following that, the Geomagic Company's (USA) Geomagic Studio13.0 software will be employed to refine the model, including the creation of non-uniform rational B-splines (NURBS), pore filling, and smoothing of sharp edges. The smoothing process will strictly adhere to the original curvature of the selected areas, ensuring the integrity of the model's large features. Afterward, the refined model will be imported into 3-matic software for further simulation and analysis preparation.

To ensure the precision of the study, we will adopt a manual segmentation method to accurately depict the cortical and cancellous bone regions in the CT images. Specifically, the cortical bone is defined as the region that is 2 mm inward from the surface (this thickness is based on actual measurements from the CT images), and the remaining internal area is defined as cancellous bone. Subsequently, the Active remesh function will be used to mesh the intramedullary nail and bone models, with all parts divided into 1 mm-sized elements to guarantee simulation accuracy. The surface mesh import and solid mesh generation will be performed in Hypermesh, and according to simulation requirements, both the bone and intramedullary nail meshes will be refined into C3D4 tetrahedral pyramid elements (as shown in Fig. 1B).

For the PFNA, InterTan nail, PFBN, and NIS intramedullary nail models, we have precisely constructed them in Siemens Product Life cycle Management Software Inc's (USA) UG-NX 12.0 software based on parameters provided by the manufacturer (North Union Medical

Technology Institute, China). Meanwhile, the BFNF model was also established in UG-NX 12.0 software and fixed with four different intramedullary nail devices (Fig. 1A). According to the latest 2018 AO (Arbeitsgemeinschaft für Osteosynthesefragen)/OTA(Orthopaedic Trauma Association) classification standard [18], the main fracture line of the BFNF model (classified as 31-B3) is located at the base of the femoral neck, forming a 70-degree angle with the horizontal plane. The construction technology of fracture models involves adopting a precise three-point positioning method to establish a cutting plane, and then using this cutting plane to precisely cut the cortical bone and cancellous bone areas of the femur, thereby producing a fracture simulation model with a clearly separated interface. This setup ensures a close fit with real clinical scenarios, providing a solid foundation for subsequent simulations and analyses.

Material properties

In this study, the femur and intramedullary nail devices are assumed to have uniform, isotropic, and linearly elastic material properties. Specifically, titanium alloy is selected as the primary material for the four different intramedullary nail devices. Referring to previous similar studies [19–21], we have set the elastic modulus of cortical bone to 16.8GPa and the elastic modulus of cancellous bone to 0.58GPa, with both having a Poisson's ratio of 0.3. For the intramedullary nail, its elastic modulus and Poisson's ratio are set to 110GPa and 0.31, respectively.

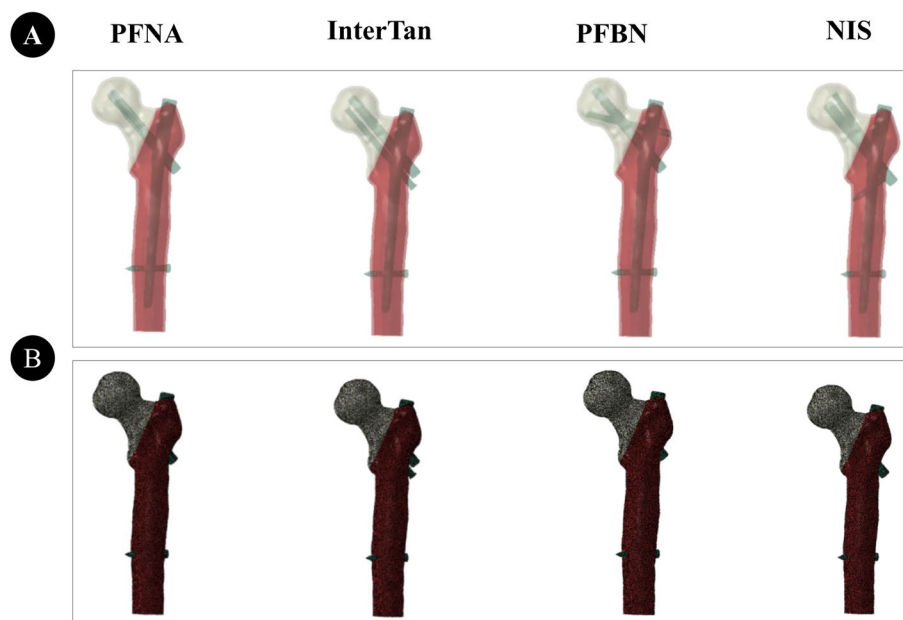


Fig. 1 A is the model diagram of the four fixed devices, and B is the grid diagram of the four models

Detailed material parameters for all components are listed in Table 1.

Boundary conditions and load settings

In this study, the bone-bone, bone-screw, and screw-screw contact relationships are set as surface contacts and utilize a friction contact model. Specifically, the friction coefficient between bone and bone is set to 0.46, the friction coefficient between bone and screw is 0.42, and the friction coefficient between screws is 0.2. In terms of boundary conditions, we have fully constrained all degrees of freedom at the distal end of the femur model and coupled the region of contact between the femoral head and the pelvis to a concentrated point, where a 2100N load simulating normal standing vertical force is applied.

Model validation

To ensure the accuracy of the study, we constructed a complete femoral fracture model and four different intramedullary nail device models, assigning corresponding material properties to these models based on the methods in references [22, 23]. Subsequently, we fully constrained the degrees of freedom at the distal end of the femoral model and applied a vertical load of 2100N on the concentrated point of the femoral head. Utilizing the advanced Ansys 19.0 finite element analysis software (ANSYS Inc., USA), we conducted in-depth analysis on these models and carefully compared the obtained results with the reported data in references [22, 23], thus validating the effectiveness of the constructed models.

Main evaluation parameters

With the ANSYS Workbench 2020 R2 software (ANSYS, Canonsburg, PA, USA), we analyzed in detail the biomechanical properties of the proximal and distal regions of the femur as well as four different intramedullary nail internal fixation devices. The main output parameters evaluated include Von Mises stress distribution maps, displacement distribution maps, and stress distribution data of the entire femur. These data provide strong

support for the comparative analysis of mechanical characteristics among the four models.

Results

Von mises distribution of four intramedullary nail devices

PFNA intramedullary nail device: The peak value of Von Mises stress (VMS) reached 632.5 MPa, which is the highest among the four devices. **InterTAN intramedullary nail device:** The VMS peak value is 370.9 MPa, significantly smaller than PFNA. The stress distribution is characterized by stress concentration at the intersection of the main nail and the head nail. **PFBN intramedullary nail device:** The VMS peak value is 288.3 MPa, the lowest among the four devices. It shows a lower stress peak, indicating that its structural design is superior in reducing stress concentration. **NIS intramedullary nail device:** The VMS peak value is 484.8 MPa, between PFNA and InterTAN.

Among these four intramedullary nail devices, the PFBN device shows the lowest stress peak, indicating that its structure has better stress dispersion ability when bearing loads (Fig. 2). The PFNA device exhibits the highest stress peak, suggesting that under the same load conditions, its structure may be more prone to stress concentration and potential fatigue failure. Although the stress peak of the InterTAN device is slightly smaller than PFNA, there is still stress concentration at the intersection of the main nail and the head nail, requiring further attention to the material strength and fatigue performance of this area. This analysis is based on Von Mises stress distribution data, providing an important reference for the design and selection of intramedullary nail devices.

Von mises distribution in proximal and distal femur

The peak value of VMS fixed by PFNA device in proximal femur was 152.2 MPa and that in distal femur was 184.5 MPa. The peak value of VMS fixed by InterTAN device was 76.46 MPa at the proximal femur and 182.10 MPa at the distal femur. The peak value of VMS in proximal femur fixed by PFBN device was 86.92 MPa and that in distal femur was 120.30 MPa. The peak value of VMS fixed on the proximal femur by NIS device was 91.52 MPa, and the peak value of VMS fixed on the distal femur was 182.20 MPa. Compared with PFNA, PFBN device can significantly reduce the peak displacement of the proximal femur and reduce the peak stress distribution range at the femoral neck. The NIS device significantly reduced the peak stress and distribution range of the proximal and medial walls of the femur compared with the other three intramedullary nail devices (Fig. 3).

Table 1 Model material parameters

Materials	Elastic modulus (GPa)	Poisson's ratio
Cortical bone	16.8	0.3
Cancellous bone	0.58	0.3
Head of femur	0.9	0.29
Collum femoris	0.62	0.29
Intramedullary nail	110	0.31

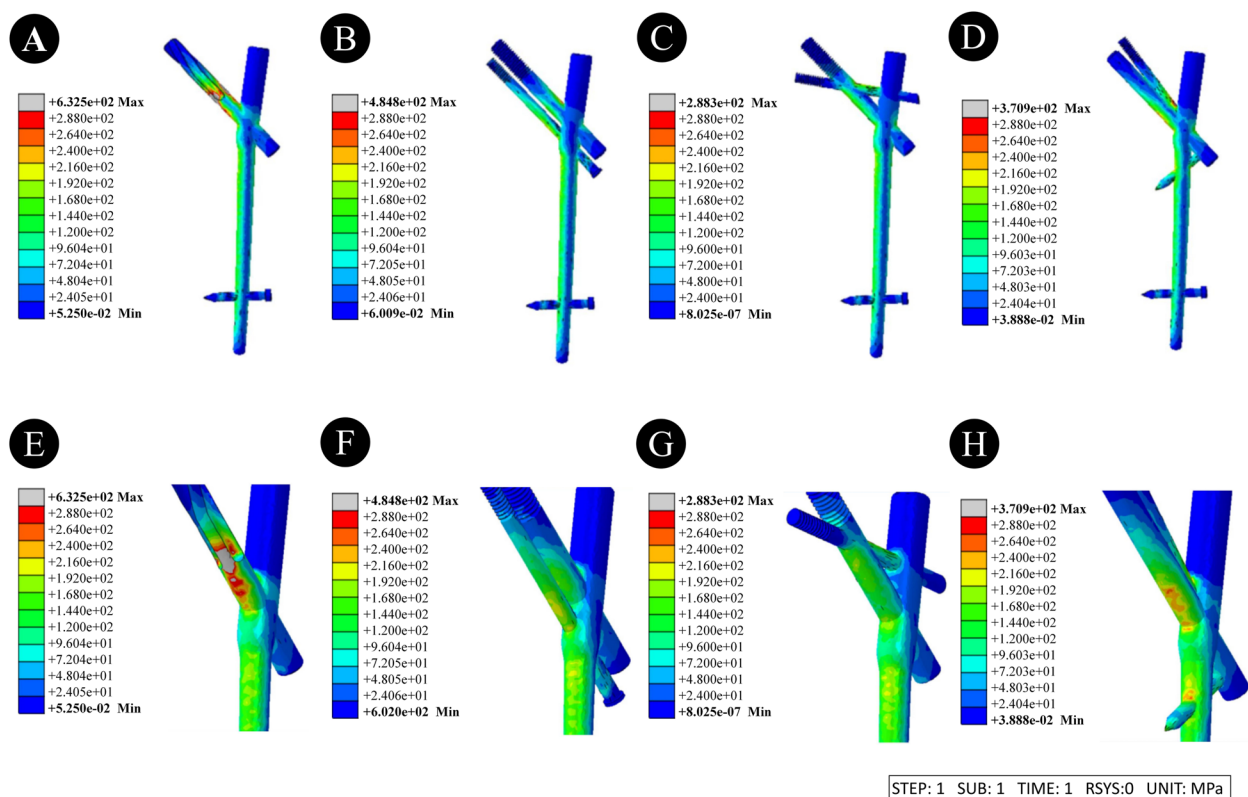


Fig. 2 Stress distribution of four kinds of intramedullary nailing internal fixation devices. **A** is the stress distribution diagram of the PFNA device, and **E** is the stress distribution at the intersections of intramedullary nails on the inner side of the PFNA device. **B** is the stress distribution diagram of the InterTan device, and **F** is the stress distribution at the InterTan device's internal and lateral intramedullary nail intertan device. **C** is the stress distribution diagram of the PFBN device, and **G** is the stress distribution at the intersections of intramedullary nails on the inner side of the PFBN device. **D** is the stress distribution diagram of the NIS device, and **H** is the stress distribution at the intersections of intramedullary nails on the internal side of the NIS device

Displacement distribution of four kinds of intramedullary nailing devices

The peak displacement of PFNA intramedullary nailing device was 6.978 mm. The peak displacement of InterTAN intramedullary nail device was 6.628 mm. The peak displacement of PFBN intramedullary nailing device was 6.475 mm. The peak displacement of the NIS intramedullary nail device was 6.534 mm. The displacement distribution areas of the four intramedullary nails were similar, all of them were located at the top of the cephalic nail. The peak displacement of PFNA device was the largest, and that of PFBN device was the smallest, but its range was smaller than that of NIS.

Of the four intramedullary nail devices, the PFBN device showed the lowest displacement peak, indicating that its structure has better stability under load, reducing the risk of screw breakage under the same load. The PFNA device showed the highest displacement peak, indicating that its structure may be more prone to internal fixation failure under the same load conditions.

Although the peak displacement of InterTAN device is slightly smaller than that of PFNA, there is also a phenomenon of displacement concentration at the top of the main pith nail, and further attention should be paid to the material strength and structural properties in this area (Fig. 4).

The displacement distribution of the entire femur

The peak displacement of proximal femur fixed by PFNA device was 7.610 mm. The peak displacement of proximal femur fixed by InterTAN device was 6.987 mm. The peak displacement of proximal femur fixed by PFBN device was 6.948 mm. The peak displacement of proximal femur fixed by NIS device was 6.958 mm. The NIS and PFBN intramedullary nailing devices provide a more stable internal fixation structure, providing strong support to the entire femur, reducing the degree of femur displacement, and reducing the incidence of complications (Fig. 4).

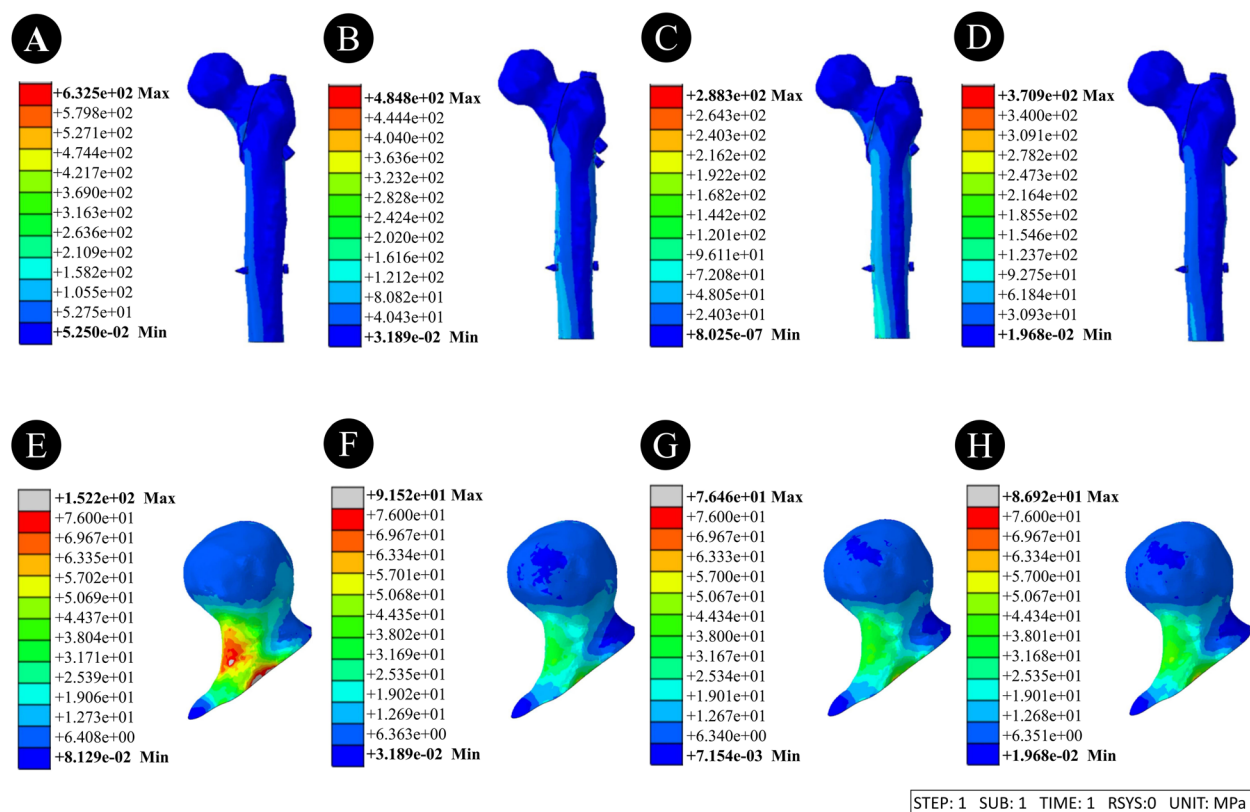


Fig. 3 Stress distribution of four intramedullary nail fixation fracture models. **A** and **E** are stress distribution maps of fracture model fixed by PFNA device; **B** and **F** are stress distribution maps of fracture model fixed by InterTan device; **C** and **G** are stress distribution maps of fracture model fixed by PFBN device; **D** and **H** are stress distribution maps of fracture model fixed by NIS device

Discussion

When exploring treatment strategies for unstable femoral neck fractures (UFNFs), internal fixation techniques have emerged as the mainstream approach, with advancements in technology and management of complications being a shared focus of attention in both the medical and bioengineering communities. Given that postoperative impairment of femoral head blood supply and instability of fixation are high-risk factors for non-union and necrosis [24], current surgical practices favor more sophisticated extramedullary fixation techniques, such as Cannulated Screws (CS), Dynamic Hip Screws (DHS), and Femoral Neck System (FNS), which have demonstrated certain therapeutic effects and indications in clinical literature [25–27]. Nevertheless, complications like femoral neck shortening and coxa vara post-surgery, which are directly associated with weakened abductor muscle function and limited hip function, exacerbate the risk of femoral head collapse [28], prompting researchers to continually explore more stable and efficient fixation solutions.

Against this backdrop, enhancing the overall stability of femoral neck fracture treatment devices and exploring

intramedullary fixation systems specifically designed for femoral neck fractures have become hot topics in current orthopedic research. Wang et al.'s biomechanical comparative study prominently revealed the superiority of the InterTan nail in terms of axial and anteroposterior (AP) bending stiffness compared to FNS and various CSs [29]. However, the parallel design of the double-neck screws of the InterTan nail still has limitations in optimizing spatial layout and fixation efficiency in the femoral neck segment, urging research teams to develop modified intramedullary nail fixation devices aimed at achieving a more robust fixation effect for UFNFs.

One of the fundamental causes of mechanical failures in internal fixation devices lies in their mismatch with the complex anatomical structure and mechanical properties of the proximal femur. In this regard, Zhang et al. proposed the triangular stability structure theory, providing a novel perspective to reduce the risk of intramedullary nail fixation device failure and subsequently facilitating the birth and development of proximal femoral bionic nail (PFBN) technology [30]. The innovation of PFBN lies in its double-triangle design, which ingeniously mimics the mechanical behavior of the normal proximal femoral

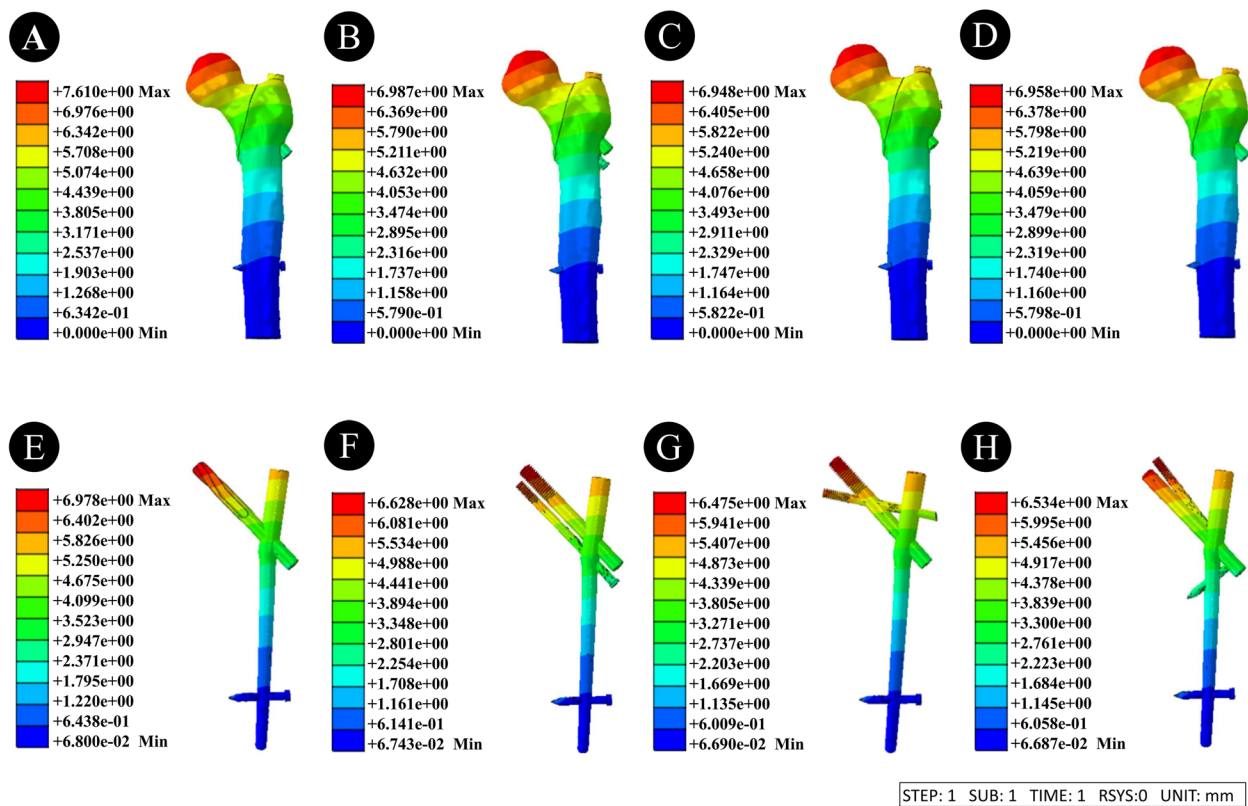


Fig. 4 Displacement profiles of femoral neck fractures fixed by four types of intramedullary nails. (A,E) femoral neck fracture model and displacement distribution map of PFNA device; (B,F) Femoral neck fracture model and displacement distribution map of InterTan device; (C,G) femoral neck fracture model and displacement distribution map of PFBN device; (D,H) Femoral neck fracture model and NIS device displacement distribution map

cantilever beam structure. Through the synergistic action of support screws, fixation screws, and the main nail, it establishes a double-pivot fixation mode, effectively shortening the length of the force arm, significantly dispersing stress concentration, and thereby significantly enhancing the biomechanical stability after femoral neck fracture surgery.

Given the importance of restoring medial wall support in enhancing the therapeutic effect of UFNFs, the specific role of PFBN in medial wall support efficacy has become a research topic in urgent need of clarification. To address this gap, Wang et al. designed the NIS internal fixation device [31], which achieves double support for the femoral head and the medial wall of the femur through the unique layout of three proximal screws. Nevertheless, its insufficient anti-rotation performance and potential risks of fracture and loosening suggest the necessity for further optimization.

This study comprehensively evaluated the biomechanical properties of PFNA, InterTAN, PFBN, and NIS in the treatment of unstable femoral neck fractures using advanced finite element analysis techniques. The results

indicate that PFBN exhibits significant advantages in overall stability, with lower stress peaks and more even stress distribution in the proximal femoral region compared to other comparative models, demonstrating its superior ability to resist loads and shear forces. These characteristics provide strong support for the improved therapeutic effects of PFBN in clinical applications. Further analysis reveals that the support screws of PFBN play a pivotal role in reducing stress concentration on the fixation screws, effectively lowering the risks of screw pullout, fracture, and coxa vara complications. For elderly patients with UFNFs, especially those with osteoporosis, the exceptional stability of PFBN provides a more reliable foundation for early postoperative rehabilitation training.

However, it must be emphatically clarified that the current research still has limitations in comprehensively analyzing the mechanical properties of PFBN and NIS in osteoporotic femoral neck fracture models, as the exploration in this crucial field is still in its preliminary stage, far from in-depth. Given that osteoporosis is a complex disease that widely affects bone structure and strength, understanding its mechanical response mechanism to

biomaterials, particularly novel internal fixation devices such as PFBN, is crucial for the development of targeted therapeutic potential internal fixation devices. Therefore, future research should focus on deepening the study of the mechanical behavior of PFBN and NIS in simulated osteoporotic environments, including but not limited to their adhesion strength at the bone tissue interface, stress transfer efficiency, and mechanical stability after long-term implantation.

This necessitates not only more sophisticated experimental designs and advanced testing technologies but also the integration of interdisciplinary knowledge from biomechanics, materials science, and medical engineering to comprehensively reveal the potential and limitations of novel devices like PFBN in osteoporotic treatment strategies, thereby facilitating further verification and expansion in related fields and providing a solid theoretical and experimental basis for clinical applications.

Conclusion

Based on the aforementioned analysis, this study employed the finite element method to deeply investigate the mechanical performance of PFNA, InterTAN, PFBN, and NIS in the treatment of BFNF. The results indicate that PFBN exhibits superior shear and load-bearing capabilities compared to PFNA, InterTAN, and NIS models. Therefore, we recommend giving priority to the use of PFBN devices in the treatment of BFNF. This study not only provides solid biomechanical evidence for further scientific research on PFBN in BFNF patients, but also lays a theoretical foundation for its widespread application in clinical practice.

Authors' contributions

ZT and BW: wrote the main manuscript text and prepared figures 1-4. ZZ, YL, CZ and YZ: wrote the main manuscript text and prepared figures 1-3. YL and SH: prepared figures 4 and table 1. All authors reviewed the manuscript.

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Availability of data and materials

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

Declarations

Ethics approval and consent to participate

The studies involving humans were approved by the Ethics Committee of the Second Affiliated Hospital of Xuzhou Medical University. The studies were conducted in accordance with the local legislation and institutional requirements.

The participants provided their written informed consent to participate in this study. All patients signed a written informed consent before recruitment.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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