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Biomechanical characteristic differences of two new types of intramedullary nail devices in the treatment of comminuted intertrochanteric fractures of femur: a comparative study based on finite element analysis

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Abstract

Objective Given the recent application of two new types of intramedullary nail devices in the treatment of comminuted femoral intertrochanteric fractures (CFIFs), there is still a lack of deep understanding and comparative evaluation of their biomechanical properties. Therefore, this study aims to systematically compare the advantages and disadvantages of these two new devices with traditional proximal femoral nail antirotation (PFNA) and InterTan nails in the fixation of CFIFs through finite element analysis.

Methods Based on the validated finite element model, this study constructed an accurate CFIFs model. In this model, PFNA, InterTan nails, proximal femoral bionic nails (PFBN), and new intramedullary systems (NIS) were implanted, totaling four groups of finite element models. Each group of models was subjected to simulation tests under a vertical load of 2100 N to evaluate the displacement and Von Mises stress (VMS) distribution of the femur and intramedullary nail devices.

Results Under a vertical load of 2100 N, a comparative analysis of the four finite element models showed that the NIS device exhibited the most superior performance in terms of peak displacement, while the PFNA device performed relatively poorly. Although the NIS device had the highest peak stress in the femur, it had the smallest peak displacement of both the femur and intramedullary nail devices, and the peak stress was mainly concentrated on the lateral side of the femur, with significantly lower stress in the proximal femur compared to the other three

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intramedullary nail devices. In contrast, the PFBN device had the lowest peak stress in the femur, and its peak displacement of both the femur and intramedullary nail devices was also less than that of PFNA and InterTan nails.

Conclusion This study demonstrates that in the treatment of CFIFs, PFBN and NIS devices exhibit superior biomechanical performance compared to traditional PFNA and InterTan nail devices. Especially the NIS device, which can achieve good biomechanical results when fixing femoral intertrochanteric fractures with missing medial wall. Therefore, both PFBN and NIS devices can be considered reliable closed reduction and internal fixation techniques for the treatment of CFIFs, with potential clinical application value.

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

Introduction

Femoral intertrochanteric fractures (FIFs) specifically refer to the type of fractures that occur between the greater trochanter and the lesser trochanter of the femur. Such fractures can have a mortality within 1 year ranged from 6.6 to 36.4%, significantly increasing the burden on medical, economic, and social systems [1–3]. Previous studies generally recommend surgical treatment within 24 to 48 h after the occurrence of fractures, especially for unstable femoral intertrochanteric fractures, which can aid in early patient recovery and reduce the risk of complications arising from prolonged bed rest [4, 5]. It is worth noting that CFIFs (especially AO 31-A2.3 type) account for over 80% of unstable femoral intertrochanteric fractures, and the failure rate of internal fixation devices is relatively high, posing a significant challenge in the field of orthopedics [6, 7]. Therefore, optimizing the biomechanical properties of internal fixation devices is crucial for improving treatment outcomes and reducing surgical failure rates.

Currently, widely used internal fixation devices for the treatment of femoral intertrochanteric fractures include PFNA, Gamma3 nails, and InterTan nails. Both PFNA and Gamma3 nails feature a single-head intramedullary nail design, which exhibits poor anti-rotation performance. Although PFNA is more commonly used in clinical practice compared to Gamma3 nails, there have been reports of insufficient anti-rotation force for proximal fracture fragments, loosening and breakage of the head medullary screw [8, 9]. In contrast, the InterTan nail adopts a double-head intramedullary screw design, enhancing anti-rotation ability through two parallel head medullary screws at the neck. However, its resistance to femoral head rotation is still limited, and it causes greater trauma to the femoral head compared to PFNA.

Previous research indicates that while intramedullary fixation methods remain the mainstream choice in the management of intertrochanteric fractures of the femur, they are confronted with non-negligible challenges, notably a risk of 6–21% for implant-related complications [10, 11]. These complications encompass, but are not limited to, varus deformity of the hip, screw loosening or backing

out, the need for implant removal, implant structural fracture, and shortening of the femoral neck length. It is particularly noteworthy that in elderly patients, this risk becomes even more pronounced, with implant failure rates potentially soaring up to 30% [12]. Therefore, enhancing the anti-rotation performance and medial support ability of CFIFs is key to reducing the failure rate of intramedullary nail devices [13].

Hence, optimizing treatment strategies for such patients, reducing the incidence of complications, and improving treatment outcomes have emerged as critical challenges in the field of traumatic surgery, necessitating relentless exploration and innovation by trauma surgeons.

Given the structural limitations of existing intramedullary nail devices, scholars have proposed two novel intramedullary nail internal fixation devices: PFBN and NIS. Preliminary research results indicate that these two novel designs exhibit potential advantages in improving anti-rotation force and medial wall support of the femur. However, there is still a lack of in-depth comparative studies on the biomechanical differences between novel intramedullary nail devices in the treatment of CFIFs.

The aim of this study is to further clarify the differences in biomechanical properties by comparing and analyzing the stress distribution and stability of two novel intramedullary nails in fixing CFIFs models, as well as comparing them with traditional PFNA and InterTan nails. This will provide clinicians with a clearer theoretical basis and recommendations when selecting internal fixation devices. To achieve this goal, we will adopt the finite element analysis (FEA) computer simulation system. FEA simulates the geometric shape and loading conditions of real objects using mathematical approximations, offering advantages such as ease of operation, convenient model acquisition, and high experimental reliability. It has been widely used and recognized in the field of trauma orthopedics for the design of novel internal fixation devices [14, 15].

Materials and methods

3D model of femoral and nail devices

A healthy male volunteer (58 years old, 68 Kg) was recruited to exclude hip disease by X-ray examination. A 3D femoral model was created from its left femoral CT scan data via Mimics21.0 (Materialise, Leuven, Belgium). During the CT scan, the voltage operating range was set to 70,140 kV and the current was 30,800 mA. Cortical and cancellous bone were identified by Hounsfield units (HU) with a boundary set at 700 (Abdul-Wahab et al., 2020). Then, based on previous literature, a standardized posteromedial unsupported CFIF model (AO / OTA 31-A2.3: the most unstable and common type of comminuted intertrochanteric fracture) was established for [16, 17]. The small tuberosity between the two cut lines and part of the greater tuberosity, especially the posterior (Fig. 1A).

SolidWorks 2021 (Dassault Systemes SolidWorks Corp., United States) was used to construct four intramedullary nail models, including PFNA, InterTan, PFBN, and NIS models. The PFNA, InterTAN, and PFBN models were constructed from the parameters of the intramedullary nail device provided by the manufacturer (NATO Institute of Medical Technology, China) in UG-NX 12.0 (Siemens Product Life Cycle Management Software, USA). The parameters of the NIS Intramedullary nail device are as follows, the main nail is the distal part is 17 mm (diameter) and the distal part is 10 mm (diameter) 170 mm (length). The specifications of the NIS sleeve, two head nails and subtrochanteric nails are 12 mm, 9 mm, 6.4 mm and 5.0 mm in diameter, respectively. In the NIS, the design angle between the lower head nail

and the main nail is 130. Furthermore, the design angle between the two heads is 7.5 and between the lower and the lower heads is 70. The four nail units were converted to stereo lithography format and imported into 3-Matic 16.0 (Materialise, Leuven, Belgium). Finally, when the format transformation was complete, the above four nail models were separately assembled onto the CFIFs models. Figures 2, 3 shows a schematic representation of the four nail models (Figs. 2, 3).

Material characteristics

The femoral and nail devices were set to uniform, isotropic and linear elastic material. In addition, the titanium alloys are designated as the device material. On the basis of previous literature on [18–20], the Young's modulus of cortical and cancellous bone was 16.8 GPa and 0.58 GPa, respectively, compared with a Poisson's ratio of 0.3. The Young's modulus and Poisson ratio of the intramedullary nail were 110 GPa and 0.31, respectively. Material parameters of each component are shown in the table (Table 1).

Boundary conditions and loading settings

In this study, the bone-screw and bone-bone interfaces were set as surface contact relationships, with the contact type designated as frictional contact. Specifically, the friction coefficient between bone and bone was determined to be 0.46, while the friction coefficient between bone and screw was set to 0.42, and the friction coefficient between screws was set to 0.2. For boundary conditions, all degrees of freedom at the distal end of the femoral model were fully constrained, and the contact area between the femoral head and the pelvis was

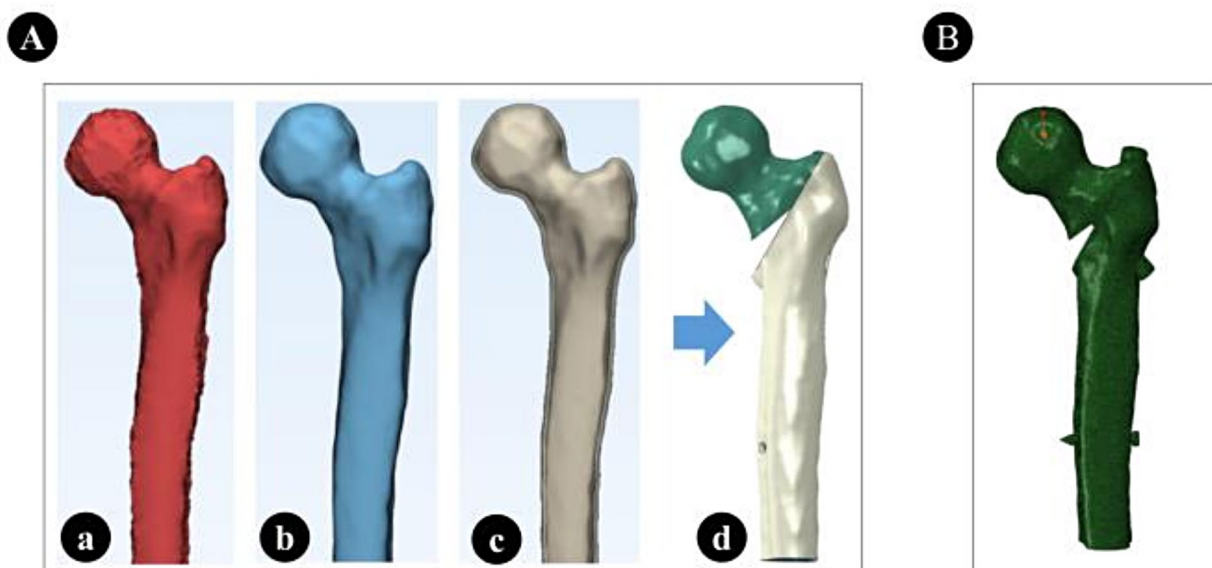


Fig. 1 **A:** a, b, c, and d are the steps to establish a model for comminuted femoral intertrochanteric fracture. **B:** The stress state of the fracture model fixed with intramedullary nail under a vertical load of 2100 N

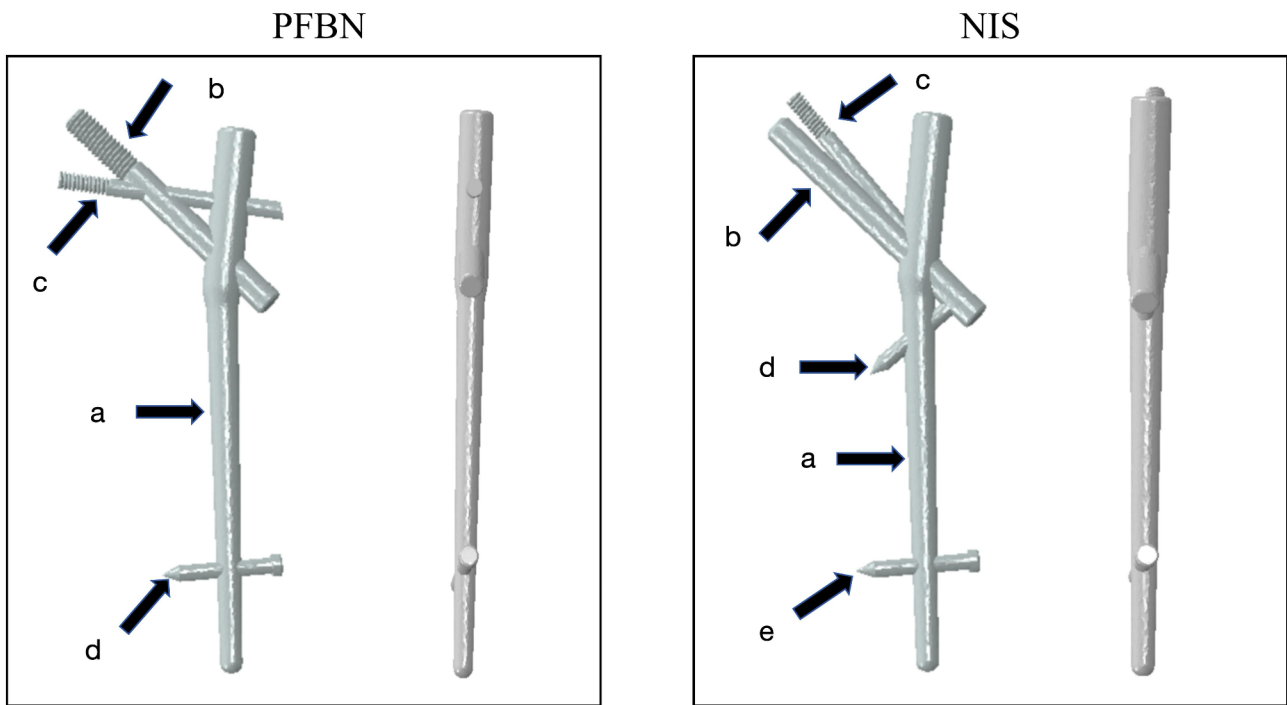


Fig. 2 Two new types of internal fixation device models were established, the three-dimensional model of Proximal Femoral Bionic Nail (PFBN), including **a** main nail; **b** compression nail; **c** tension nail; **d** locking nail. The three-dimensional model of New Intramedullary Systems (NIS), including **a** main nail; **b** lower head medullary nail; **c** upper head medullary nail; **d** subtrochanteric nail; **e** locking nail

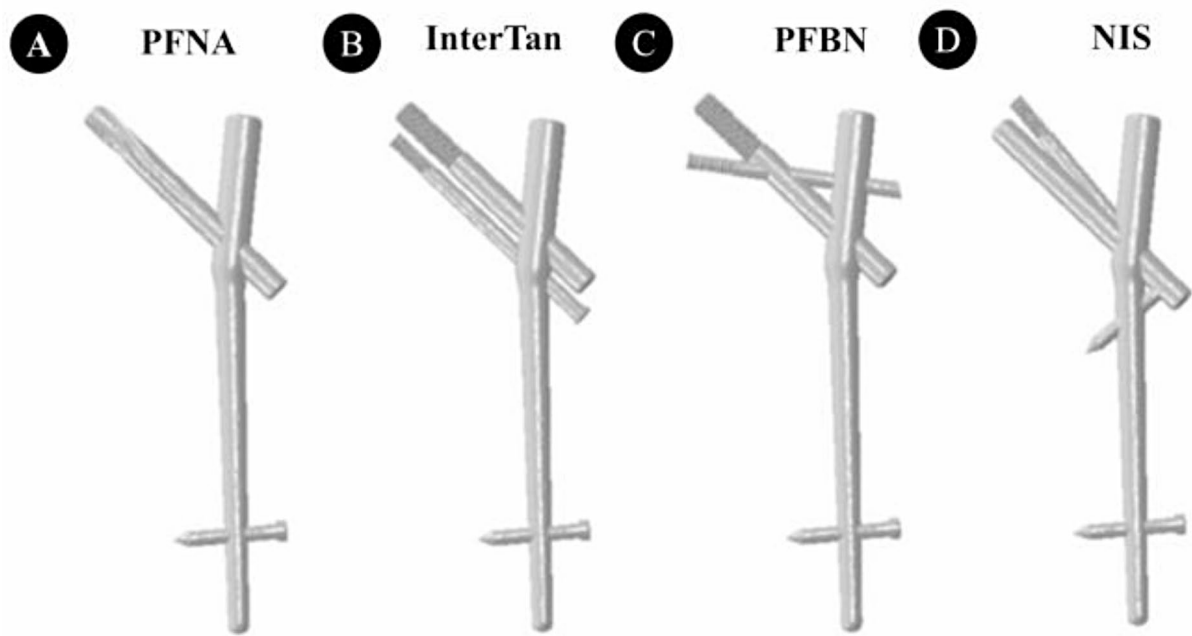


Fig. 3 Four types of intramedullary nail device model drawings: **A:** PFNA; **B:** InterTan; **C:** PFBN; **D:** NIS

coupled to a single point for the application of external loads. The loading conditions were set to 2100 N, simulating the vertical downward force during normal standing (Fig. 1B).

Model validation strategy
 To ensure the accuracy of the model, we first constructed a complete femoral model and assigned corresponding material properties to it based on the methods described in references [21, 22]. Subsequently, the degrees of

Table 1 Material parameters

Materials	Elastic modulus (MPa)	Poisson's ratio
Cortical bone	16,800	0.3
Cancellous bone	580	0.3
Head of femur	900	0.29
Collum femoris	620	0.29
Intramedullary nail	110,000	0.31

freedom at the distal end of the femoral model were fully constrained, and a vertical load of 2100 N was applied to the femoral head. Using Ansys 19.0 software (ANSYS Inc., USA), we conducted a thorough analysis of the model and carefully compared the obtained results with the reported results in references [21, 22] to verify the validity of the model.

Main evaluation parameters

We employed Ansys 19.0 software (ANSYS Inc., USA) to conduct detailed mechanical analyses of the proximal and distal ends of the femur, as well as four different intramedullary nail fixation devices. The output parameters primarily included Von Mises stress distribution maps, displacement distribution maps, and overall stress distribution data for the femur, providing comprehensive and insightful information on the mechanical characteristics of the model.

Results

The Von Mises stress distribution analysis of the four intramedullary nail devices

The peak Von Mises stress (VMS) value for the PFNA nail device was measured to be 406.5 MPa. For the InterTAN nail device, the peak VMS was recorded as 238.6 MPa. Similarly, the peak VMS for the PFBN nail device was 280.5 MPa, and for the NIS nail device, it was 413.4 MPa. Among the four nail devices, the peak stress of the PFNA device was slightly lower than that of the NIS devices. However, the distribution of peak stress was quite widespread, with the highest concentration observed at the junction between the main nail and the head nail (Fig. 4).

The Von Mises stress distribution within the proximal and distal regions of the femur

The PFNA device exhibited peak VMS values of 152.2 MPa and 107.2 MPa at the distal femur. For the InterTAN device, the peak VMS was 239.5 MPa and 147.5 MPa at the same location. The PFBN device maintained peak VMS values of 133.6 MPa and 114.9 MPa at the distal femur. Meanwhile, the NIS device exhibited peak VMS values of 89.01 MPa and 143.4 MPa at the distal femur. Notably, the PFBN device effectively reduced the peak displacement at the proximal femur compared to the PFNA device, narrowing the distribution range of peak stress at the femoral neck. Furthermore, the NIS

device demonstrated a significant reduction in both peak stress and its distribution range within the proximal and medial femoral walls, compared to the other three nail devices (Fig. 4).

The displacement distribution analysis of the four intramedullary nail devices

The peak displacement of the PFNA nail device was 6.469 mm. InterTAN The peak displacement of the nail device was 6.565 mm. The peak displacement of the PFBN nail device was 6.329 mm. The peak displacement of the NIS nail device was 6.214 mm. The region of displacement distribution was similar for the four nails, all on the top of the head nail, with the NIS device having the smallest peak displacement, but a broader range than the PFBN (Fig. 5).

Analysis of displacement distribution in proximal and distal femur with four kinds of intramedullary nail devices

The peak displacement of the proximal femur was 7.013 mm. InterTAN The peak displacement of the proximal femur in the device was 6.921 mm. The peak displacement of the PFBN device was 6.723 mm. The peak displacement of the proximal femur in the NIS device was 6.668 mm. The NIS and PFBN intramedullary nail devices provide a more stable internal fixation structure, providing strong support for the whole femur, reducing the degree of femoral displacement, and reducing the incidence of complications (Fig. 5).

Discussion

This study delves into the treatment options for femoral intertrochanteric fractures (FIFs), particularly the application of intramedullary nail devices. As a common type of hip fractures, FIFs has always been a major clinical challenge due to its high mortality and morbidity rates [14, 15, 23]. During the treatment process, the quality of reduction and effective fixation are considered as key factors that influence treatment outcomes. The intramedullary nail device has become a mainstream treatment for FIFs due to its minimal soft tissue damage, easy operation, and main nail fixation characteristics [24, 25].

Among the existing intramedullary nail devices, PFNA is widely regarded by scholars as the gold standard for treating complex intertrochanteric fractures (CFIFs) due to its unique advantages [26, 27]. However, with the increasing occurrence of violent fractures, the treatment difficulty of CFIFs has gradually increased. Previous studies have shown that when PFNA is used to treat CFIFs, the incidence of surgical complications is relatively high, including nail withdrawal, nail breakage, and varus collapse of the femoral neck [28]. These complications undoubtedly increase the risk of reoperation and death in elderly patients.

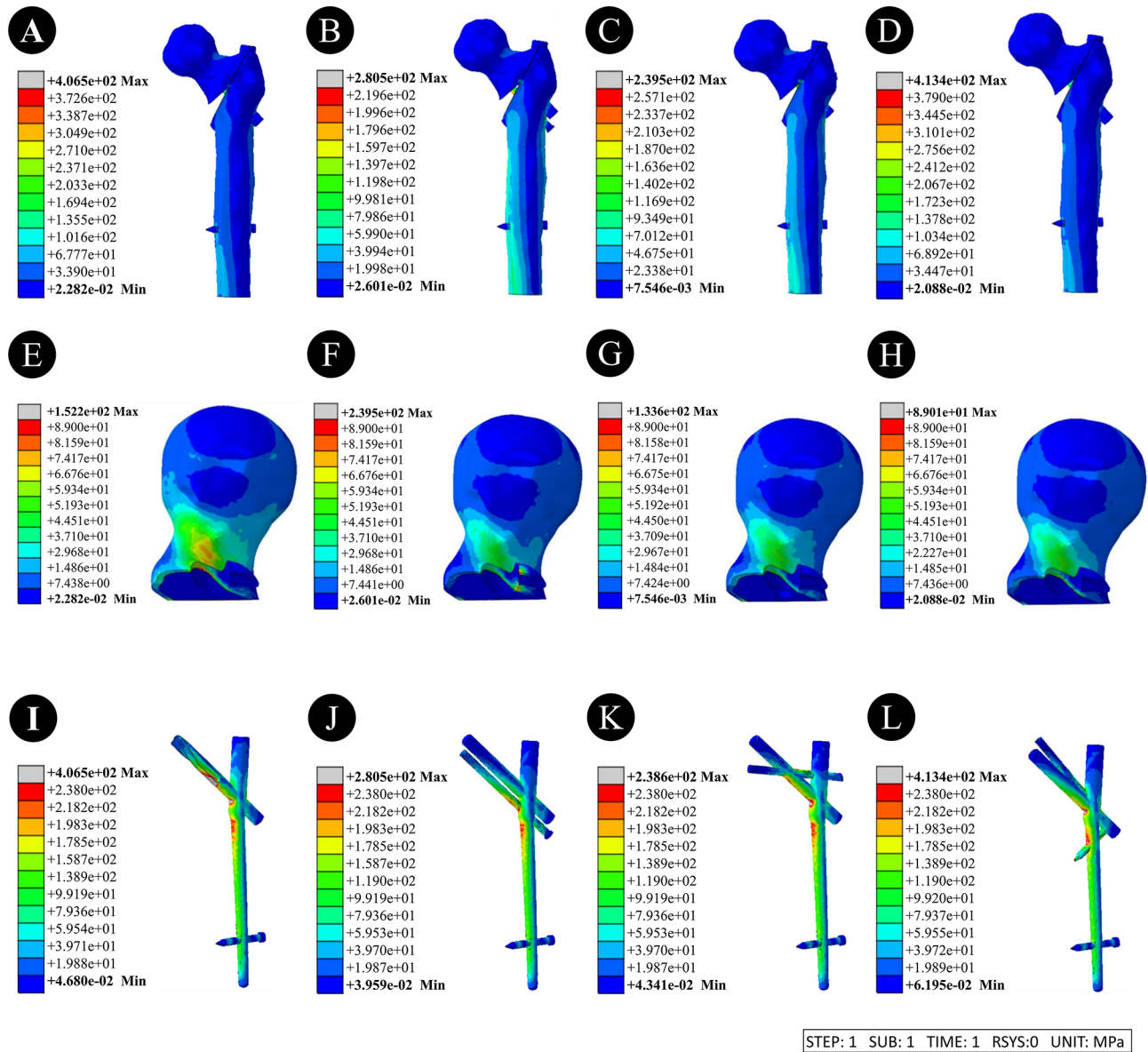


Fig. 4 Stress distribution charts of four kinds of intramedullary nail devices used for the fixation of comminuted femoral intertrochanteric fractures. (A,E,I) Stress distribution charts of femoral fracture models and PFNA devices; (B,F,J) Stress distribution charts of femoral fracture models and InterTan devices; (C,G,K) Stress distribution charts of femoral fracture models and PFBN devices; (D,H,L) Stress distribution charts of femoral fracture models and NIS devices

This study, through in-depth and meticulous analysis, further elucidates the significant stress concentration phenomenon observed in the intersection area between the femoral head nail and the main nail in both PFNA (Proximal Femoral Nail Antirotation) and InterTan devices. This discovery not only deepens our understanding of the biomechanical behaviors of these two internal fixation devices but also explicitly identifies this connection site as a potential high-risk area, where stress concentration is highly likely to be a crucial factor inducing screw fracture, loosening, and other related clinical complications.

Specifically, stress concentration typically occurs in regions of structural discontinuity or abrupt geometric changes, such as the junction between the femoral head nail and the main nail in PFNA and InterTan devices. This stress concentration not only increases the local load on the material but also accelerates material fatigue, leading to a decline in the mechanical properties of the screw, ultimately manifesting as screw fracture or loosening. These complications not only compromise patient treatment outcomes but also prolong the recovery period, increase treatment costs, and even adversely affect patients' quality of life.

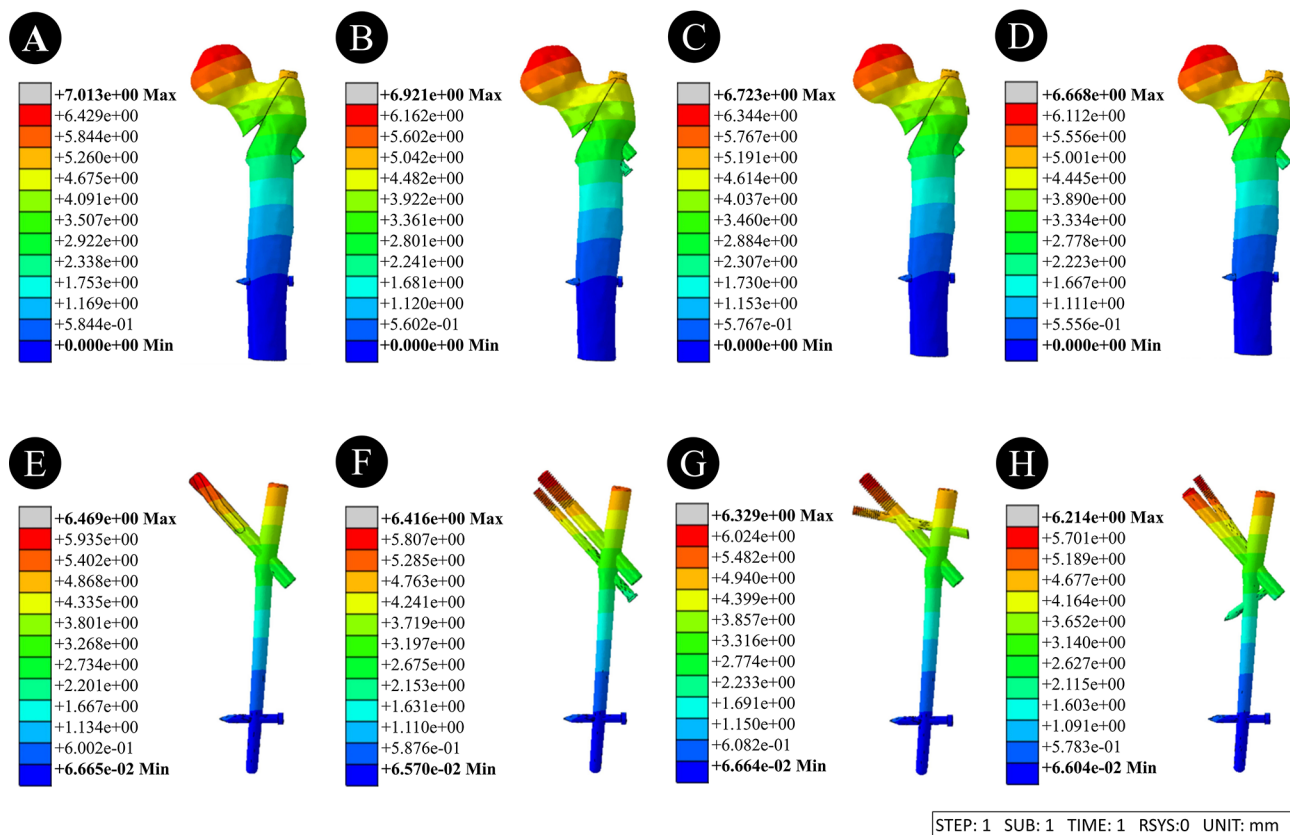


Fig. 5 Displacement distribution maps of four types of intramedullary nail devices for fixation of comminuted femoral intertrochanteric fractures. (A,E) femoral fracture model and PFNA device displacement distribution map; (B,F) femoral fracture model and InterTan device displacement distribution map; (C,G) femoral fracture model and PFBN device displacement distribution map; (D,H) femoral fracture model and NIS device displacement distribution map

Therefore, the findings of this study hold significant implications for guiding the selection, application, and postoperative management of PFNA and InterTan devices in clinical practice. In the future, researchers should further explore the possibilities of optimizing the design of this connection site, such as by improving material properties, adjusting geometric structures, or introducing novel connection mechanisms, to effectively reduce stress concentration, enhance the stability and durability of internal fixation devices, thereby minimizing the occurrence of clinical complications and facilitating faster and better patient recovery. At the same time, these two devices have insufficient support for the medial wall of the femur and cannot provide sufficient biomechanical support for CFIFs.

Therefore, the development of intramedullary nail devices with better biomechanical properties has become a current research hotspot. Through a thorough analysis of the advantages and disadvantages of existing intramedullary nail devices, we can provide powerful suggestions and biomechanical evidence for selecting treatment options during clinical diagnosis and treatment.

With the deepening of biomechanical research, we have a clearer understanding of different types of trabeculae and their mechanical distribution. The proximal trabecular bone of the femur includes compressive trabeculae, tensile trabeculae, and intertrochanteric trabeculae, which together form the Ward triangle to adapt to the mechanical loads of the human body in various positions and movements [29]. Based on this understanding, scholars such as Zhang proposed the PFBN device, which is an improvement based on PFNA. By introducing compressive nails and tensile nails, it forms a stable triangular structure, thereby enhancing support for the medial wall of the femur [30].

Previous studies and this study's results indicate that PFBN achieves the inward movement of the femoral fulcrum and the reconstruction of anatomical fulcrums by optimizing the combination and distribution of screws [29]. The tensile nail shares most of the stress while reducing stress concentration at the intersection of the main nail and the compressive nail, thereby reducing the risk of nail breakage. Additionally, PFBN enhances anti-rotation capabilities by forming an anti-rotation triangle. However, PFBN also exhibits certain limitations

in clinical applications and finite element analysis, particularly its insufficient support for the medial wall of the femur, which may increase the risk of varus deformity.

To overcome this limitation, scholars such as Wang proposed the NIS internal fixation device. The innovation of this device lies in its proximal structure, which consists of three nails. Two cephalic nails are inserted into the femoral head at specific angles, while a subtrochanteric nail is used to support the medial wall of the femur [31]. Finite element analysis results show that the NIS device can effectively distribute vertical loads, reduce the incidence of varus deformity, and improve overall stability by providing medial wall support. Although the stress peak of the NIS device is relatively high, its stress distribution is more reasonable, helping to reduce complications such as nail withdrawal, nail breakage, and screw loosening.

As two advanced intramedullary nail fixation systems, PFBN and NIS have demonstrated remarkable capabilities in displacement control and stress distribution during the treatment of intertrochanteric fractures of the femur. These features not only ensure efficient reduction and stable fixation of the fracture site but also significantly reduce the risk of failure of the internal fixation device due to mechanical factors. Specifically, they provide robust support and constraint for the fracture ends through precise anatomical adaptation design and optimized material mechanical properties, thereby facilitating the smooth progress of fracture healing.

Furthermore, the exceptional stability and superior shear resistance characteristics of PFBN and NIS systems offer solid guarantees for patients to ambulate early after surgery. This advantage not only accelerates the patients' rehabilitation process, reduces the risks of complications such as pressure sores and deep venous thrombosis that may arise from prolonged bed rest, but also effectively improves patients' quality of life, promoting their comprehensive physical and mental recovery.

In conclusion, PFBN and NIS intramedullary nail devices have emerged as essential therapeutic options in the treatment of intertrochanteric fractures of the femur due to their superior displacement and stress management capabilities, highly reliable fixation effects, and potential to facilitate early recovery. They have brought safer, more effective, and convenient rehabilitative experiences to numerous patients in modern orthopedic surgery.

This study provides a useful reference for the selection of clinical surgical options by comparing and analyzing the biomechanical advantages and disadvantages of four intramedullary nail devices in fixing CFIFs. However, this study still has certain limitations, such as focusing only on CFIFs, differences between model material parameters and actual bone characteristics, and incomplete consideration of muscle group effects in experimental loading

settings. Future studies will further expand the range of fracture types and internal fixation devices, improve the accuracy of models and the complexity of experiments, to better guide clinical practice and optimize the design of intramedullary nail devices.

Conclusion

This study indicates that there are significant biomechanical defects in PFNA and InterTan nails in the treatment of CFIFs with intramedullary nail fixation. In contrast, PFBN significantly reduces stress concentration between screws and the risk of fracture and loosening. Although the NIS device has a more concentrated stress distribution between screws, it provides better support for the medial side of the femur. Overall, as new internal fixation devices, PFBN and NIS have significant biomechanical advantages over PFNA and InterTan nails. However, there is no absolute biomechanical difference between the two, so it is recommended that patients with CFIFs with significant medial wall defects should give priority to NIS, and PFBN should be selected otherwise. The findings of this study have important reference value for the design optimization of intramedullary nail devices, but the differences in clinical effects of different devices in the treatment of CFIFs still need to be further clarified through clinical retrospective analysis.

Author contributions

ZJT, YXL and ZXZ wrote the main manuscript text, ZJT, YFL, ZXZ and HBZ prepared Table 1; Figs. 1 and 2. YZZ and YFL prepared Figs. 3 and 4. All authors reviewed the manuscript.

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Data availability

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

Declarations

Ethical approval

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.

Consent to participate

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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References

- Huang Q, Xu Y, Xue H, et al. Percutaneous reduction with double screwdrivers versus limited open reduction in the treatment of irreducible extracapsular hip fractures. *BMC Musculoskelet Disord*. 2022;23(1):429. <https://doi.org/10.1186/s12891-022-05390-x>. Published 2022 May 6.
- Guzon-Illescas O, Perez Fernandez E, Crespi Villarias N, et al. Mortality after osteoporotic hip fracture: incidence, trends, and associated factors. *J Orthop Surg Res*. 2019;14(1):203. <https://doi.org/10.1186/s13018-019-1226-6>. Published 2019 Jul 4.
- Maffulli N, Aicale R. Proximal femoral fractures in the elderly: a few things to know, and some to forget. *Med (Kaunas)*. 2022;58(10):1314. <https://doi.org/10.3390/medicina58101314>. Published 2022 Sep 20.
- Queally JM, Harris E, Handoll HH, Parker MJ. Intramedullary nails for extracapsular hip fractures in adults. *Cochrane Database Syst Rev*. 2014;2014(9):CD004961. Published 2014 Sep 12. <https://doi.org/10.1002/14651858.CD004961.pub4>
- Brox WT, Roberts KC, Taksali S, et al. The American academy of orthopaedic surgeons evidence-based guideline on management of hip fractures in the elderly. *J Bone Joint Surg Am*. 2015;97(14):1196–9. <https://doi.org/10.2106/JBJS.O.00229>.
- Grønhaug KML, Dybvik E, Matre K, Östman B, Gjertsen JE. Intramedullary nail versus sliding hip screw for stable and unstable trochanteric and subtrochanteric fractures: 17,341 patients from the Norwegian hip fracture Register. *Bone Joint J*. 2022;104–B(2):274–82. <https://doi.org/10.1302/0301-620X.104B2.BJJ-2021-1078.R1>.
- Marsillo E, Pintore A, Asparago G, Oliva F, Maffulli N. Cephalomedullary nailing for reverse oblique intertrochanteric fractures 31A3 (AO/OTA). *Orthop Rev (Pavia)*. 2022;14(6):38560. <https://doi.org/10.52965/001c.38560>. Published 2022 Oct 13.
- Wu D, Wang T, Li C, et al. The effect of distal locking mode on postoperative mechanical complications in intertrochanteric fractures: a retrospective cohort study of five hundred and seven patients. *Int Orthop*. 2024;46. <https://doi.org/10.1007/s00264-024-06168-7>.
- Wang C, Hou M, Zhang C, et al. Biomechanical evaluation of a modified intramedullary nail for the treatment of unstable femoral trochanteric fractures. *Heliyon*. 2024;10(8):e29671. <https://doi.org/10.1016/j.heliyon.2024.e29671>. Published 2024 Apr 14.
- Wang C, Duan N, Li Z, et al. Biomechanical evaluation of a new intramedullary nail compared with proximal femoral nail antirotation and InterTAN for the management of femoral intertrochanteric fractures. *Front Bioeng Biotechnol*. 2024;12:1353677. <https://doi.org/10.3389/fbioe.2024.1353677>. Published 2024 Feb 23.
- Quaranta M, Miranda L, Oliva F, Migliorini F, Pezzuti G, Maffulli N. Haemoglobin and transfusions in elderly patients with hip fractures: the effect of a dedicated orthogeriatrician. *J Orthop Surg Res*. 2021;16(1):387. <https://doi.org/10.1186/s13018-021-02524-0>. Published 2021 Jun 16.
- Chapman T, Zmistowski B, Krieg J, Stake S, Jones CM, Levicoff E. Helical blade versus screw fixation in the treatment of hip fractures with cephalomedullary devices: incidence of failure and atypical medial cutout. *J Orthop Trauma*. 2018;32(8):397–402. <https://doi.org/10.1097/BOT.0000000000001193>.
- Zhang J, Wan S, Luo X et al. Increasing the angle between caudal screw and the transverse plane may aggravate the risk of femoral head necrosis by deteriorating the fixation stability in patients with femoral neck fracture. *Eur J Med Res*. 2024;29(1):170. Published 2024 Mar 12. <https://doi.org/10.1186/s40001-024-01737-3>
- Basironi I, Daud R, Ijaz MF, Rojan MA, Basaruddin KS. Stability analysis of plate-screw fixation for femoral midshaft fractures. *Mater (Basel)*. 2023;16(17):5958. <https://doi.org/10.3390/ma16175958>. Published 2023 Aug 30.
- Kujala MA, Hongisto MT, Luukkaala T, Stenholm S, Nuotio MS. Ptertrochanteric hip fracture is associated with mobility decline and poorer physical performance 4 to 6 months post-hip fracture. *BMC Geriatr*. 2023;23(1):722. <https://doi.org/10.1186/s12877-023-04415-x>. Published 2023 Nov 8.
- Li J, Zhang L, Zhang H, et al. Effect of reduction quality on post-operative outcomes in 31-A2 intertrochanteric fractures following intramedullary fixation: a retrospective study based on computerised tomography findings. *Int Orthop*. 2019;43(8):1951–9. <https://doi.org/10.1007/s00264-018-4098-1>.
- Nie S, Li J, Li M, et al. Finite-element analysis of a novel cephalomedullary nail for restricted sliding to reduce risk of implant failure in unstable intertrochanteric fractures. *Orthop Surg*. 2022;14(11):3009–18. <https://doi.org/10.1111/os.13497>.
- Stoffel K, Zderic I, Gras F, Sommer C, Eberli U, Mueller D, Oswald M, Gueorguiev B. Biomechanical evaluation of the femoral neck system in unstable pauwels iii femoral neck fractures: a comparison with the dynamic hip screw and cannulated screws. *J Orthop Trauma*. 2017;31(3):131–7. <https://doi.org/10.1097/BOT.0000000000000739>.
- Huang S, Zhang Y, Zhang X, Zhou C, Li W, Wang Y, Wang B, Zhu Z. Comparison of femoral neck system and three cannulated cancellous screws in the treatment of vertical femoral neck fractures: clinical observation and finite element analysis. *Biomed Eng Online*. 2023;22(1):20. <https://doi.org/10.1186/s12938-023-01083-1>.
- Chen P, Fan Z, Xu N, Wang H. A biomechanical investigation of a novel intramedullary nail used to salvage failed internal fixations in intertrochanteric fractures. *J Orthop Surg Res*. 2023;18(1):632. <https://doi.org/10.1186/s13018-023-04112-w>. Published 2023 Aug 28.
- Baca V, Horak Z, Mikulenska P, Dzupa V. Comparison of an inhomogeneous orthotropic and isotropic material models used for FE analyses. *Med Eng Phys*. 2008;30(7):924–30. <https://doi.org/10.1016/j.medengphys.2007.12.009>.
- Papini M, Zdero R, Schemitsch EH, Zalzal P. The biomechanics of human femurs in axial and torsional loading: comparison of finite element analysis, human cadaveric femurs, and synthetic femurs. *J Biomech Eng*. 2007;129(1):12–9. <https://doi.org/10.1115/1.2401178>.
- Chen YP, Kuo YJ, Hung SW, et al. Loss of skeletal muscle mass can be predicted by Sarcopenia and reflects poor functional recovery at one year after surgery for geriatric hip fractures. *Injury*. 2021;52(11):3446–52. <https://doi.org/10.1016/j.injury.2021.08.007>.
- Haidukewych GJ. Intertrochanteric fractures: ten tips to improve results. *J Bone Joint Surg Am*. 2009;91(3):712–9.
- Nikoloski AN, Osbrough AL, Yates PJ. Should the tip-apex distance (TAD) rule be modified for the proximal femoral nail antirotation (PFNA)? A retrospective study. *J Orthop Surg Res*. 2013;8:35. Published 2013 Oct 17. <https://doi.org/10.1186/1749-799X-8-35>
- Lewis SR, Macey R, Lewis J, et al. Surgical interventions for treating extracapsular hip fractures in older adults: a network meta-analysis. *Cochrane Database Syst Rev*. 2022;2(2):CD013405. <https://doi.org/10.1002/14651858.CD013405.pub2>. Published 2022 Feb 10.
- Gargano G, Poeta N, Oliva F, Migliorini F, Maffulli N. Zimmer Natural Nail and ELOS nails in pertrochanteric fractures. *J Orthop Surg Res*. 2021;16(1):509. <https://doi.org/10.1186/s13018-021-02634-9>. Published 2021 Aug 18.
- Li J, Han L, Zhang H, et al. Medial sustainable nail versus proximal femoral nail antirotation in treating AO/OTA 31-A2.3 fractures: Finite element analysis and biomechanical evaluation. *Injury*. 2019;50(3):648–56. <https://doi.org/10.1016/j.injury.2019.02.008>.
- Wang Y, Chen W, Zhang L, et al. Finite element analysis of proximal femur bionic nail (pfbn) compared with proximal femoral nail antirotation and intertan in treatment of intertrochanteric fractures. *Orthop Surg*. 2022;14(9):2245–55. <https://doi.org/10.1111/os.13247>.
- Zhao H, Deng X, Liu W, et al. Proximal femoral bionic nail (PFBN)—an innovative surgical method for unstable femoral intertrochanteric fractures. *Int Orthop*. 2023;47(4):1089–99. <https://doi.org/10.1007/s00264-023-05696-y>.
- Bai H, Liu L, Duan N, et al. Biomechanical evaluation of three implants for treating unstable femoral intertrochanteric fractures: finite element analysis in axial, bending and torsion loads. *Front Bioeng Biotechnol*. 2023;11:1279067. <https://doi.org/10.3389/fbioe.2023.1279067>. Published 2023 Nov 7.

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