

Biomechanical Effects of Cement Distribution Zone on PFNA Fixation Stability: A Comparative Finite Element Study

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Title

Biomechanical Effects of Cement Distribution Zone on PFNA Fixation Stability: A Comparative Finite Element Study

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Declarations**Ethics approval and consent to participate**

This study utilized a retrospectively collected CT image of the femoral neck from a healthy adult participant. The image data were obtained from Shanghai Tongji Hospital. Ethical approval for the use of these data was granted by the Ethics Committee of Shanghai Tongji Hospital (Approval No. SBKT-2024-204). The ethical approval documents are available in the Supplementary material.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and materials

The CT image datasets analyzed in this study are not publicly available due to patient privacy and ethical restrictions but may be made available upon reasonable request and with permission from the relevant ethics committee and data custodians. Requests for data access should be directed to wangxin1681@126.com.

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Consent to participate

Informed consent was obtained from all individual participants included in the original study from which the CT images were sourced. For retrospective data, a waiver of consent was granted by the ethics committee given the anonymized nature of the data and the study's observational design.

Consent for publication

All participants provided informed consent for the use of their anonymized imaging data for research purposes and publication of results in scientific literature.

Authors' contributions

1. Conceptualization: Xin Wang
2. Data curation: Yang Yang and Lei Yao
3. Formal analysis: Yang Yang
4. Investigation: Yang Yang

5. Methodology: Lei Yao
6. Project administration: Xin Wang
7. Resources: Xin Wang
8. Software: Yang Yang
9. Supervision: Xin Wang
10. Validation: Xin Wang
11. Visualization: Yang Yang and Lei Yao
12. Roles/Writing - original draft: Yang Yang and Lei Yao
13. Writing - review & editing: Xin Wang

Abstract

Background: Proximal femoral anti-rotation intramedullary nailing (PFNA) is a commonly used treatment for osteoporotic intertrochanteric fractures. Intraoperative cement augmentation is frequently employed to enhance fixation stability. However, the impact of variations in cement distribution on mechanical properties remains unclear. This study investigated the biomechanical effects of different cement distribution regions (femoral head and femoral neck) on the stability of cement-augmented PFNA fixation using finite element analysis.

Methods: Three-dimensional models of a healthy adult male femur and an A2.3 intertrochanteric femoral fracture were established. PFNA fixation models were constructed for three groups: non-augmented, head-augmented (cement augmentation in the femoral head), and neck-augmented (cement augmentation in the femoral neck). Total displacement, peak von Mises stress, peak pressure, and femoral neck varus angle were evaluated for each group using finite element analysis in ANSYS.

Results: Finite element analysis demonstrated that both augmented groups exhibited superior mechanical stability compared with the non-augmented group. Regarding displacement control, the head-augmented group showed less displacement (7.15 mm) than the neck-augmented group (7.52 mm), with both exhibiting substantially less displacement than the non-augmented group (10.34 mm). Regarding stress distribution, the neck-augmented group exhibited a lower peak von Mises stress (640.5 MPa) than both the head-augmented (1035.3 MPa) and non-augmented (1296.5 MPa) groups. In terms of resistance to deformation, the varus angle was smaller in the head-augmented group (2.62°) than in the neck-augmented group (3.19°), and both were smaller than that in the non-augmented group (4.33°). Additionally, cement augmentation expanded the load-bearing area of the helical blade, localising the expansion to the tip in the head-augmented group and to the middle segment in the neck-augmented group.

Conclusion: Cement augmentation improves the overall stability of the fixation construct by expanding the load-bearing area between the helical blade and the cancellous bone, with the region of load-bearing expansion corresponding directly to the site of cement aggregation. Different cement distribution zones exhibit distinct effects on mechanical stability: cement located in the femoral neck more effectively reduces peak implant stress, thereby mitigating the risk of implant fatigue failure, whereas cement located in the femoral head more effectively limits femoral head displacement and minimises femoral neck varus angulation. In clinical decision-making, surgeons should weigh the trade-off between ‘reducing implant loading’ and ‘maintaining reduction stability’ according to the patient's fracture pattern and bone quality.

Keywords: Proximal femoral anti-rotational intramedullary nail; Intertrochanteric fracture; Finite element analysis; Bone cement augmentation.

Introduction

With the acceleration of global ageing, hip fractures have become a growing public health concern [1]. Research indicates that approximately 90% of patients with hip fractures have osteoporosis [2], making hip fracture a major osteoporotic fracture that imposes a substantial economic burden on both individual patients and society. Among common osteoporotic fracture sites (such as the hip, spine, shoulder, and wrist), hip fractures account for more than 50% of cases,

while intertrochanteric femoral fractures constitute approximately 41%–50% [3]. Currently, surgical treatment for intertrochanteric femoral fractures is widely recognised as superior to conservative management, significantly reducing postoperative complications and mortality [4]. Clinically, internal fixation is commonly performed using plate-screw systems or proximal femoral anti-rotation intramedullary nailing (PFNA). Intramedullary nailing is favoured by orthopaedic surgeons because of its advantages of minimal trauma, short operative time, relatively short learning curve, and anatomical conformity [5]. However, internal fixation carries a risk of failure, particularly in patients of advanced age, with reported failure rates as high as 30% [6]. Osteoporosis, unstable fracture types, and suboptimal reduction are high-risk factors for early mechanical failure [7]. In older adults with osteoporosis, common complications include hip varus deformity, spiral blade cut-out, internal fixation loosening, and femoral neck shortening [8]. These complications arise from insufficient bone mass, which fails to provide adequate support and resistance to shear forces, presenting a significant clinical challenge.

Bone cement augmentation is a technique with broad clinical application prospects and is frequently employed in various orthopaedic procedures to enhance bone support strength [9]. In the treatment of osteoporotic intertrochanteric femoral fractures, cement-augmented PFNA has become a routine clinical option. From a biomechanical perspective, once bone cement is injected into the femur through the internal channel of the anti-rotation blade, it diffuses between the trabeculae, immediately enhancing the mechanical properties of the bone matrix during surgery. Concurrently, the cement increases the contact area between the cancellous bone and the intramedullary nail, dispersing and reducing the pressure exerted on the cancellous bone. It also functions as an ‘anchoring point’ that limits displacement of the internal fixation system [10]. This technique not only markedly enhances fracture stability and screw pullout resistance [11] but also improves the anti-rotational performance of the internal fixation system [12], thereby increasing the stability of the fixation construct and reducing the risk of reoperation [13].

Furthermore, cement augmentation enhances the failure resistance of eccentrically implanted spiral blades [14], providing a degree of tolerance for suboptimal blade positioning. Consequently, cement augmentation serves as an effective adjunct to PFNA for osteoporotic intertrochanteric fractures [15].

Current research focus has shifted from merely comparing overall implant performance toward investigating nuanced factors affecting fixation success, such as screw positioning and cement augmentation parameters, aiming to provide individualized mechanical rationale. However, clinical practice reveals considerable variability in cement distribution (femoral head vs. neck), and no systematic study has compared how these zones affect fixation stability. Therefore, this study employed finite element analysis to delineate the mechanical differences conferred by cement location (head vs. neck).

Establishment of three-dimensional geometric models of the femur and fracture models

Based on computed tomography scan data of the femur from a healthy male volunteer (age, 35 years; height, 175 cm; weight, 75 kg) with a slice thickness of 0.6 mm, a three-dimensional femoral model was reconstructed using Mimics 21.0 software. This model was subsequently surface-optimised and smoothed in Geomagic Studio 2021 before being converted into a solid model. To distinguish cortical from cancellous bone, the solid model was imported into SolidWorks 2021. The cancellous bone segment was generated by applying an inward offset of 3.64 mm [16], thereby

creating a complete femoral model incorporating both cortical and cancellous bone.

Based on the AO/OTA 31-A2.3 fracture classification, the complete femoral model was segmented in SolidWorks using sketching and division commands into three primary components: the femoral head, posterior bone fragment ('banana-shaped' fragment), and femoral shaft. The cortical and cancellous bone structures were preserved in each segment, thereby establishing an unstable intertrochanteric fracture model (Figure 1A–C).

Assembly of internal fixation and bone cement models

Based on commonly used clinical specifications, a three-dimensional model of the PFNA was constructed in SolidWorks (Figure 1D). Its parameters comprised a main nail length of 195 mm, a proximal diameter of 10 mm, a distal diameter of 30 mm, and a varus angle of 4°. The spiral blade had a diameter of 12 mm, a length of 105 mm, and a neck-shaft angle of 130°. The PFNA model was assembled with the fracture model (Figure 1E), ensuring that the spiral blade apex distance was ≤ 25 mm [17].

To investigate the effect of bone cement distribution on mechanical stability, two different cement-augmented models were created in ANSYS SpaceClaim 2023 R1. In accordance with the recommended injection volume [18], all bone cement models were assigned a volume of 5 mL and designed as spheres (approximately 10.62 mm in diameter). The bone cement was positioned either in the femoral head region (adjacent to the tip of the helical blade) or in the femoral neck region (30 mm proximal to the helical blade towards the main nail), thereby forming two experimental groups: the head-augmented group and the neck-augmented group (Figure 2B, C). These were analysed in comparison with a control group without bone cement augmentation (Figure 2A).

Finite element analysis setup

All models were imported into ANSYS Workbench 2023 R1 for static structural analysis. Material properties for each component were defined as homogeneous, isotropic, linear elastic materials, with the corresponding elastic moduli, Poisson's ratios, and densities shown in Table 1. To simulate osteoporotic conditions, the elastic modulus of cancellous bone was set at 66% of the healthy adult reference value. Contact conditions between the models were configured as follows: the friction coefficient between fracture fragments was set to 0.46, between bone and the internal fixation device to 0.3, and between internal fixation components to 0.23 [19]. A bonded connection was established between the bone cement and the spiral blade to simulate their intimate union. All models were meshed using tetrahedral elements with a global element size of 1 mm (Figure 3A). The numbers of elements and nodes for each model are detailed in Table 2. To simulate loading of the proximal femur during single-leg stance, all degrees of freedom at the distal femur were constrained (Figure 3B), and a concentrated load of 1500 N was applied perpendicular to the femoral head surface (approximately equivalent to twice body weight) (Figure 3C) [20]. The solution yielded mechanical parameters, including total displacement, von Mises stress, contact pressure, and femoral neck varus angle.

Finite element analysis

The aforementioned models were solved using ANSYS Workbench software. The evaluated parameters included the maximum total displacement of the femur and internal fixation device, equivalent (von Mises) stress, femoral neck varus angle, and the distribution and extent of contact

pressure between the femoral head cancellous bone and the spiral blade.

Results

Displacement of femur and PFNA

Figures 4 and 5. The maximum total displacement was 10.342 mm in the non-augmented group, 7.145 mm in the head-augmented group, and 7.516 mm in the neck-augmented group. Both augmented groups demonstrated substantially lower displacement than the non-augmented group, with the head-augmented group showing slightly better displacement control than the neck-augmented group.

von Mises stress distribution in femur and PFNA

Figures 6 and 7. The peak equivalent stress on the implant was consistently localised at the junction of the main nail and the helical blade across all groups. The peak values were 1296.5 MPa in the non-augmented group, 1035.3 MPa in the head-augmented group, and 640.5 MPa in the neck-augmented group. The neck-augmented group exhibited the greatest reduction in stress concentration, with the peak stress decreasing by approximately 50.6% compared with the non-augmented group and by 38.1% compared with the head-augmented group.

Femoral neck varus angulation

Figure 8. The varus angles were 4.33° in the non-augmented group, 2.62° in the head-augmented group, and 3.19° in the neck-augmented group. The head-augmented group provided the greatest resistance to varus deformation, followed by the neck-augmented group, with both groups performing markedly better than the non-augmented control.

Pressure distribution in femur and PFNA

Figure 9. The peak pressure was consistently localised at the junction of the helical blade and the main nail across all groups. The peak pressure values were 610.8 MPa in the non-augmented group, 501.13 MPa in the head-augmented group, and 222.21 MPa in the neck-augmented group, representing a 63.6% reduction in the neck-augmented group compared with the non-augmented control.

Figure 10. The peak compressive stress at the interface between the femoral head cancellous bone and the intramedullary nail was 18.383 MPa in the non-augmented group, 84.646 MPa in the head-augmented group, and 23.246 MPa in the neck-augmented group. The head-augmented group exhibited the highest interfacial stress, suggesting stronger mechanical coupling between the implant and the surrounding bone following cement augmentation in the femoral head region. Notably, the location of the maximum pressure point differed among the groups: it was situated at the upper portion of the helical blade in the non-augmented group, whereas it shifted to the lower portion in both augmented groups, potentially indicating a change in the mechanical load transmission pathway following cement augmentation.

Load-bearing area

Figure 11. To better visualise the extent of the load-bearing area, a probe function was used to identify the region, and a simplified schematic diagram was generated. Compared with the non-

augmented group, both cement-augmented groups demonstrated a notably expanded load-bearing area. In the head-augmented group, the expansion was localised at the tip of the helical blade, whereas in the neck-augmented group, it was located in the middle segment of the blade, suggesting that the location of load-bearing area enlargement corresponds directly to the cement aggregation zone. Comparisons of all biomechanical parameters among the three study groups are presented in Table 3.

Discussion

Finite element analysis is an effective simulation and modelling tool [21] that is widely used in orthopaedic research and clinical practice. This study further confirms that cement augmentation combined with PFNA is a reliable treatment option for unstable osteoporotic intertrochanteric femoral fractures (A2.3). Compared with the non-augmented group, both cement-augmented models demonstrated superior mechanical stability, with marked reductions in maximum displacement, peak stress, peak pressure, and femoral neck varus angulation.

Our results indicate that the introduction of bone cement—whose elastic modulus is substantially higher than that of cancellous bone—between the cancellous bone and the implant not only expands the load-bearing area but also alters the load distribution characteristics of the fixation construct (Figure 11). Following cement augmentation, the load-bearing area expanded in both the transverse and longitudinal directions, with a more uniform pressure distribution observed over the upper portion of the helical blade, while the pressure peak shifted from the blade tip to its lower segment. According to the lever-fulcrum-balance reconstruction theory proposed by Zhang et al. [22,23], the PFNA functions as a new lever system that replaces the original femoral lever system. A ‘leverage effect’ exists between the helical blade and the main nail, with the fulcrum located at their junction—the region of concentrated pressure. The addition of bone cement increases the load-bearing area of the helical blade, thereby helping to disperse the load and attenuate the leverage effect. Concurrently, expansion of the load-bearing area reduces the load borne by the cancellous bone per unit area, thereby minimising cancellous bone deformation and ultimately reducing femoral displacement.

Furthermore, we observed that the location of load-bearing area expansion corresponds directly to the cement distribution zone: when cement is located in the femoral head region, the expanded area is situated at the tip of the helical blade; when it is located in the femoral neck region, the expanded area is closer to the main nail, resulting in a shorter lever arm and consequently a less pronounced leverage effect. However, although cement distribution in the femoral neck more effectively reduces stress concentration on the implant, it is associated with relatively greater femoral head displacement and neck varus angulation. This may be attributed to the fact that although cement can restrict micromotion, its effect is primarily confined to the vicinity of the cement-bone interface [24]. Compared with femoral head distribution, cement located in the femoral neck places the blade tip farther from the ‘anchor point,’ leading to greater micromotion at the blade tip under loading, which ultimately results in increased displacement and varus angulation.

The novelty of this study lies in directly addressing the clinical uncertainty regarding cement aggregation zones (Figure 12) and systematically quantifying their mechanical effects. By constructing and comparing two cement distribution models (head versus neck) and analysing them under standing loads, this study provides orthopaedic surgeons with valuable biomechanical

evidence to support clinical decision-making.

This study has several limitations. First, only a single fracture model was evaluated, limiting the generalisability of the findings. Second, the femoral geometric model was simplified and smoothed and therefore could not fully reproduce the mechanical properties of actual anatomical structures. Third, the bone cement was modelled as an idealized sphere for strict variable control. It must be explicitly emphasised that, in actual intraoperative practice, cement dispersion within osteoporotic bone is highly irregular—shaped by trabecular density, injection pressure, and delivery speed—and rarely conforms to the clean, controlled geometry used here. Thus, our results primarily reflect the 'locational effect' of cement aggregation, rather than providing absolute mechanical values for a specific shape. Fourth, the analysis was confined to static standing conditions, excluding the mechanical responses associated with dynamic activities such as walking or running. Finally, the loading conditions simulated only vertical forces and did not account for the multidirectional loading encountered during daily activities.

Conclusion

This finite element study systematically compared the biomechanical effects of cement distribution in the femoral head and femoral neck on PFNA fixation for osteoporotic intertrochanteric fractures.

(1) Cement augmentation enhances fixation stability by expanding the load-bearing area between the helical blade and the cancellous bone, with the region of expansion corresponding directly to the cement aggregation site.

(2) The cement distribution zone exhibits a distinct locational effect: femoral neck distribution more effectively reduces peak implant stress and mitigates the risk of fatigue failure, whereas femoral head distribution more effectively limits femoral head displacement and minimises femoral neck varus angulation.

(3) Surgeons should weigh the trade-off between 'reducing implant loading' and 'maintaining reduction stability' according to the fracture pattern and bone quality. These findings provide biomechanical evidence for optimising surgical strategies for cement-augmented PFNA procedures.

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Table 1.

Material properties of the finite element models

Project	Cortical bone	Spongy bone	PFNA	Bone cement
Apparent density (g/cm ³)	1.8	0.2	4.43	1.18
Modulus of elasticity (MPa)	15 000	105.2	110 000	22 000
Poisson ratio	0.37	0.4	0.35	0.2

Table 2.

Numbers of elements and nodes in each finite element model

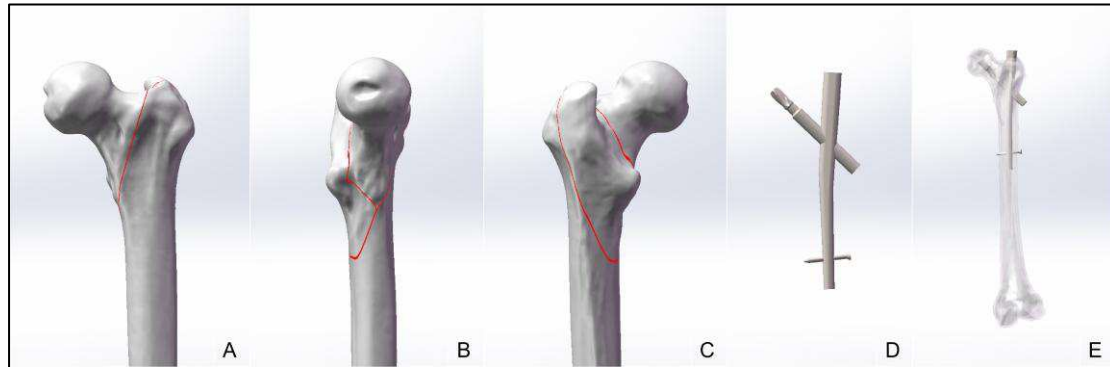
Model	Femur		PFNA		Bone cement	
	Element	Node	Element	Node	Element	Node
Non-augmented group	2 794 870	4 134 818	314 380	451 602	-	-
Head-augmented group	2 758 378	4 088 311	314 380	451 602	39 807	57 148
Neck-augmented group	2 770 038	4 102 545	314 380	451 602	28 257	42 172

Table 3.

Comparison of biomechanical parameters among the three study groups

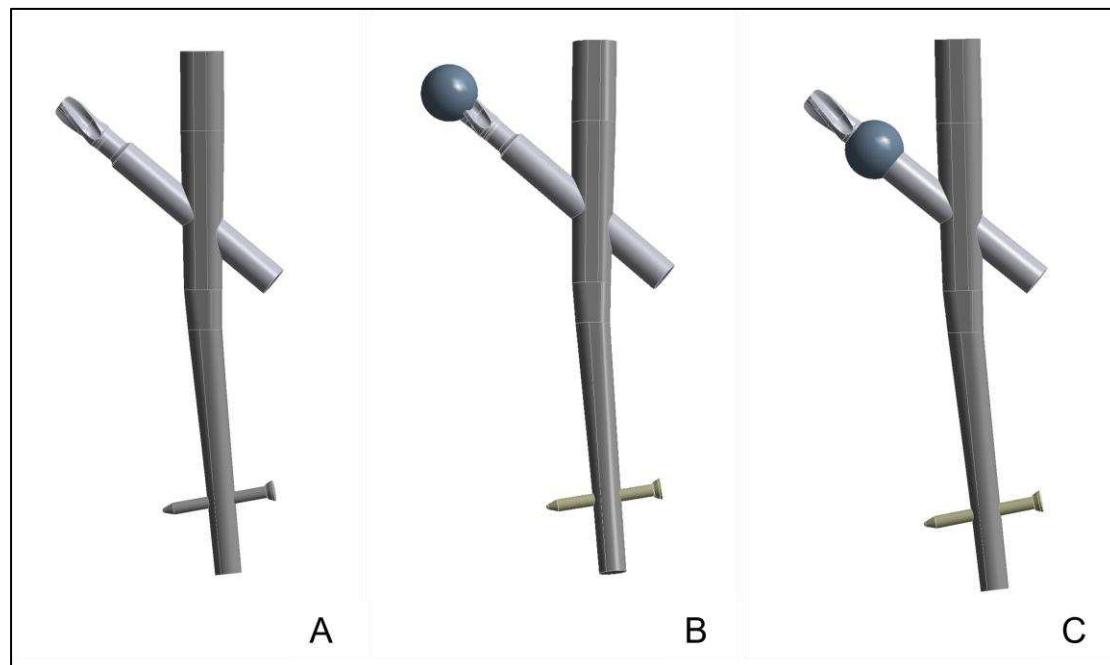
Project	Non-augmented group	Head-augmented group	Neck-augmented group
Maximum displacement (mm)	10.342	7.1451	7.5166
Maximum stress (MPa)	1296.5	1035.3	640.5
Varus Angulation (°)	4.33	2.62	3.19
Maximum pressure (MPa)	610.8	501.13	222.21
Peak Femoral Head–Blade Pressure (MPa)	18.383	84.646	23.246
Enlarged load-bearing area	-	Tip of the blade	The middle of the blade

Fig. 1



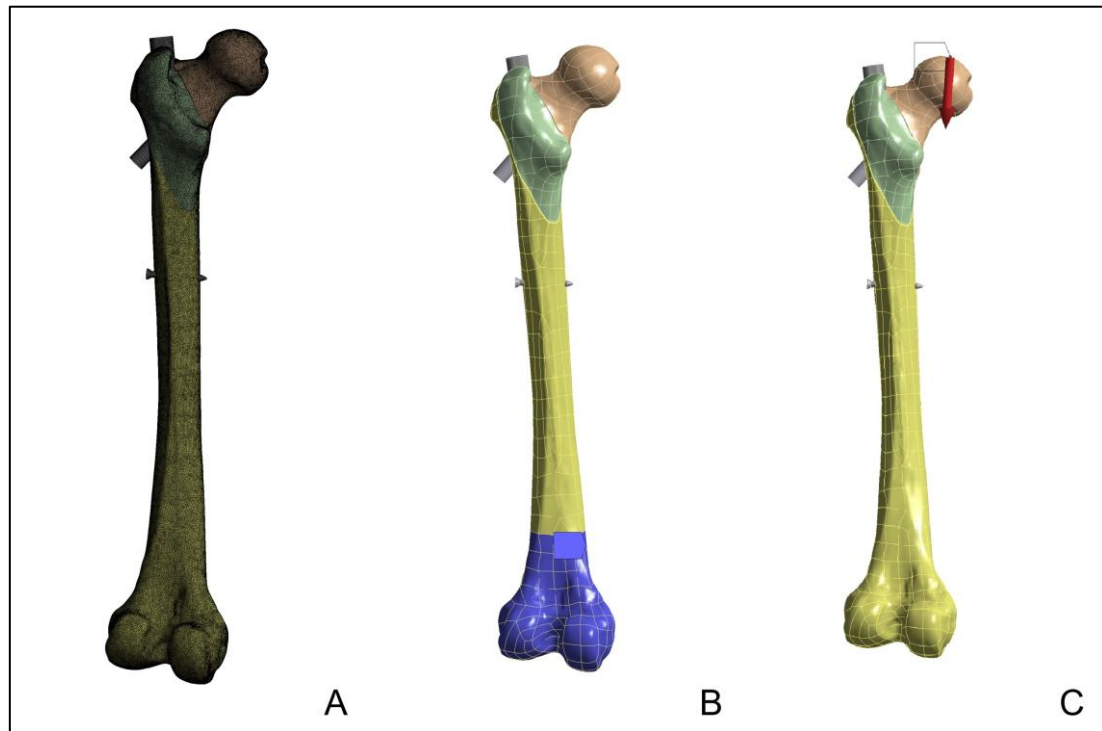
(A–C) Anterior, medial, and posterior views of the A2.3 intertrochanteric fracture model. (D) Internal fixation model. (E) Fracture model assembled with the internal fixation model.

Fig. 2.



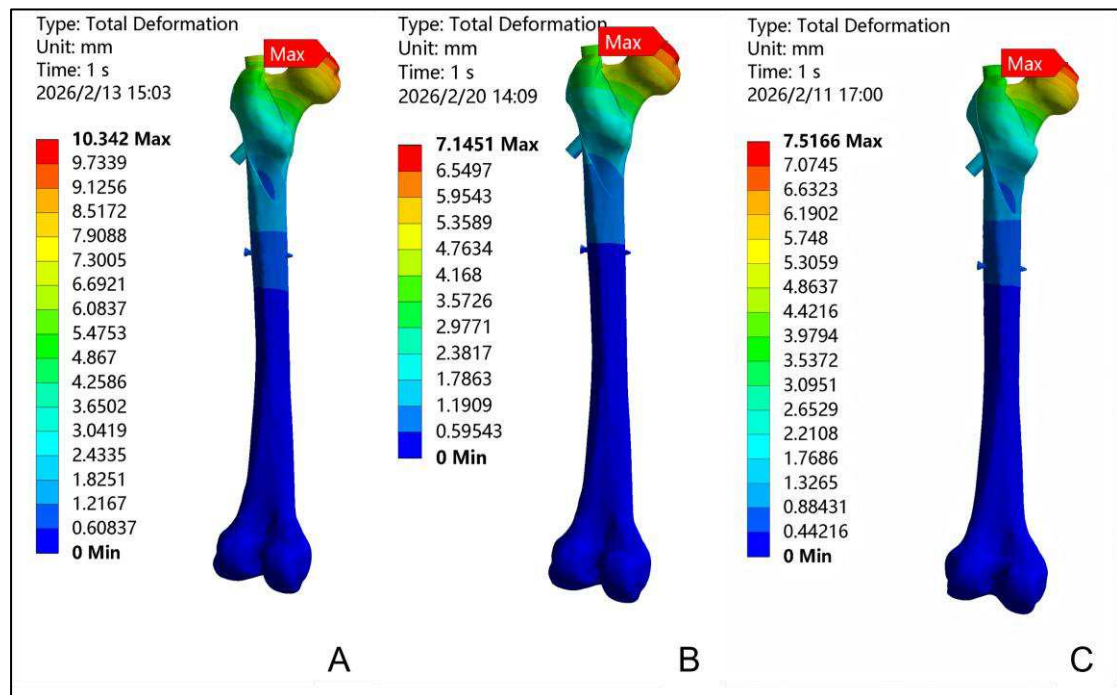
(A) The non-augmented PFNA model and the PFNA models with cement augmentation in the (B) femoral head and (C) femoral neck.

Fig. 3.



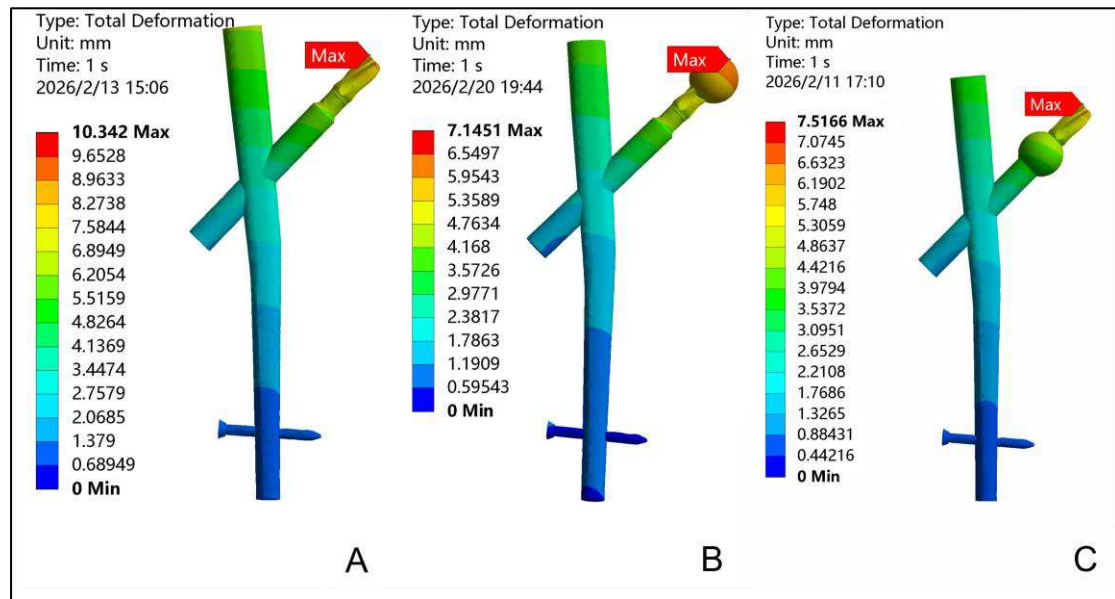
(A) Model with a 1-mm mesh. (B) Boundary constraints applied to the distal femur. (C) Application of a 1500-N load perpendicular to the femoral head surface along the Z-axis in ANSYS Workbench.

Fig. 4.



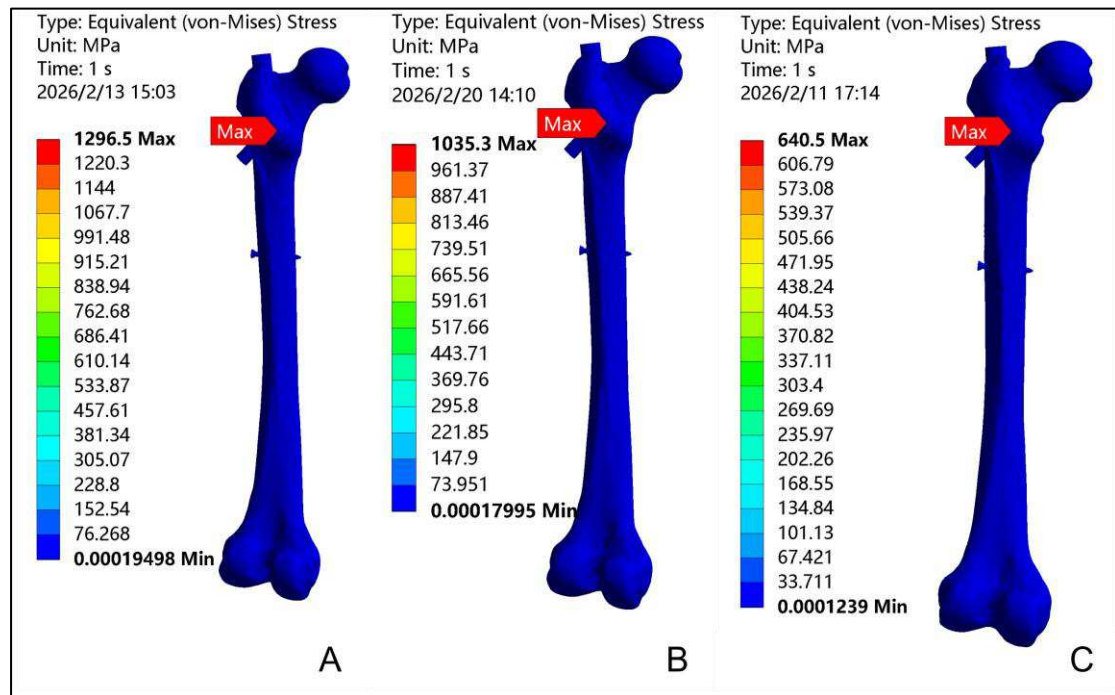
Total displacement distribution of the femur in the (A) non-augmented group, (B) head-augmented group, and (C) neck-augmented group.

Fig. 5.



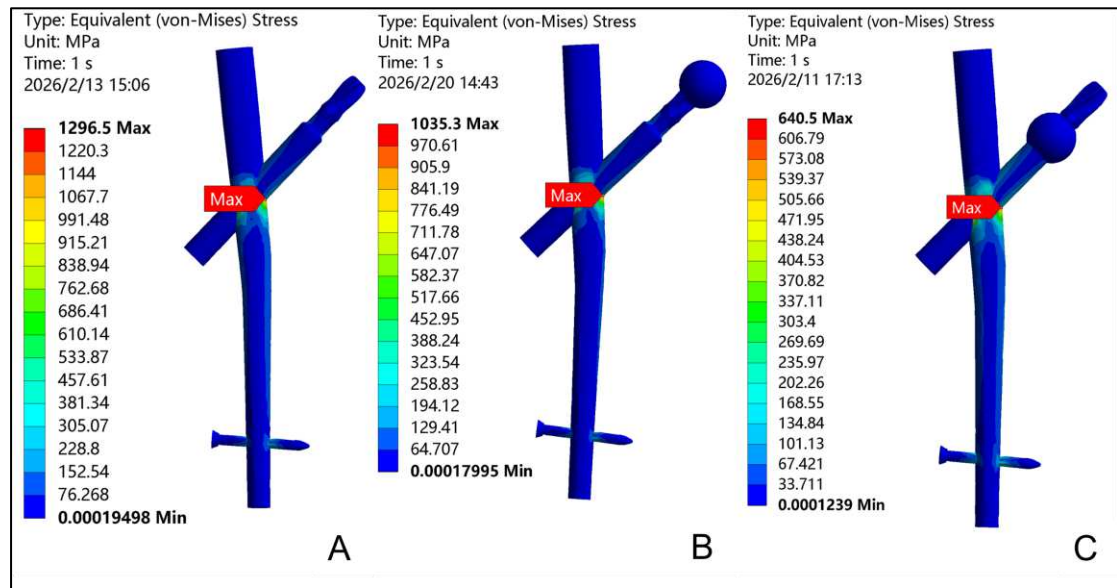
Total displacement distribution of the PFNA implant in the (A) non-augmented group, (B) head-augmented group, and (C) neck-augmented group.

Fig. 6.



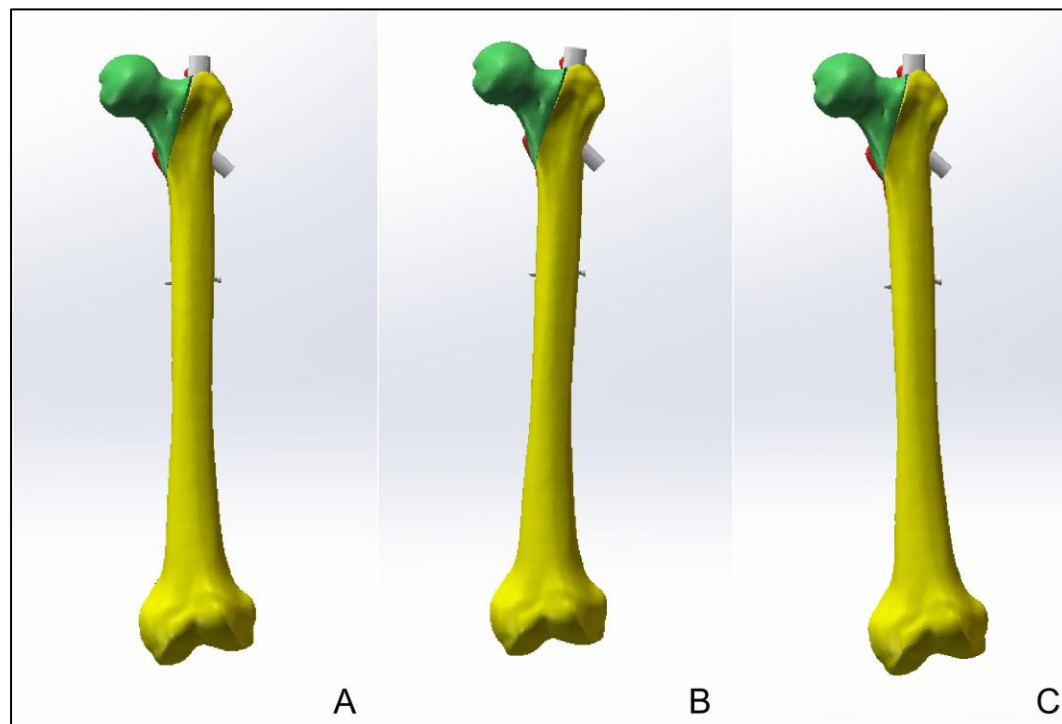
von Mises stress distribution in the femur in the (A) non-augmented group, (B) head-augmented group, and (C) neck-augmented group.

Fig. 7.



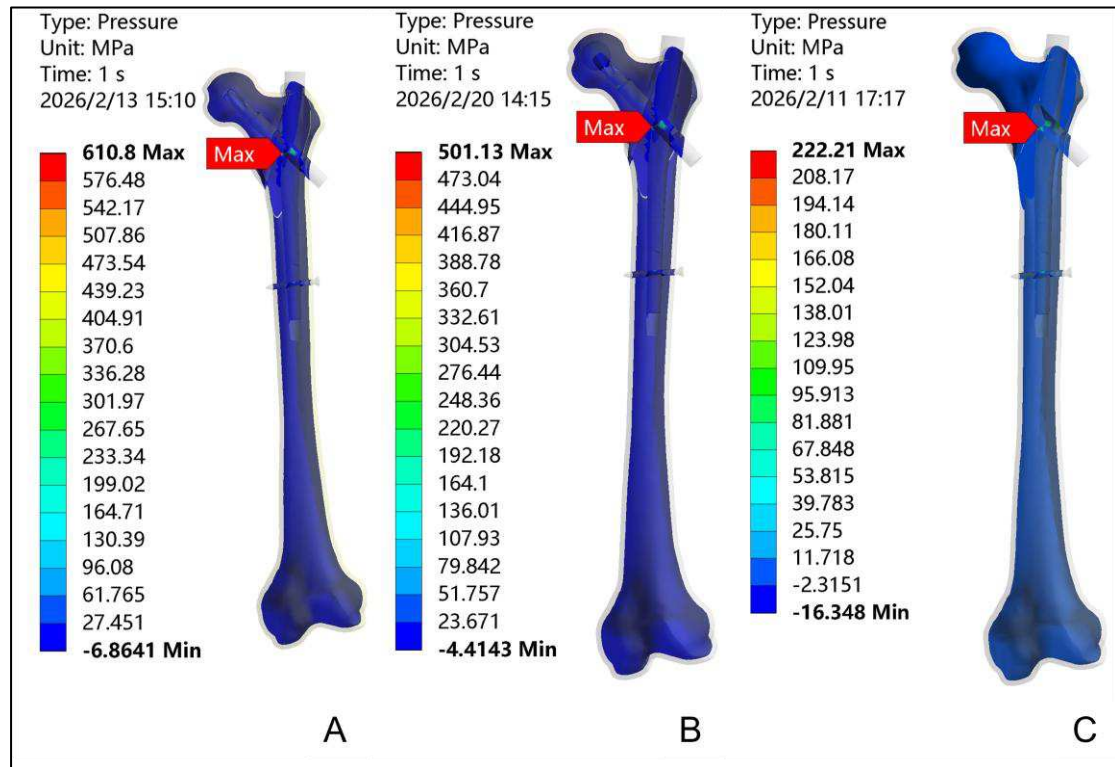
von Mises stress distribution in the PFNA implant in the (A) non-augmented group, (B) head-augmented group, and (C) neck-augmented group.

Fig. 8.



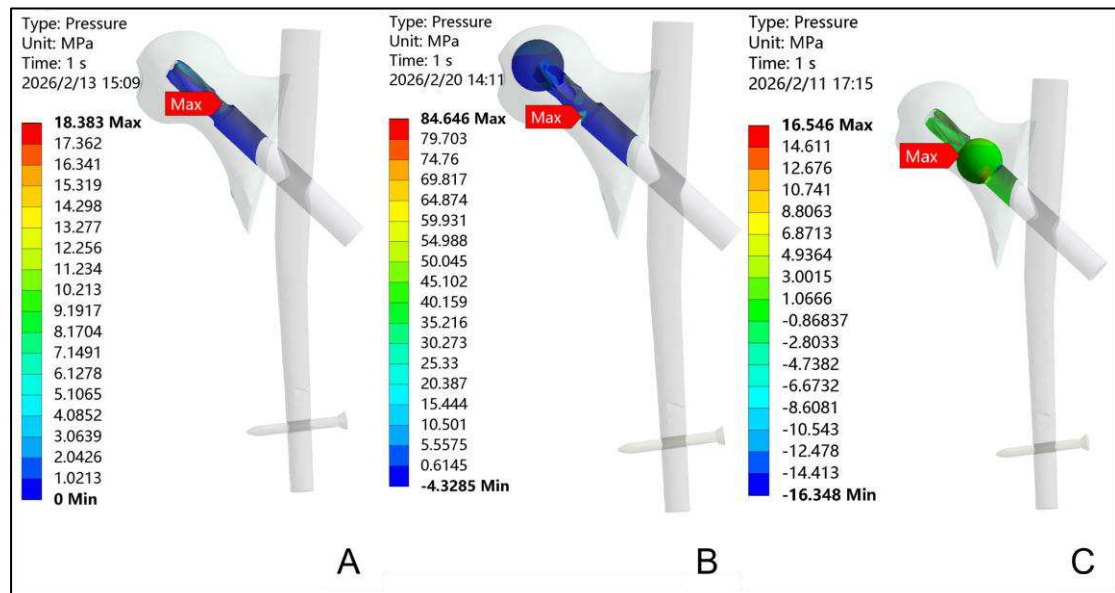
Femoral neck varus angulation in the (A) non-augmented group, (B) head-augmented group, and (C) neck-augmented group.

Fig. 9.



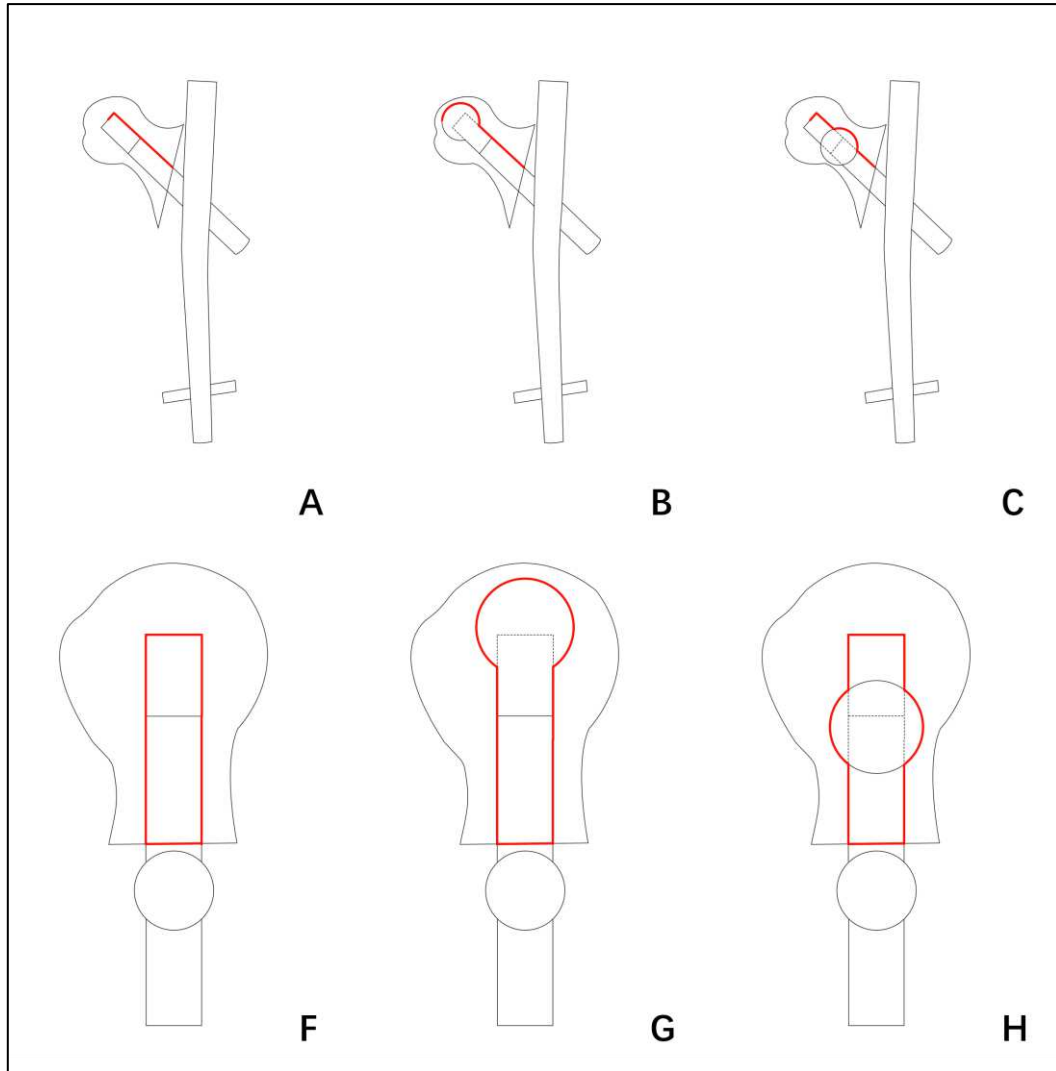
Pressure distribution in the PFNA implant in the (A) non-augmented group, (B) head-augmented group, and (C) neck-augmented group.

Fig. 10.



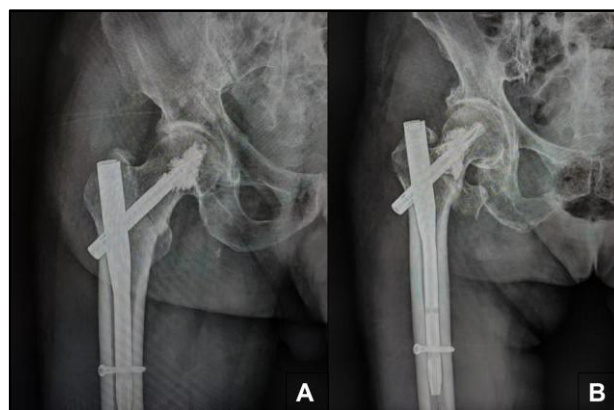
Compressive stress distribution at the interface between the femoral head cancellous bone and the intramedullary nail in the (A) non-augmented group, (B) head-augmented group, and (C) neck-augmented group.

Fig. 11.



Load-bearing area distribution. (A–C) Anterior views of the non-augmented, head-augmented, and neck-augmented groups, respectively. (D–F) Superior views of the non-augmented, head-augmented, and neck-augmented groups, respectively.

Fig. 12.



Clinical examples of cement distribution patterns. (A) Cement confined to the femoral head. (B)

Cement confined to the femoral neck.

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