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Research Article

Biomechanical Effects of Anterior Cephalomedullary Nail Entry-Point Modification in a Geriatric Bowed Femur: A Finite Element Analysis

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ABSTRACT

Objective: This study aimed to evaluate the biomechanical effects of anterior cephalomedullary nail entry-point modification, proposed to reduce distal anterior cortical contact in geriatric patients with pronounced anterolateral femoral bowing, using finite element analysis (FEA).

Methods: A three-dimensional FEA was performed using a femur model reconstructed from computed tomography data of an 80-year-old patient with pronounced anterolateral femoral bowing. A stable pertrochanteric fracture (AO/OTA 31-A1) was modeled and fixed with a proximal femoral nail antirotation (PFN-A) using three entry-point configurations: standard central entry (Model A), 5-mm anterior shift (Model B), and 10-mm anterior shift (Model C). Blade position within the femoral head and distal locking screw alignment were kept constant across the models. Nonlinear static analyses were performed under an axial load of 1400 N simulating single-leg stance. Displacement and von Mises stress distributions were evaluated for both the implant and femur.

Results: Femoral head–neck displacement was −3.19 mm in Model A, −3.23 mm in Model B, and −3.25 mm in Model C. Implant displacement was 20.20, 20.25, and 20.42 mm, respectively. Maximum implant stress, concentrated at the nail–blade junction, increased from 295.17 MPa in Model A to 333.10 MPa in Model B and 389.63 MPa in Model C. Maximum femoral stress at the bone–blade interface increased from 101.25 MPa to 138.66 MPa and 176.23 MPa, respectively. Maximum stress along the fracture line was concentrated medially and measured 68.70, 72.64, and 74.69 MPa in Models A, B, and C, respectively.

Conclusion: Anterior shifting of the cephalomedullary nail entry point had minimal effect on displacement but was associated with progressively increased stress in both the implant and femur. These findings suggest a potential biomechanical trade-off when anterior entry-point modification is used to avoid distal anterior cortical contact in patients with pronounced femoral bowing.

Level of Evidence: Level V, Therapeutic study.

Introduction

Trochanteric femoral fractures represent one of the most prevalent fracture types in the geriatric population, typically arising on a background of osteoporosis.[1] The primary objective of treatment is to enable safe and rapid functional mobilization by effectively transferring load to the affected extremity. Currently, intramedullary nails are widely regarded as the gold standard for managing geriatric trochanteric femoral fractures, owing to their advantages in permitting early weight-bearing, superior biomechanical stability, and minimally invasive surgical technique.[2]

In geriatric patients, age-related morphological changes in the femur can technically complicate the application of intramedullary nails. In particular, the increased anterior bowing of the femur may cause standard straight nails to advance incompatibly within the femoral canal when conventional entry points are used.[3] This mismatch can lead to complications such as penetration of the distal nail tip through the anterior cortex, restricted distal advancement, eccentric placement of proximally positioned screws, and increased implant stresses.[4] These issues contribute to intraoperative technical difficulties and complications, as well as postoperative thigh pain, implant failure, cut-out, and elevated risk of reoperation.[5]

To mitigate these complications, various nail designs, alternative reduction maneuvers, and entry point modifications have been proposed in the literature.[6] In particular, shifting the entry point more anteriorly has emerged as a promising strategy, as it may enable more centralized nail advancement along the femoral canal, thereby potentially reducing cortical contact and stress concentration.[7] However, the biomechanical effects of this entry point modification on the femur–implant complex remain insufficiently investigated in the literature.[7]

In this study, finite element analysis was employed to evaluate the effects of shifting the intramedullary nail entry point more anteriorly (relative to the standard entry point) on stress distribution, mechanical behavior, and stability within the femur–implant complex. Specifically, the analysis focused on the biomechanical effects of the progressively eccentric positioning of the blade resulting from anterior modification of the nail entry point.

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Material and methods

The study protocol was approved by the Human Research Ethics Committee Ankara University Faculty of Medicine (Decision No: I:01-59-25) and was performed in accordance with the principles of the Declaration of Helsinki.

All 3-dimensional finite element modeling, mesh generation, and stress analyses were performed on a workstation equipped with an 11th-generation Intel® Core i9-11900 processor (Intel Corporation, Santa Clara, CA, USA) operating at 2.50 GHz and 64 GB of ECC memory. The analysis workflow consisted of geometric modeling, mesh optimization, and solution phases.

Femoral model generation

The femur model used in this study was generated from computed tomography data of an 80-year-old patient exhibiting pronounced anterolateral bowing. Computed tomography images were acquired using a Toshiba Aquilion Prime 128-slice spiral CT scanner (Otawara, Tochigi, Japan) with a slice thickness of 0.5 mm. Following image reconstruction, the DICOM (.dcm) data were imported into 3D Slicer software, and segmentation was performed using appropriate Hounsfield unit thresholds. Artifacts and undesired regions were removed using the *Erase* and *Scissors* tools, and the segmented 3-dimensional femur model was subsequently exported in stereolithography (STL) format.

The femur model was then imported into Rhinoceros 3D software (Robert McNeel & Associates, Seattle, WA, USA), where geometric inconsistencies were corrected, and the cortical and cancellous bone layers were separated to prepare the model for implant planning.

Implant modeling and placement

The proximal femoral nail antirotation (PFN-A; DePuy Synthes, Warsaw, IN, USA) was modeled in Rhinoceros 3D (Seattle, WA, USA) software based on parametric implant dimensions. The implant consisted of 3 main components: the nail, blade, and distal locking screw. All components were defined as being composed of biocompatible, high-strength Ti-6Al-4V alloy.

An anatomically representative fracture line consistent with a stable pertrochanteric fracture (AO/OTA 31-A1) was created on the 3-dimensional femur model (Figure 1). The PFN-A was positioned in a centrally referenced alignment within the femur exhibiting anterolateral bowing, and this configuration was designated as the baseline model. A total of 3 models were generated in this study (Figures 2 and 3).

1. The model with the PFN-A positioned in the central alignment (Model A),
2. The model in which the proximal end of the nail component was shifted 5 mm anteriorly (Model B),

HIGHLIGHTS

- Anterior entry point modification may warrant consideration in geriatric patients with pronounced anterolateral femoral bowing, as a potential alternative approach.
- Notable differences in stress values were observed across models, and these results should be interpreted cautiously.
- Under the specific loading conditions of this study, variations in entry point position did not have a significant effect on displacement.

Figure 1. Three-dimensional femur model with an anatomically representative stable pertrochanteric fracture configuration (AO/OTA 31-A1).

3. The model in which the proximal end of the nail component was shifted 10 mm anteriorly (Model C).

In all 3 models (Figure 4), the blade tip was centered within the femoral head, and the centers of the distal locking screws were aligned to isolate only the differences in the nail entry point.

Mesh generation and analysis

After the geometric models were prepared in the Rhinoceros 3D environment, they were imported into ALTAIR HyperMesh (ALTAIR, Troy, MI, USA) software. During mesh generation, triangular (tria) surface elements with a size range of 0.5-1 mm were used, followed by the creation of solid mesh structures using regular tetrahedral elements. The mesh density was optimized to be consistent with previously published biomechanical studies in the literature.[8] The ALTAIR OptiStruct (ALTAIR, Troy, MI, USA) solver was used to compute the solutions of the generated mathematical models.

Loading scenarios and boundary conditions

An axial load of 1400 N was applied to the proximal spherical surface of the femoral head (Figure 5). A 15° angle between the femoral shaft and the vertical axis was defined in the coronal plane, and the direction of the applied force was determined according to this angle.[8-11] This loading scenario was used to simulate the physiological loads acting on the proximal femur of a 70-kg individual during the single-support phase of the gait cycle.[9]

The nodal points at the distal end of the femur were fully constrained in all degrees of freedom along the 3 axes. Under the defined loading

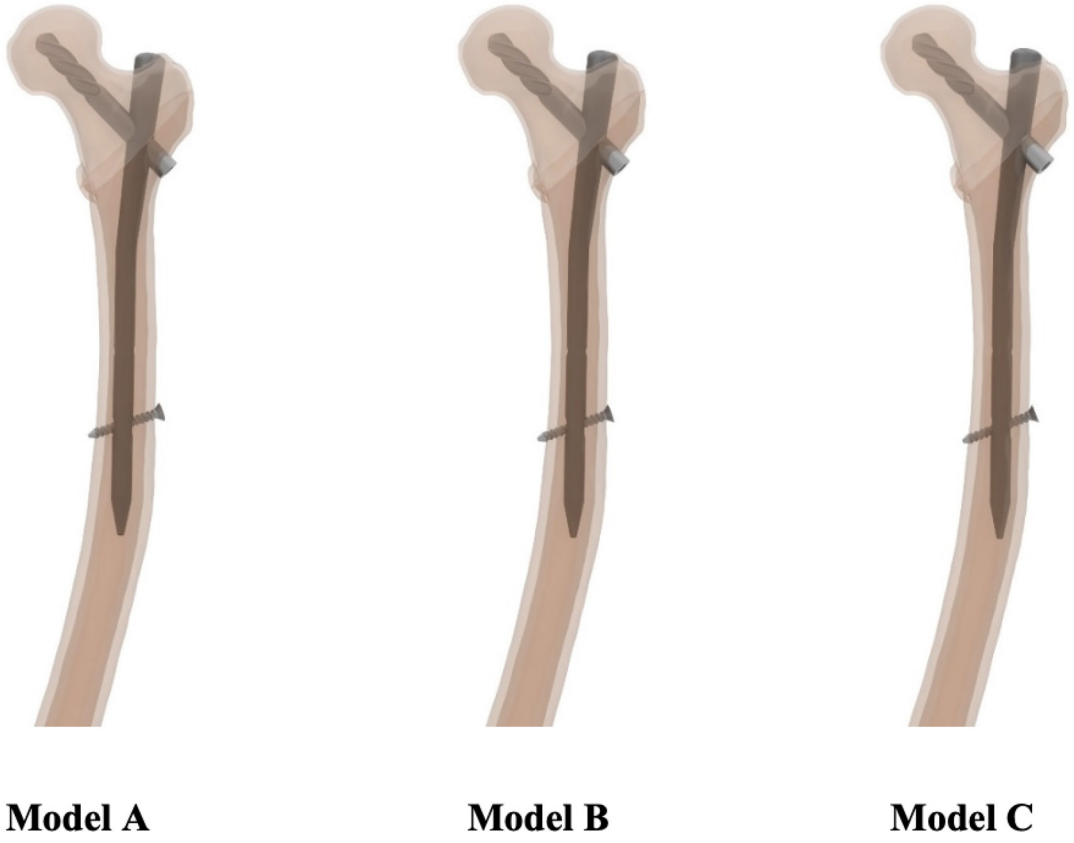

Figure 2. Anteroposterior (AP) view of all models.

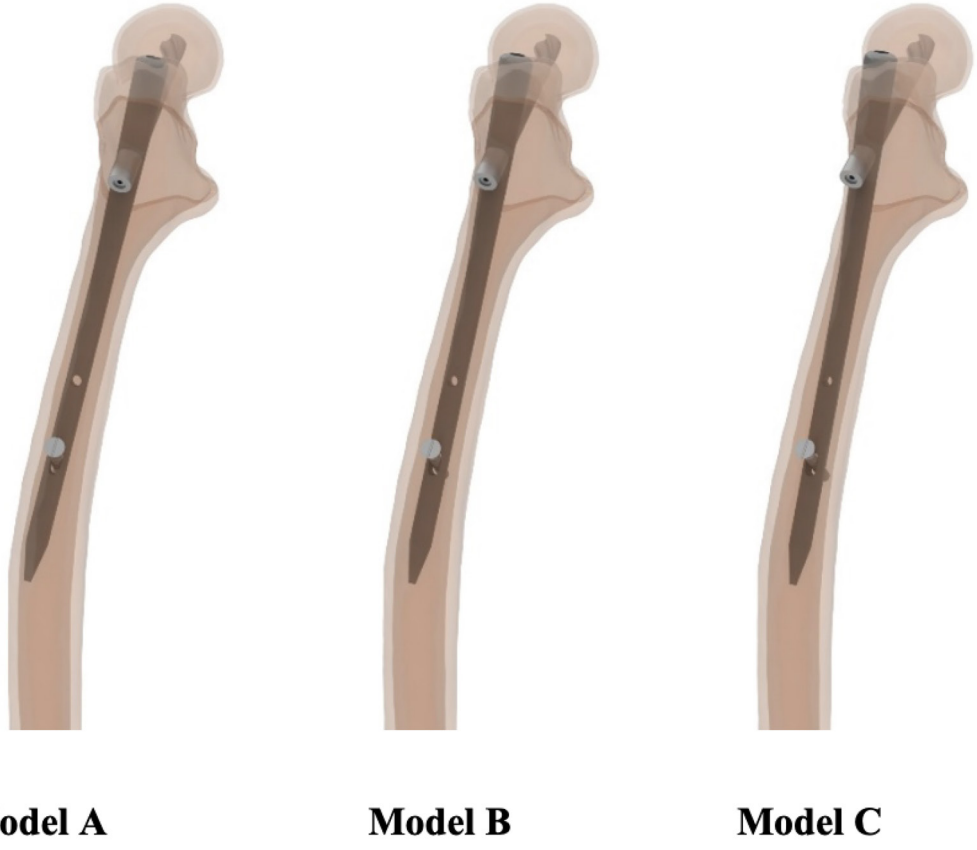

Figure 3. Lateral view of all models.

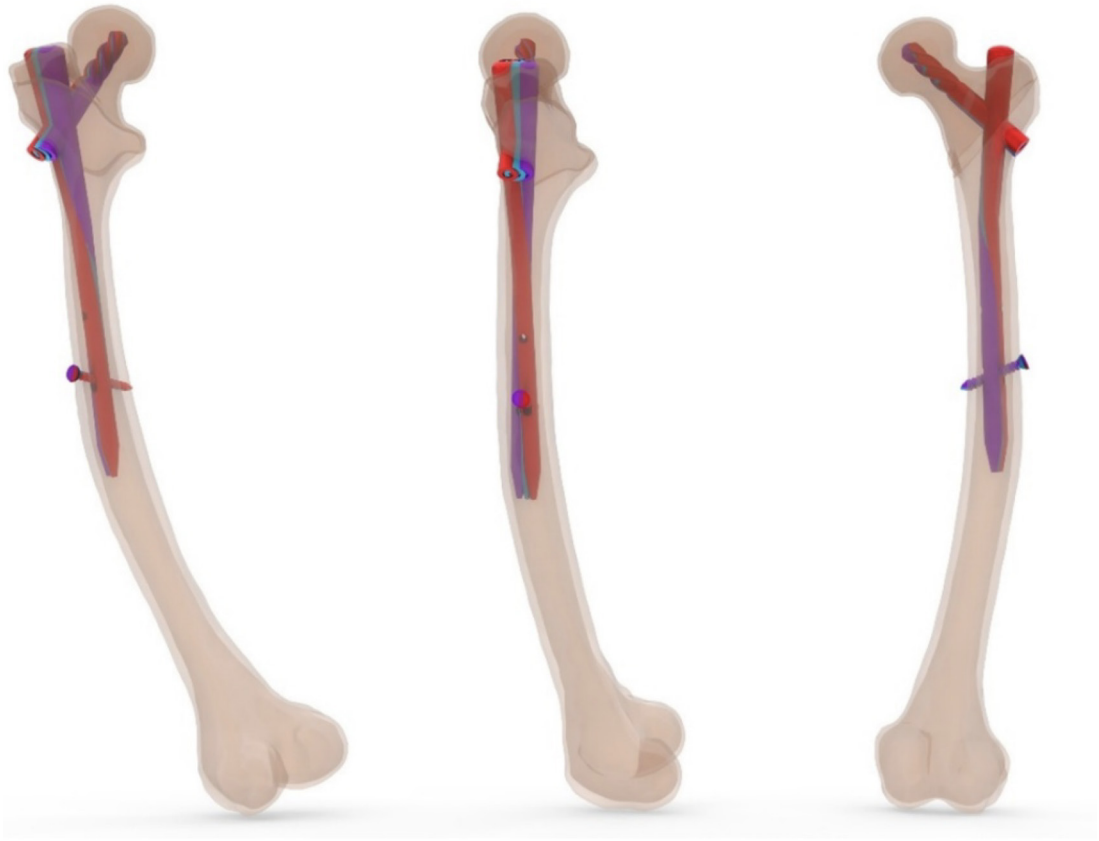

Figure 4. All models shown together.

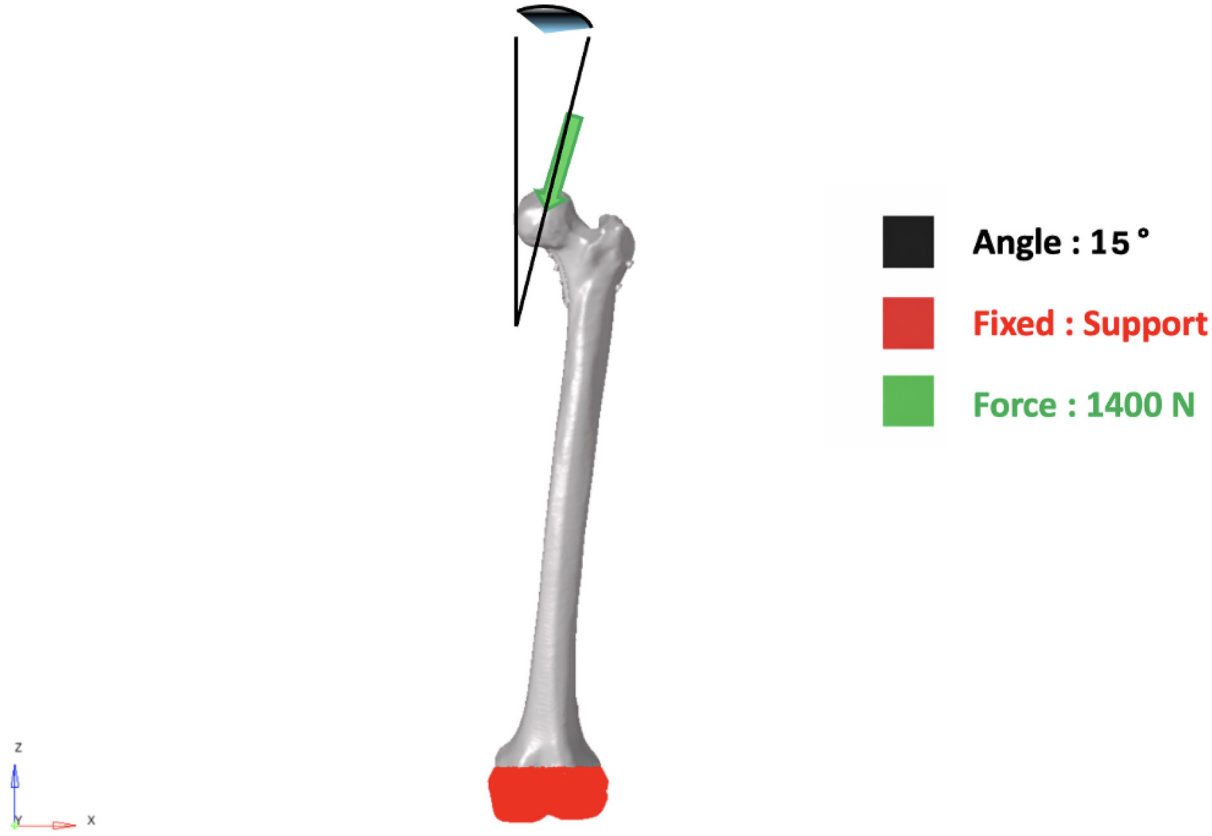

Figure 5. Loading scenarios applied in the finite element analysis.

and boundary conditions, nonlinear static analyses were performed for each model, and the following parameters were evaluated as follows:

1. Axial displacement occurring in the femoral head–neck region,
2. Resultant displacement of the PFN-A,
3. von Mises stress values in the PFN-A,
4. von Mises stress values in the trochanteric fracture region and femoral diaphysis, and
5. von Mises stress values in the femoral head–neck and medial regions.

Results

Axial displacement occurring in the femoral head–neck region.

In all models, displacement of the femoral head occurred in the inferomedial direction. The magnitude of displacement was −3.19 mm in Model A, −3.23 mm in Model B, and −3.25 mm in Model C (Figure 6). The negative sign indicates that the direction of the applied force was downward. The difference in displacement among the models was approximately 1%.

Resultant displacement of the PFN-A.

In all models, the maximum displacement occurred at the blade tip. The displacement values were 20.20 mm in Model A, 20.25 mm in Model B, and 20.42 mm in Model C (Figure 7). The difference in displacement among the models was less than 1%.

von Mises stress values in the PFN-A.

In all models, the highest stress on the PFN-A was observed at the nail–blade junction. The maximum von Mises stress values were 295.17 MPa in Model A, 333.10 MPa in Model B, and 389.63 MPa in Model C (Figure 8). The stress difference among the models ranged between approximately 10% and 15%. Given that the yield strength of Ti-6Al-4V alloy is 830 MPa, the stress values observed in all 3 models remained below the yield strength of the material.[12]

von Mises stress distribution in the femur.

In all models, the maximum von Mises stress in the femur was observed at the bone–blade interface. The stress values at this region were 101.25 MPa in Model A, 138.66 MPa in Model B, and 176.23 MPa in Model C (Figure 9). High stress concentrations were also noted at the bone–locking screw interface. When the overall stress distribution in the femur was evaluated, stresses were predominantly concentrated in the medial and lateral regions.

von Mises stress distribution in the femoral head–neck and medial regions.

No meaningful difference was observed among Models A, B, and C. In all models, the highest stress along the fracture line was concentrated in the medial region. The maximum stress values in this region were 68.70 MPa in Model A, 72.64 MPa in Model B, and 74.69 MPa in Model C (Figure 10). The stress variation along the fracture line among the models ranged between approximately 2% and 5%.

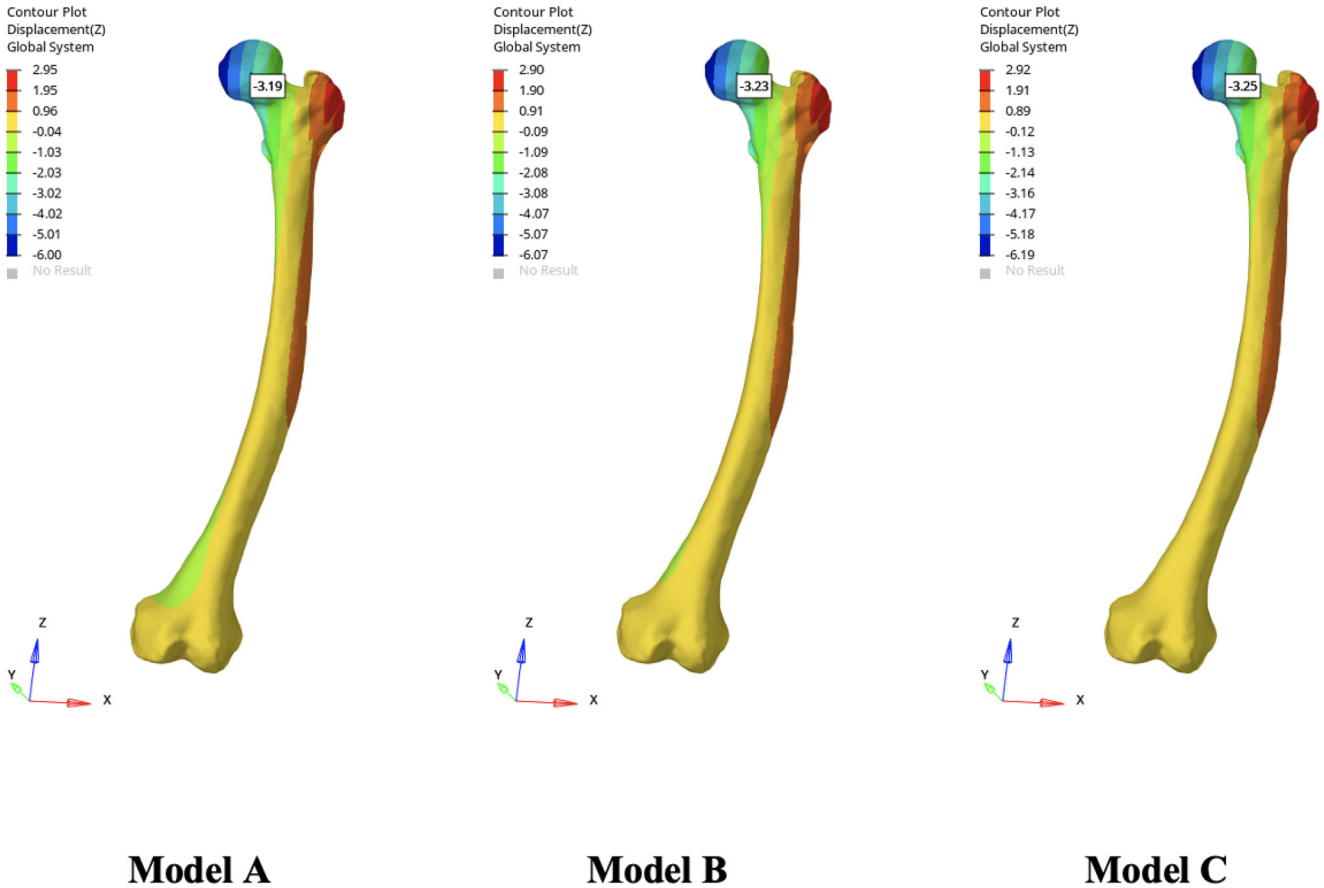

Figure 6. Axial displacement occurring in the femoral head–neck region.

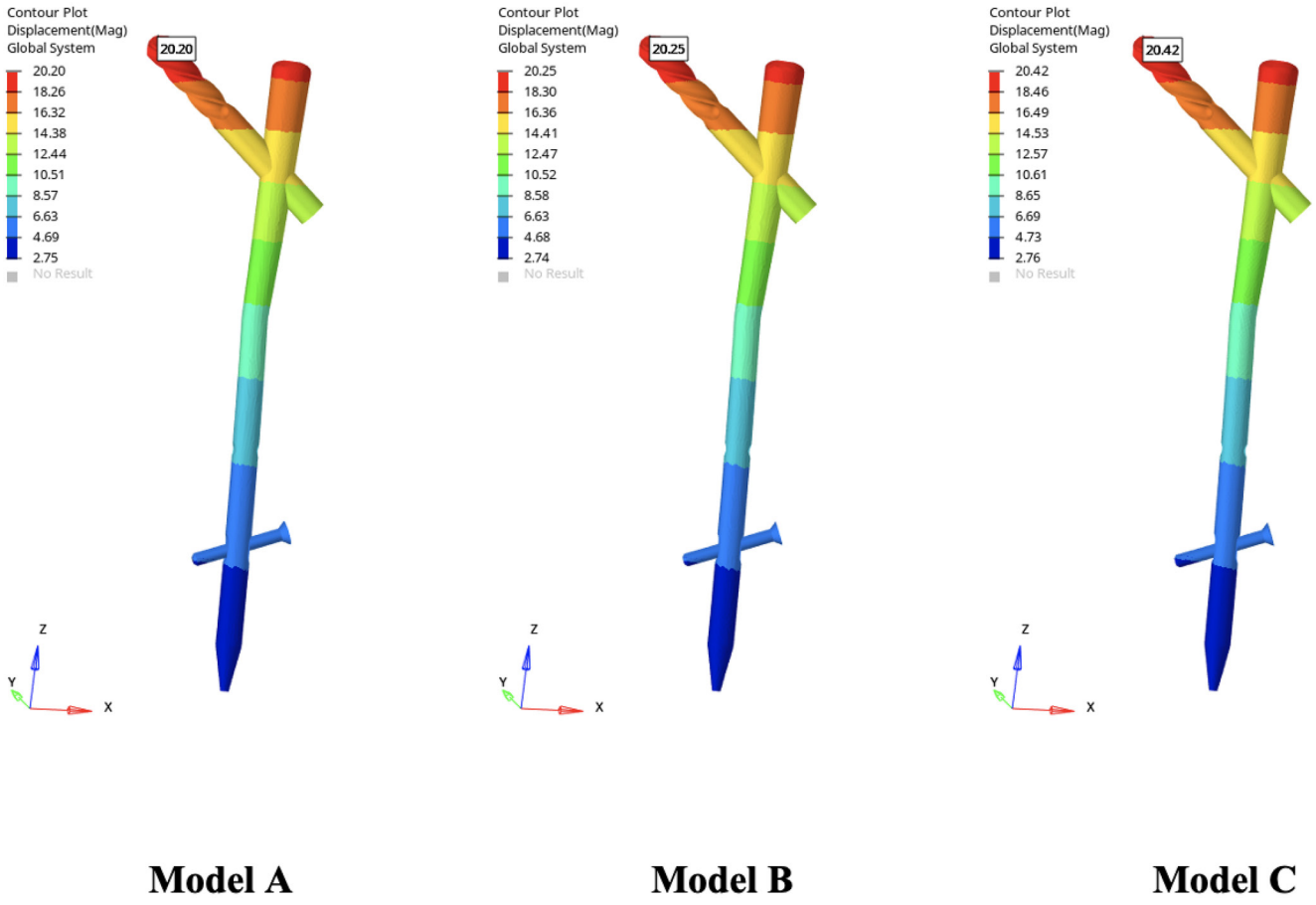

Figure 7. Resultant displacement of the PFN-A. PFN-A, proximal femoral nail antirotation.

Discussion

Intramedullary nailing is widely preferred in the surgical treatment of intertrochanteric femoral fractures in geriatric patients. However, age-related increases in anterolateral femoral bowing may lead to implant–bone mismatch, technical difficulties during implantation, and associated intraoperative and postoperative complications. Therefore, alternative entry point approaches have gained increasing importance in recent years, particularly in patients with pronounced femoral bowing. In the present study, the mechanical outcomes of different entry point configurations were evaluated under a specific loading scenario.

Several anatomical and radiological studies have demonstrated that the anterolateral bowing of the femur is more pronounced in Asian populations compared with Western populations. This anatomical difference may compromise the conformity between standard long intramedullary nails and the femoral canal, potentially leading to mechanical issues such as distal anterior cortical contact, an increased risk of cortical perforation, and localized stress concentrations on the implant.[5,13-16] Therefore, particularly in East Asian countries, the use of short intramedullary nails that better conform to femoral canal geometry and reduce the risk of anterior cortical contact has been reported to be preferred.[5] However, short intramedullary nails may lead to stress concentration over a shorter segment and reduced rotational stability due to the limited length of distal fixation.[17]

In the analyzed models, anterior modification of the intramedullary nail entry point from the central position was found to impair implant–femur conformity, leading to increased bending and shear moments. This effect was reflected by increased stress concentrations on the implant, particularly around the nail–blade junction. From a mechanical perspective, these findings may be explained by the additional moments generated when the nail trajectory becomes less compatible with the natural structural curvature of the femur following anterior entry point modification. Previous finite element studies have reported similar biomechanical alterations associated with non-central nail positioning and emphasized the mechanical challenges created by femoral bowing.[8,11,18-20] Nevertheless, under the loading conditions applied in the present study, the yield limits of the implant were not exceeded.[21] However, it should not be overlooked that these limits may be exceeded under more demanding or alternative loading scenarios.

Von Mises stress accounts for the 3-dimensional state of stress; therefore, stress concentrations at the nail–blade junction may be relevant to the risk of mechanical failure.[9,18] Studies conducted by Aminian et al[22] have demonstrated that stress concentrations occurring in such regions may adversely affect mechanical performance. Therefore, the biomechanical effects of anterior entry-point modification on the nail–blade junction should be carefully considered during surgical application. In the present study, the maximum von Mises stress was concentrated at the nail–blade junction. This stress concentration may be related to alterations in the nail trajectory resulting from anterior entry-point modification. In addition, maintaining the intended blade position within the femoral head despite the altered nail trajectory required a progressively more eccentric blade orientation

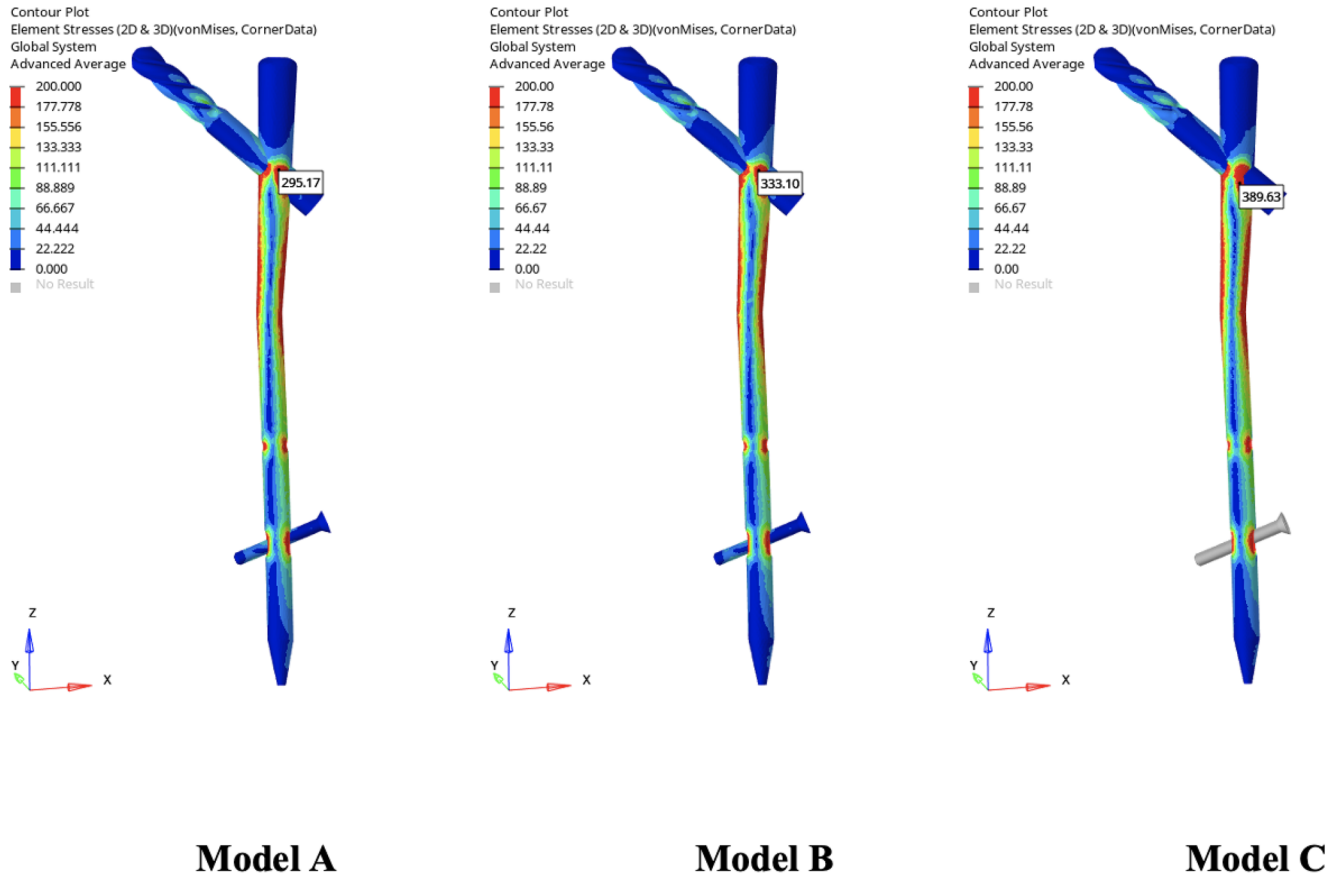

Figure 8. von Mises stress values in the PFN-A. PFN-A, proximal femoral nail antirotation.

relative to the nail, which may have further contributed to stress accumulation at the nail–blade junction. As this junction represents a critical transition point for load transfer, variations in implant alignment may influence the local mechanical stress distribution.

Osteoporotic bone is characterized by a more porous trabecular structure and reduced cortical thickness, which compromises its mechanical properties and decreases resistance to loading by rigid osteosynthesis implants.[23] Consequently, complications such as implant loosening, cut-out, and peri-implant fractures are more frequently observed in the treatment of osteoporotic fractures.[24] In addition, the reduced holding capacity of osteoporotic bone for implants is associated with an increased risk of fixation failure in both the short and long term.[24] Studies by Ito et al[25] have also demonstrated that high stress concentrations at the bone–implant interface may lead to implant loosening. Especially in osteoporotic patients, the reduced mechanical strength of bone tissue may increase the risk of complications.[26] In this study, analyses performed on the bone tissue demonstrated that anterior shifting of the entry point tended to increase von Mises stress concentrations, particularly around the anterior cortex and the blade–bone interface. Although the observed values were not directly associated with a clear mechanical failure, the reduced mechanical strength and implant holding capacity of osteoporotic bone may contribute to higher stress values and stress-related complications under more demanding or alternative loading scenarios. Therefore, these stress elevations should be interpreted with caution.

The natural load transfer mechanisms of the femur occur through the medial and lateral columns, and it has been reported in the literature that stress concentrations in these regions may influence the overall mechanical behavior of the fixation.[27] In this study, anteriorization of the nail entry point was associated with higher stress values in the medial and lateral regions of the femur compared with the standard entry point. Similarly, an increasing trend in stress values was observed in the anterior portion of the fracture line with anterior placement.

Studies by Asnis et al[28] have demonstrated that, as in other proximal femoral fractures, accurate determination of the entry point improves operative efficiency and reduces the risk of complications during the surgical procedure. Accordingly, meticulous identification of the entry point during preoperative planning and intraoperative guidance is of paramount importance. Undesired or incorrectly positioned entry points, as in all surgical procedures, may lead to intraoperative complications and subsequently necessitate implant repositioning.[29] In this study, anterior shifting of the implant entry point from the central position was associated with increased loading at the femoral head–neck junction. However, more comprehensive studies are needed to better clarify the potential implications of this increase. This strategy may facilitate implantation by mitigating challenges associated with femoral bowing and reducing time lost in overcoming distal anterior cortical contact and the risk of iatrogenic fracture, thereby contributing to a shorter operative duration.

This study has several important limitations that should be clearly acknowledged. First, all analyses were performed using a single patient-specific femur model, which inherently limits the generalizability of the findings. Since variations in bone quality, anatomical

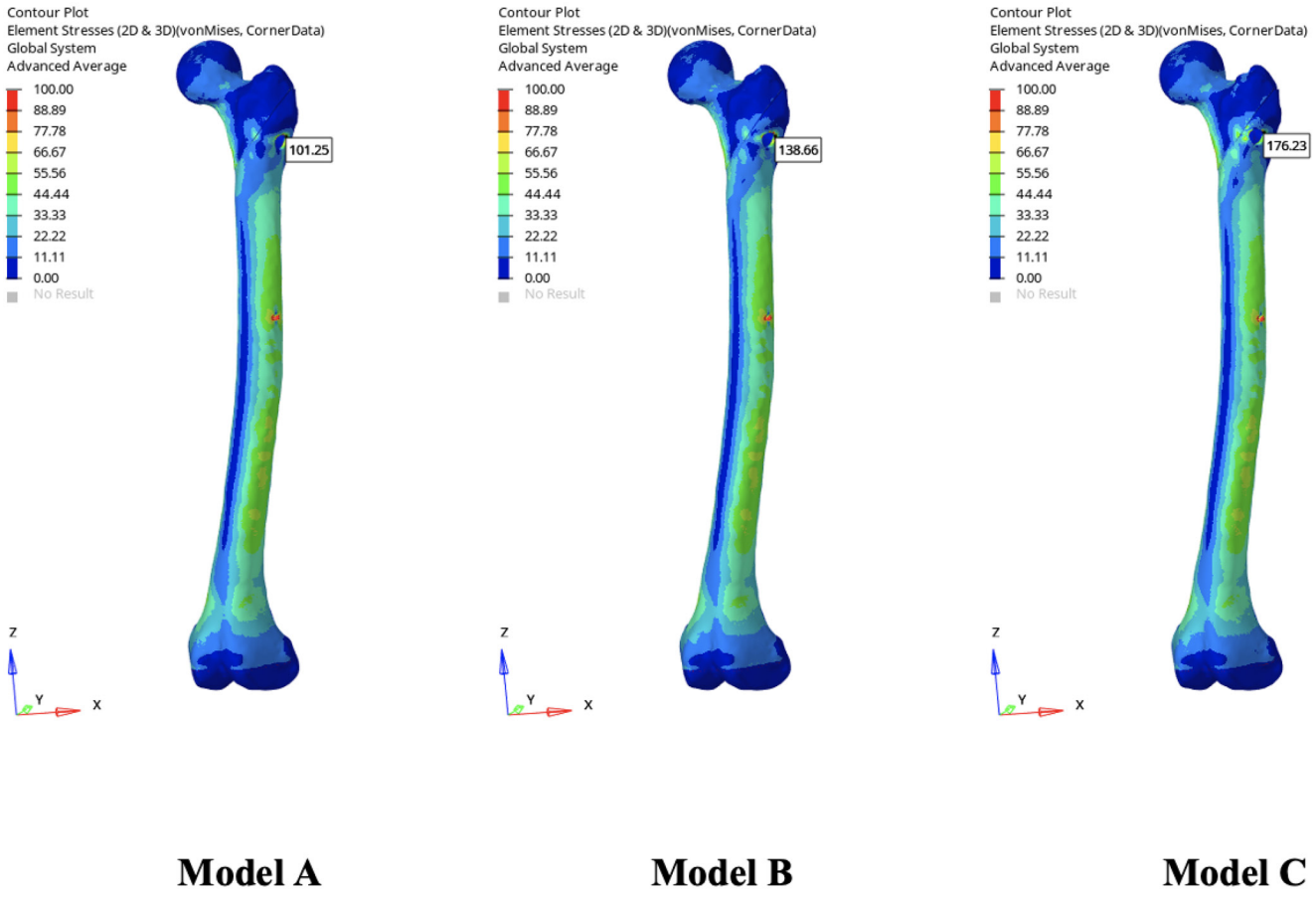

Figure 9. von Mises stress distribution in the femur.

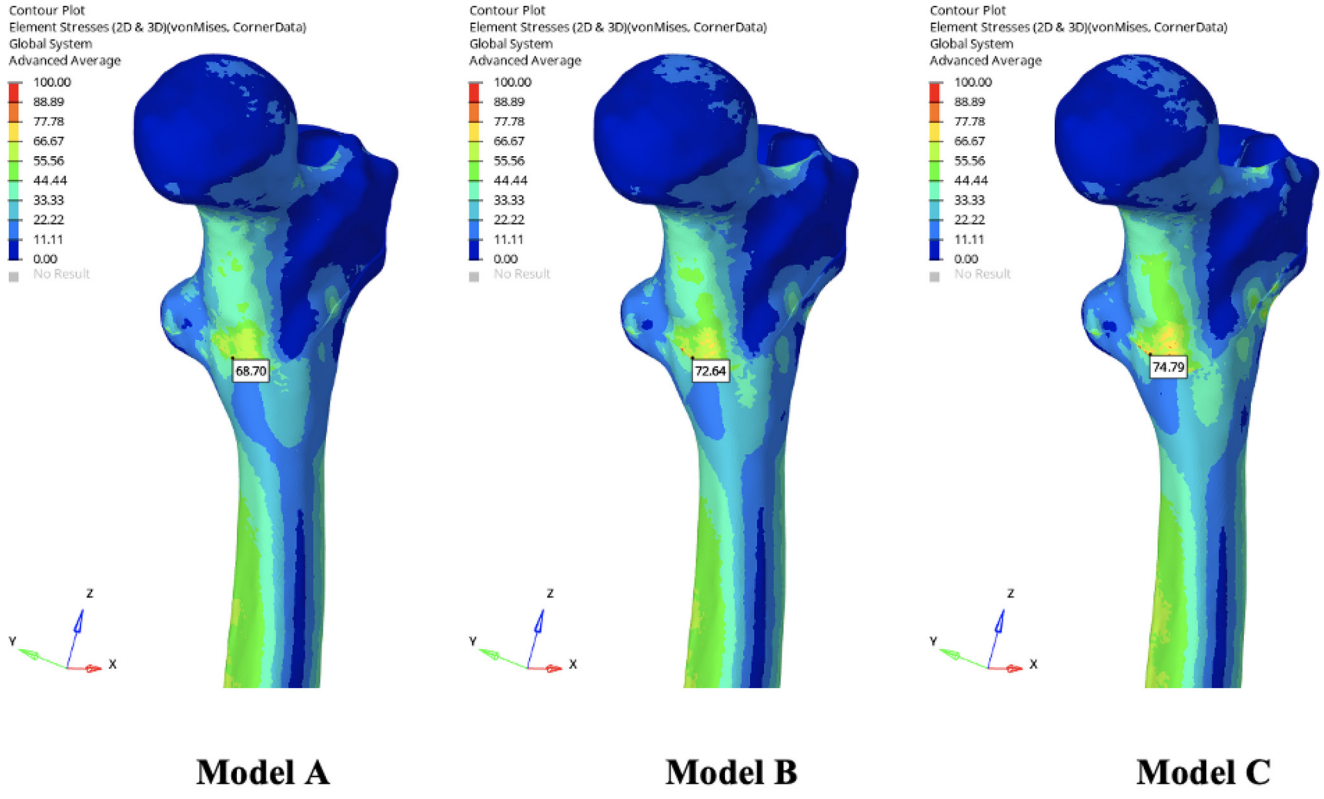

Figure 10. von Mises stress distribution in the femoral head–neck and medial regions.

morphology, and the degree of femoral bowing may substantially influence biomechanical behavior, the present results should be interpreted as model-specific rather than universally applicable. Second, the finite element analyses were performed under a static axial load of 1400 N only. Physiological loading conditions such as cyclic loading, torsional forces, muscle forces, and soft tissue effects were not incorporated into the model. Finally, bone and implant materials were modeled assuming isotropic, homogeneous, and linear elastic properties, which may not fully reflect the true mechanical behavior of biological tissues. Future studies incorporating multiple femoral models, experimental validation, and more physiological loading scenarios may help to further clarify the biomechanical effects observed in the present study.

In conclusion, anterior entry-point modification, proposed to reduce distal anterior cortical contact in patients with pronounced anterolateral femoral bowing, was associated with increased stress in both the implant and femur despite minimal changes in displacement. These biomechanical consequences suggest that this modification should be used cautiously when considered to avoid distal anterior cortical contact. However, the present findings are based on biomechanical analyses conducted under simplified and limited modeling conditions and should not be directly generalized to clinical outcomes. Therefore, the clinical effectiveness and reliability of the anterior entry point should be further validated through experimental studies and prospective clinical investigations.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Artificial Intelligence Usage Statement: During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to improve English language clarity, grammar, and readability. The authors reviewed and edited the suggested revisions and take full responsibility for the final content of the manuscript.

Ethics Committee Approval: Ethical committee approval was received from the Ethics Committee of Ankara University Faculty of Medicine (Approval No: I:01-59-25, Date: January 29, 2025).

Informed Consent: Written informed consent was obtained from the patients who agreed to take part in the study.

Peer-review: Externally peer-reviewed.

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Declaration of Interests: The authors have no conflict of interest to declare.

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