Finite element analysis of proximal femoral nail anti-rotation in the treatment of osteoporotic AO3.3 intertrochanteric fracture

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Research Article

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Finite element analysis of proximal femoral nail anti-rotation in the treatment of osteoporotic AO3.3 intertrochanteric fracture

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Abstract

Background: We aimed to use the finite element method to simulate the biomechanical effects of bone cement on the treatment of unstable intertrochanteric fractures with different degrees of osteoporosis using proximal femoral nail anti-rotation (PFNA) to provide personalized treatment plans for patients with type 31-A3.3 intertrochanteric fractures based on the AO Foundation/Orthopaedic Trauma Association classification.

Methods: A finite element model of a normal right femur was created from CT images using related finite element analysis software, and its effectiveness was verified. In the experimental group, 12 types of fracture models with different degrees of osteoporosis were fixed using PFNA, while in the control group, 12 types of osteoporotic fracture models were fixed using bone cement augmented PFNA. A 700 N force was applied to the femoral head in a direction that simulated the direction of load-bearing while standing. The differences in the maximum displacement of the femur, PFNA, femoral stress, and varus angle between the two groups were observed and compared in ANSYS software.

Results: Compared with the common PFNA model, the femoral head displacement, PFNA displacement, and varus angle of the femoral head were significantly smaller in the bone cement augmented PFNA model. However, the maximum stress in the femur was significantly increased. Compared with the experimental group, the change rate of femoral head displacement, PFNA displacement, and varus angle decreased from 2.94% to 5.89%, 3.23% to 4.79%, and 0.41% to 8.51% with increase in the degree of femur osteoporosis. The maximum stress change rate of the femur increased from 12.2% to 5.74%.

Conclusion: Common PFNA for treatment of A3.3 intertrochanteric fracture is likely to fail in severe osteoporosis, and the varus angle and

displacement can be significantly reduced with cement reinforcement. Therefore, PFNA internal fixation with bone cement should be considered for treatment of severe osteoporosis. When used in mild osteoporosis, bone cement increases the stress at the joint between the screw blade and the main nail; therefore, the use of PFNA alone should be considered for treatment in such cases to increase the service life of internal fixation devices.

Key words: Osteoporosis, PFNA, Unstable intertrochanteric fracture, Finite element, Bone cement

0 Background

In recent years, intertrochanteric fracture has attracted much attention, and its incidence is increasing year by year. It is estimated that the number of patients with hip fracture worldwide will reach 4.5 million in 2050 [1], and it is still one of the most common fracture types among the elderly [2]. Based on available statistics, the fatality rate of conservative treatment for elderly patients with intertrochanteric fracture is as high as 20% [3]. Intramedullary fixation is the dominant treatment method at present, of which the use of proximal femoral nail anti-rotation (PFNA) is recognized in the treatment of intertrochanteric fracture of the femur [4]. Intertrochanteric fractures could be stable or unstable fractures. Postoperative failure is the most important clinical problem [5-6] of internal fixation and may occur in up to 13% [7] of cases. AO 31-A3.3 intertrochanteric fractures are unstable fractures, and the treatment of these fractures in the background of osteoporosis is still controversial. In this study, we compare the outcomes of the use of PFNA augmented with bone cement and PFNA alone in the treatment of intertrochanteric fractures with different levels of osteoporosis. The postoperative stability of A3.3 fractures are rarely discussed among intertrochanteric fractures. We perform a biomechanical study to determine which treatment is better amongst the available treatment options for type A3.3 intertrochanteric fractures with different degrees of osteoporosis using the finite element method, thereby providing reference information for clinical treatment.

1 Methods

1.1 Femur model establishment

Using a 64-slice spiral CT (GE, USA) scan, we performed computed tomography of the right proximal femur, and the images were downloaded in DICOM format and imported into Mimics 21.0 (Materialise, Belgium). Threshold segmentation, noise reduction, filling and other methods of image processing were used to initially build a 3D model of the bone. Data of the obtained model were imported into the reverse engineering software Geomagic Studio (Raindrop Inc., USA) as

STL files for smooth optimization, surface mesh reconstruction, and surface fitting [8]. After this, a 3D smooth right femur model was obtained.

1.2 PFNA model establishment

PFNA specifications include long nails and short nails. Hong CC et al. [9] have verified that short nails are more effective in the treatment of type A3 intertrochanteric femoral fractures. We drew the internal fixation sketch in Solidworks 2017 (Dassault Systemes Solidworks Corp., USA) according to the Double Medical PFNA dimensions. The three-dimensional model of proximal femoral anti-rotation intramedullary nail internal fixation was obtained through stretching, rotation, cutting, and combination. The main parameters of the model were as follows: the length of the main nail was 170 mm with a valgus angle of 5°, the diameter of the proximal end was 16 mm, the diameter of the distal end was 10 mm; the diameter of the spiral blade was 10 mm, the length was 105 mm, and the neck angle was 130°. The other specific parameters were measured using a vernier caliper.

1.3 Femoral intertrochanteric fracture and PFNA assembly model

In the Solidworks 2017 (Dassault Systemes Solidworks Corp., USA) software, we assembled cortical bone with cancellous bone. Next the femoral head, the lesser trochanter, and the femoral body were divided twice by the base plane which based on the A3.3 fracture line in AO

Trauma Association classification. The segmental fracture model and PFNA internal fixation model were assembled according to standard surgical techniques, as shown in Figure 1. In the upper view, the position of the intramedullary nail was co-located with the middle and posterior 1/3 of the greater trochanter. In the frontal view, the spiral blade was placed as close to the lower part of the femoral head as possible, and the apex distance was kept between 20–25 mm [10]. After this, the combined model was extracted, saved in "X_T" format, and imported into ANSYS Workbench (ANSYS Inc., USA) for mechanical analysis.

1.4 Material properties and boundary conditions

Femoral cortical bone and spongy bone were set as an isotropic continuum [11-13]; the elastic modulus of internal fixation was 11,000 MPa and the Poisson's ratio was 0.3 [14]. Normal femoral cortical bone elastic modulus is 151,000 MPa with a Poisson's ratio of 0.3; normal femoral cancellous bone elastic modulus is 445 MPa with a Poisson's ratio of 0.2; the elastic modulus of bone cement is 220,000 MPa with a Poisson's ratio of 0.2. According to the study by Polikeit et al. [15-16], the elastic modulus of cancellous bone was reduced by 66% with a gradient of 6%, and the elastic modulus of cortical bone was reduced by 33% with a gradient of 3% to build 12 models of different degrees of osteoporosis. The friction coefficient between bone and bone was 0.3, that between screw blade and main nail was 0.3, and that between internal fixation and femur was 0.23. Other contact relationships were set as bond[17].

1.5 Constraints and loads

The distal femur was completely constrained and fixed, and the force on the femur surface during bipedal standing was simulated. A force of about 700 N, twice the patient's body weight (70 KG), was applied perpendicular to the sphere of the femoral head in a direction 10° to the long axis of the femoral shaft [18].

1.6 Main outcome measures

Proximal femur stress, proximal femur displacement, PFNA displacement, and femoral neck varus angle were the main outcome measures.

1.7 Model Verification

The unsegmented right femur model was imported into the ANASYS software with the same material parameters given to the cortical and spongy bone, and a concentrated load of 700 N was applied at the same position of the femoral head. In Figure 2, the results showed that the stress on the right femur was mainly concentrated in the medial femur moment and transmitted downward, and the amount of stress was similar to that found in previous studies [17]. The stress distribution and stress magnitude of the model confirm that the model is reliable and that the research results are in keeping with reality.

2 Results

2.1 Proximal femur stress

PFNA provides the main support to the fracture of the proximal femur. Comparing the control and experimental groups, the proximal femur maximum stress value was significantly higher in the bone cement augmented PFNA group; the maximum stress, determined by simulation, was in the joint between the helical blade and the main nail; and the rate of change in maximum stress in the two groups decreased with increasing osteoporosis, from an initial increase of 12.2% to a final increase of 5.74%, as shown in Figure 4. Meanwhile, based on the color distribution of the force on the proximal femur in Figure 3, it can be seen that in the control group, the force site at the fracture junction between the medial lesser trochanter bone block and the femoral head bone block has a tendency to decrease.

2.2 Proximal femoral displacement

The surface of the femoral head bears the main stress in the femur. As shown in Figure 5, the maximum displacement of the femur occurs at the junction of the femoral head and acetabulum. As shown in Figure 6, the proximal femoral displacement in the experimental group increased with the increase in the degree of osteoporosis, from 0.34 cm to 0.51 cm, and the change in femoral displacement showed an obvious trend of increase subsequently. The calculated displacement in the bone cement control group was smaller than that in the experimental group in all 12 groups of experiments. The rate of change in displacement reduction in the first 9 groups was less than 3%, and the rate of change in visible displacement reduction in the last three groups was significantly increased, with a maximum reduction of 5.89%.

2.3 Varus of the femoral neck

In ANSYS Workbench software, remote point A was set on the surface of the femoral head, and remote point B was set on the bottom of the femur. Since the bottom of the femur was constrained and fixed, the changes in the angle of remote point A in the X, Y, and Z axes were regarded as the angle of femur varus.

Formula for calculation of the angle

$$= \sqrt{(rotx)2 + (roty)2 + (rotz)2},$$

(rotx stands for angle change in the X-axis; roty represents angle change in the Y-axis; rotz represents angle change in the Z-axis)

The angle of femoral neck varus in 12 degrees of osteoporosis is shown in Figure 7. It can be seen that the angle of femoral neck varus increased with the increase in the degree of osteoporosis in the experimental group, and the range of varus angle increased significantly in the later period. The maximum angle of femoral neck varus in the experimental group was 5.05°. In the cement control group, except for group 1, the other 11 groups had lower femoral neck varus angle than that of the experimental group. With increase in osteoporosis, the rate of change in the femoral neck varus angle increased significantly, from 0.41% to 8.51%.

2.4 PFNA displacement

The maximum PFNA displacement occurred at the tip of the spiral blade, as shown in Figure 8. In the experimental group, PFNA displacement increased with increase in osteoporosis, up to 0.46 cm. In the control group, the maximum displacement of PFNA was also at the tip of the spiral blade; however, in the analysis involving 12 degrees of osteoporosis, the displacement was smaller than that of the experimental group. The displacement change rate was less than 3.5% in the first 7 groups, and significantly increased in the last 5 groups to a maximum of 5.13%, as shown in Figure 9.

3 Discussion

Hip fracture often leads to decreased quality of life, disability and even death in elderly patients [19]. PFNA is currently the main and most common treatment for intertrochanteric fracture because of its short operation time, low intraoperative blood loss, and low risk of peri-prosthesis fracture and dislocation compared to hip arthroplasty [20]; it also has better mechanical stability compared to other devices [21]. However, the outcome of treatment of intertrochanteric fractures is poor. In AO 31-A3.3 type intertrochanteric fractures, the fracture line involves the lateral wall of femur and the medial lesser trochanter, and the instability of the fracture end leads to a significantly higher postoperative failure rate than that of other types of fractures [22-23]. The bone mass of patients with osteoporosis is reduced, and the internal bone microstructure is damaged, resulting in loose trabecular bone and increased bone brittleness. When the screw blade is pressed into the femoral head, the surrounding cancellous bone can undergo chain fracture, and the decreased support of the screw blade can lead to nail withdrawal and cutting. Fracture type and degree of osteoporosis are the direct factors leading to postoperative failure of internal fixation [24]. Therefore, it is of great importance to explore the clinical treatment of patients with A3.3 intertrochanteric fracture accompanied by osteoporosis.

In this study, the effect of simulated bone cement surrounding the spiral blade on postoperative stability of type A3.3 intertrochanteric fracture was observed. We found that the bone cement augmented PFNA group had less proximal femoral displacement with all 12 degrees of osteoporosis than the PFNA only group. By simulating osteoporosis, we found that the rates of change in proximal femoral displacement in the control and experimental groups were relatively stable (less than 3%), and the change in proximal femoral displacement was largest in severe osteoporosis, which could be up to 5.89%. Regarding PFNA displacement analysis, the displacement of bone cement reinforced PFNA was smaller than that of PFNA alone, and the rate of change in PFNA displacement was relatively stable in mild and moderate osteoporosis but significantly increased in severe osteoporosis, with a maximum of 5.13%. For the varus angle of the femur, the varus angle of the femur in the cement-reinforced PFNA group was smaller than that of the common PFNA group, and the rate of change in the varus angle gradually increased with increase in osteoporosis, increasing from 0.4% to 8.51%. By comparing the differences in proximal femoral displacement, PFNA displacement, and varus angle between the experimental and control groups, it can be seen that the overall stability of the femur is effectively improved when PFNA is augmented by bone cement, which is consistent with the conclusion reached by Hanke MS [25]. However, in the first trial on the varus angle of the femur, we found that the varus angle of the femur was higher with cement reinforcement than with PFNA alone. Considering that in terms of PFNA displacement, femur displacement, and varus angle, the differences between the two groups were small at the early stages of osteoporosis (normal, or mild osteoporosis), we concluded that bone cement augmented PFNA had little influence on the stability of normal bone or bone with mild osteoporosis. This is consistent with the conclusion obtained by Erhart S scholars [26] in biomechanical simulation experiments on a hydraulic servo test machine.

Bone cement and bone cementing agents are widely used in lu mbar cone shaping and pedicle screw fixation. Hanke MS [25] treat ed a 90-year-old patient with severe osteoporotic intertrochanteric fr acture with PFNA combined with bone cement, and the X-ray film showed good fracture healing without implant displacement during the one-year follow-up after surgery. However, in this finite element analysis, the proximal femur maximum stress occurred in the main nail and spiral blade joint in both groups, and the maximum stress in the proximal femur was higher in the bone cement reinforced P FNA than in the PFNA alone group. In the first set of experiments, the maximum stress rate reached 12.2%, but with increase in the degree of osteoporosis, the stress rate gradually decreased; in the las t group of experiments, the stress change rate was only 5.74%. The cement reinforced the screw blade's contact with the femoral head cancellous bone. Although the stress at the proximal end of the femur is concentrated at the connection between the main nail and the spiral blade, it was found in this experiment that the value of the rate of change in stress in the two groups decreased with severe osteoporosis, which proves that the concentrated stress does not exceed the maximum yield stress of internal fixation. It also further proves that cement-enhanced PFNA has little effect on the stability of normal bone or bone with mild osteoporosis; we may even suggest that it is unsuitable in such cases.

This study also has the following limitations: (1) In the experiment, the material properties of the femur were set as homogenous and isotropic. (2) Quantitative CT (QCT), which measures volumetric bone mineral density (BMD), is the most accurate method for the diagnosis of osteoporosis [27]. The BMD unit assigned to the femur in this study was also volumetric bone mineral density (BMD). However, there is no diagnostic grading standard of femur QCT for osteoporosis, and the classification of osteoporosis may refer to the WHO recognized DXA diagnostic standard. (3) Conclusions were only obtained from the biomechanical perspective and will be verified by a large clinical trial in the future.

4 Conclusion

Considering the risk of postoperative side effects with the use of bone cement [28] and the finite element analysis of the data in this experiment, we draw the following conclusions: First, in patients with type A3.3 intertrochanteric fractures with normal bone or mild to moderate osteoporosis, we recommend the use of PFNA alone for fixation, because cement reinforcement is associated with the risk of cement complications and may increase the duration of internal fixation. Second, for patients with severe osteoporosis, we recommend cement-enhanced PFNA internal fixation because it significantly improves mechanical stability.

List of Abbreviations

BMD: bone mineral density, CT: computed tomography, PFNA: proximal femoral nail anti-rotation, QCT: Quantitative CT

Declarations

Ethics approval and consent to participate: Ethical clearance was obtained through the Ethics Review Committee of Mudanjiang Medical University (Z 202170) and the informed consent was obtained from individual or guardian participants. Data collected from participants were kept confidential and were accessible only to the researchers. All methods were performed in accordance with the relevant guidelines and regulations.

Consent for publication: Not applicable.

Availability of date and materials: All data generated or analysed during this study are included in this published article [and its supplementary information files].

Competing interests: The authors declare that they have no competing interests.

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Authors' contribution: All authors conceived of the study, took active part in all aspects of the study and read and approved the final manuscript. ZT L was the lead author of the original report. HG was the main contributor in the process of up-dating and revising the contents of the original report and in preparing this manuscript.

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Figure Legends

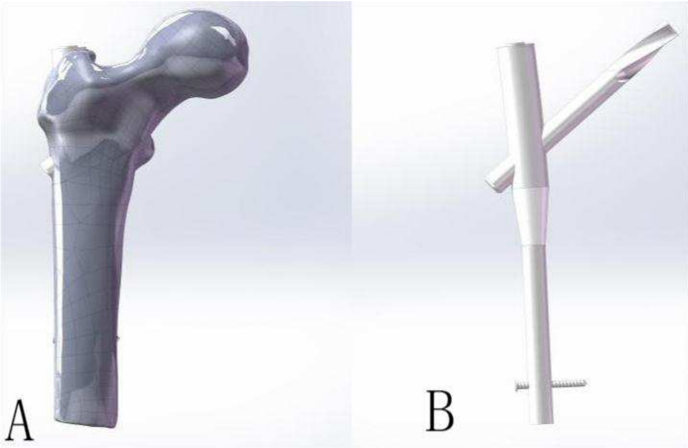


Figure 1 Femur and PFNA assembly model

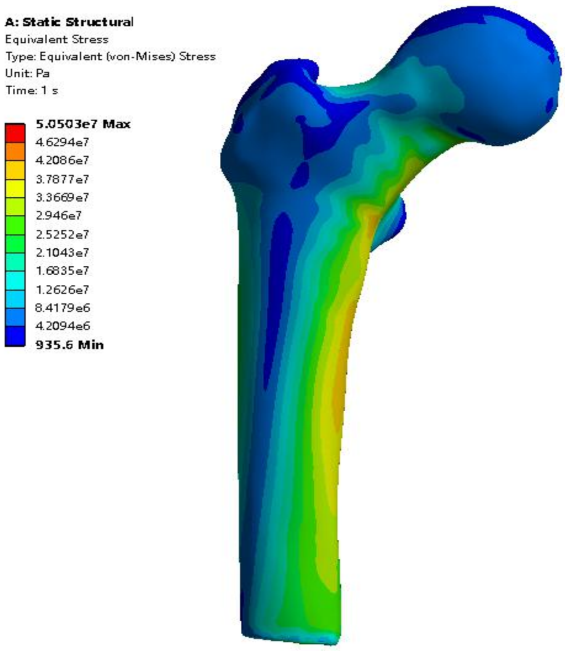
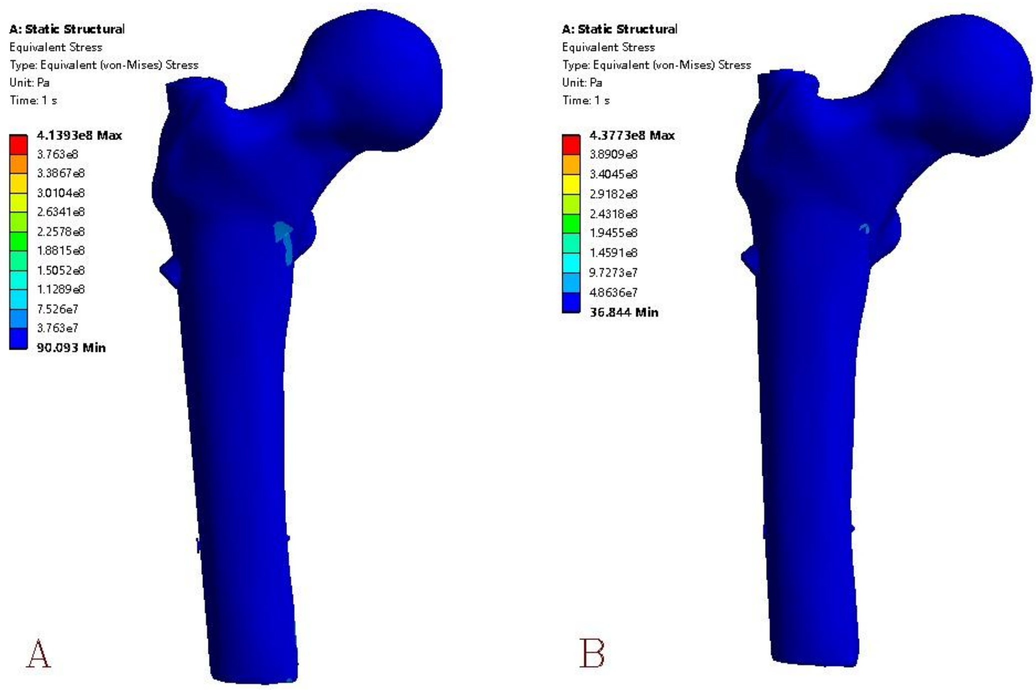


Figure 2 Model Validation



Note: Figure A shows the common PFNA model of stock bone, and Figure B shows the bone cement reinforced PFNA model

Figure 3 The proximal femur stress in the PFNA model was enhanced in the PFNA model with bone cement

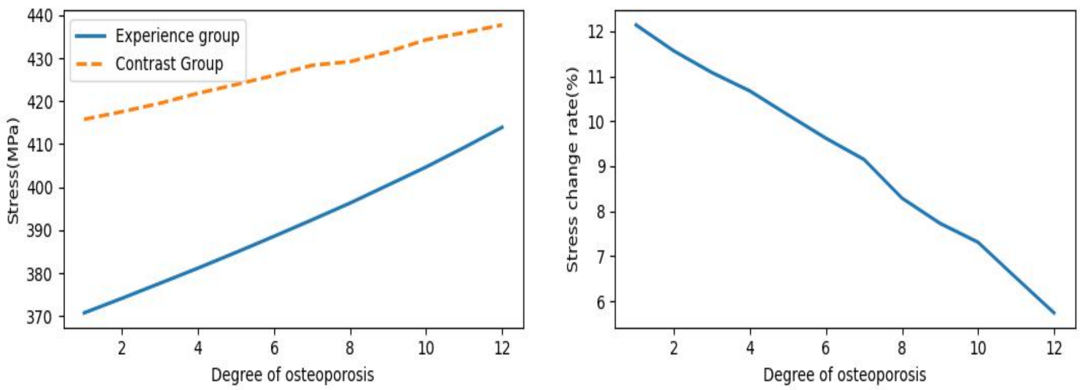
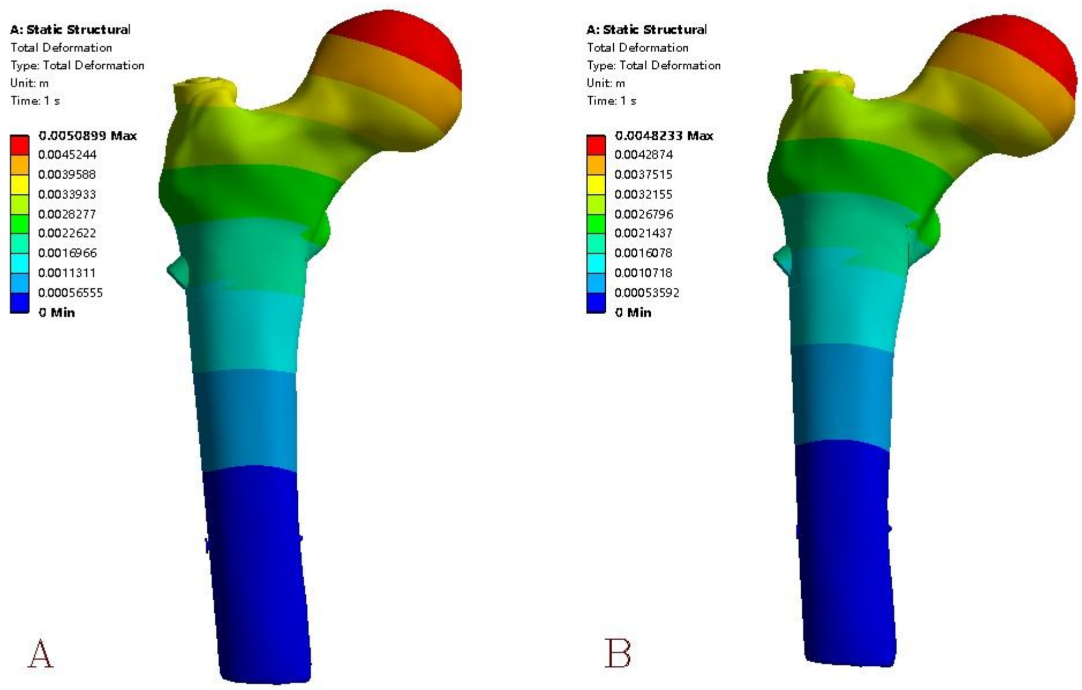


Figure 4 Line plot of the maximum stress change and rate of change in the proximal femur



Note: Figure A shows the common PFNA model of stock bone, and Figure B shows the PFNA model with the nail channel reinforced with bone cement

Figure 5 Proximal femoral displacement in PFNA model and bone cement reinforced PFNA model

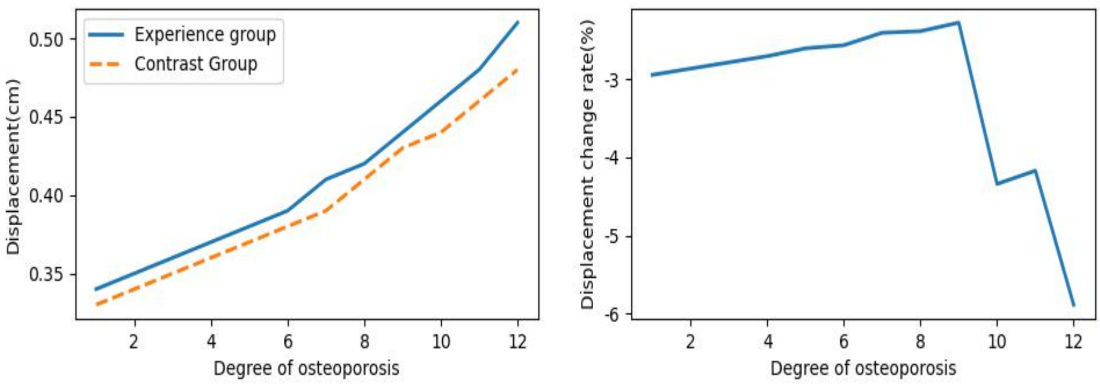


Figure 6 Line plot of the change in displacement and displacement change rate in the proximal femur

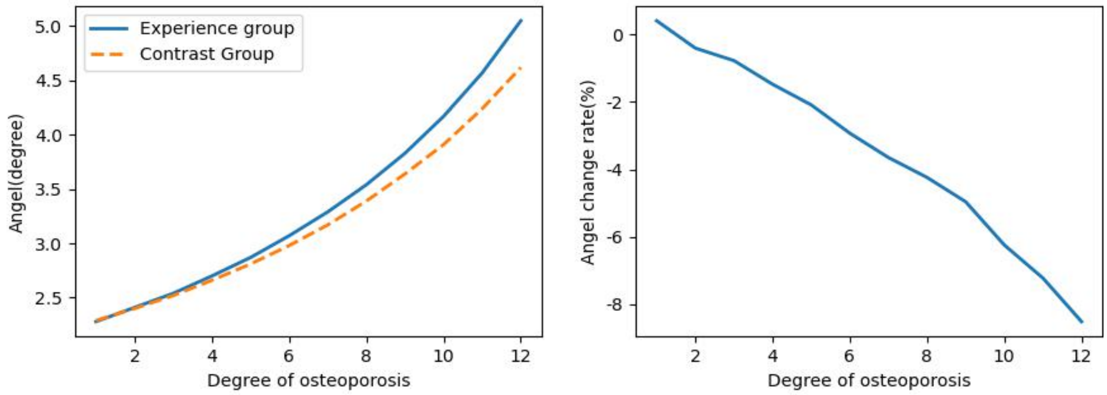
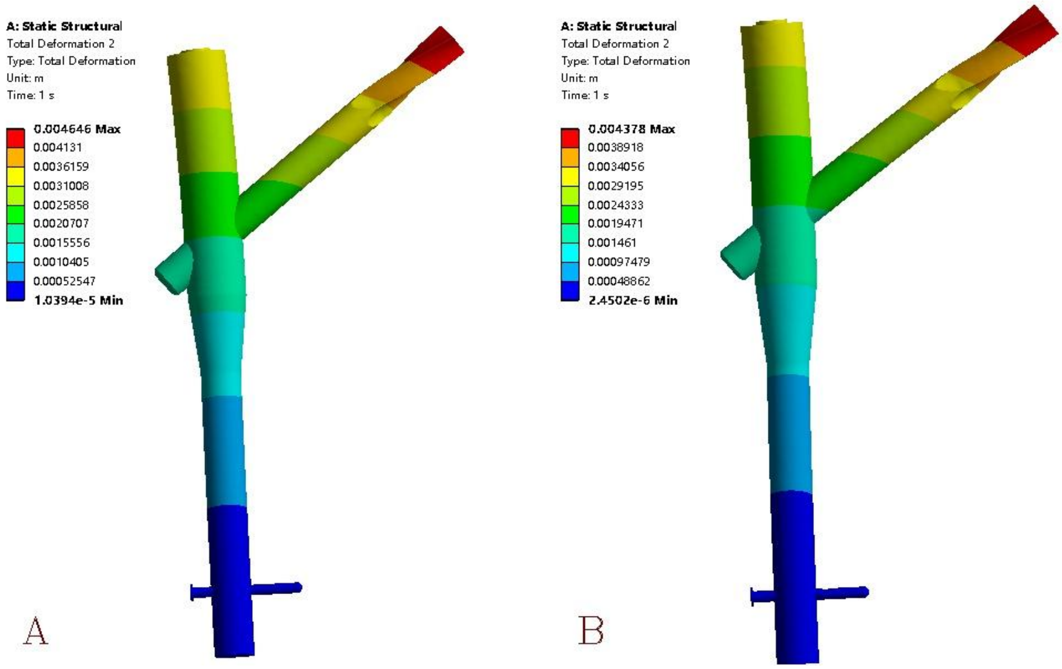


Figure 7 Line plot of angular change and rate of angular change



Note: Figure A shows the ordinary PFNA model, and Figure B shows the bone cement nail channel reinforced PFNA model

Figure 8 PFNA displacement changes in the common PFNA model and bone cement nail channel reinforced PFNA model

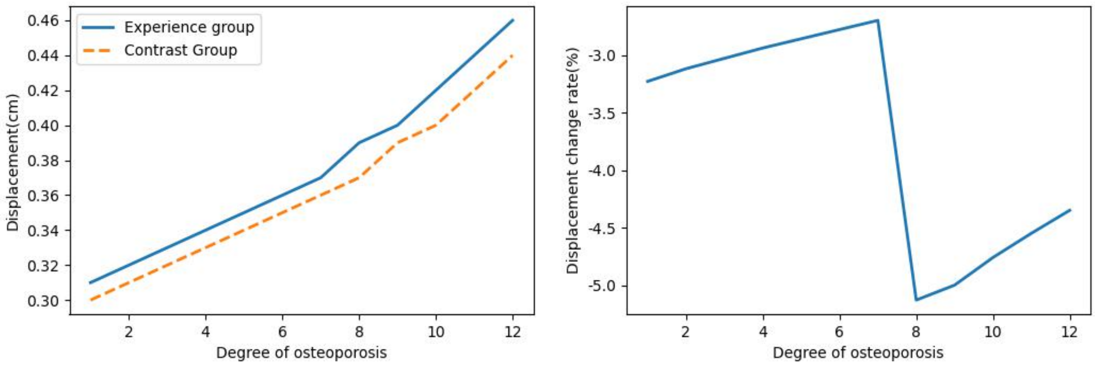


Figure 9 Line plot of PFNA displacement change and change rate