Finite Element Analysis of Biomechanical Effects of Proximal Femur Shortening After Intertrochanteric Fracture

Weilong Li
Zhejiang University School of Medicine First Affiliated Hospital Beilun Branch
Bo Dai
Zhejiang University School of Medicine First Affiliated Hospital Beilun Branch
Jian Guo
Zhejiang University School of Medicine First Affiliated Hospital Beilun Branch
Xuchao Shi
Zhejiang University School of Medicine First Affiliated Hospital Beilun Branch
Jie Gu
Zhejiang University School of Medicine First Affiliated Hospital Beilun Branch
Zhennian He
Zhejiang University School of Medicine First Affiliated Hospital Beilun Branch
Yuanlin Xu (xylblrmyy@163.com)
Zhejiang University School of Medicine First Affiliated Hospital Beilun Branch

Research Article

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Abstract

Purpose

Proximal femoral shortening is common after intertrochanteric fractures treated with proximal femoral nail anti-rotation (PFNA) .We investigated the effects of biomechanical stability of the proximal femur and helical blade which on proximal femoral shortening in intertrochanteric fractures treated with PFNA using the finite element method.

Methods

Using the computed tomography data of the proximal femur of a healthy middle-aged volunteer and Mimics software. We established the proximal femoral shortening model after intertrochanteric fracture (Evans-Jensen type III) treated with PFNA. The models were divided into non-shortening, mild shortening (4mm), moderate shortening (8mm), and severe shortening (12mm) group. Abaqus were used for mechanical analysis and to obtain the overall stiffness of the different models, stress and stress nephograms of the proximal femur, fracture surface, whole femur and helical blade.

Results

In the non-shortening, mild-, moderate-, and severe-shortening groups, the overall stiffness of the proximal femur was 6491.8N/mm, 7264.8N /mm, 8168.0N /mm and 9222.8 N /mm and the maximum stress in the cancellous bone area of the proximal femur was 4.39MPa, 3.96MPa, 3.63MPa and 3.43MPa respectively. The stress on the fracture surface gradually decreased, while the stress at the end of the helical blade increased. However, the stress at the tip decreased gradually with the increase in shortening of the proximal femur.

Conclusion

With increased proximal femur shortening, fracture stability gradually increases. Intertrochanteric fractures involving the lateral wall may increase the probability of screw blade nail withdrawal and decrease the probability of proximal cutting as shortening increases.

Introduction

Intertrochanteric fractures are a common type of hip fracture, accounting for approximately 50% of hip fractures in the elderly[1].Due to the poor outcome of conservative treatment and high disability and fatality rates, surgical treatment of intertrochanteric fractures is generally advocated[2].Since intertrochanteric fractures occur mostly in the elderly, most of whom suffer from osteoporosis, proximal femoral nail anti-rotation (PFNA) was developed. With its widespread clinical application, occurrence of proximal femoral shortening (PFS) after PFNA has attracted the attention of clinicians[3–5].Shortening of the proximal femur leads to a reduction in femoral neck offset, a reduction in the abductor force arm, and impaired gait speed, symmetry, and physical function, resulting in hip dysfunction. Studies have shown that proximal femur shortening of ≥ 5 mm significantly reduces the abductor arm of patients, increases the probability of lower limb claudication and the use of walking aids, and increases the discomfort of hip pain[6].At present, there are no strict experiments to verify the biomechanical effect of PFS on the proximal femur after PFNA internal fixation. This leads to confusion among clinicians regarding the extent to which internal fixation may fail and whether timely revision surgery is needed to preserve the maximum limb function. Therefore, this study aimed to establish a three-dimensional model for finite element analysis, to restore the stress distribution and changes in the proximal femur, and to clarify the biomechanical effects of proximal femur shortening after PFNA for intertrochanteric fractures.

Materials And Methods

Study design and the finite element model of femur and proximal femur shortening

A healthy male volunteer (age, 59 years; height, 175cm; weight, 70kg) was recruited and signed an informed consent form. The man was placed on a continuous tomography (CT) scanning bed with both hips straight and neutral, and the volunteer was scanned by spiral CT (from the upper margin of the acetabulum to the lower femur).512×512 CT images obtained after scanning were exported in Dicom format. It was imported into Mimics Medical, and its grey value range was 226–2961. The bone region was quickly screened, the right femur was selected for coating and smoothing, and the STL file was derived. Imported into the Geomagic Studio software, surface fitting and smoothing are optimised to transform into an accurate 3D solid model of the proximal femur.

Establish the finite element model of the implant

According to the size of the Asian type proximal intramedullary nail fixation, the proximal diameter of the main nail was 16.6mm, and the end diameter was 11mm, the length of the main nail was 200mm, the rake angle was 15°, the cervical stem Angle was 130°, the proximal valgus angle was 5°, the diameter of the screw blade was 10.5mm, and the length of the thread part was 35mm, The overall length of the helical blade was determined by the actual length of the proximal femur, and the diameter of the transverse locking nail was 4.9mm. The main nail structure was treated as a tetrahedral grid structure, and the friction coefficient between the unthreaded part of the helical blade and the fracture surface was set as 0.2. It was assumed that the fracture had been reduced and the fracture surface was completely fractured. The threaded part of the helical blade can be treated as a helical structure because it is in close contact with the bone. According to the structural rules, the horizontal locking nails were treated as hexahedral meshes in the finite element analysis. Simultaneously ,the intertrochanteric fracture of the femur was set as Evans-Jensen type III, and the femoral structural grid was processed into a tetrahedron. The geometric models of shortening after internal fixation of intertrochanteric fractures of the femur were completed, including the non-shortening model, mild shortening model (4mm), moderate shortening model (8mm) and severe shortening model (12mm).(Fig. 1).

Material parameters

The material parameters are presented in Table 1

Table 1
Material mechanics property parameter of the model

Structure of the organization	Modulus of elasticity	Poisson's ratio
Cancellous bone	660MPa	0.2
Cortical bone	8844MPa	0.26
The main nail	114GPa	0.33
Helical blade	114GPa	0.33
Transverse locking	114GPa	0.33

Set boundary conditions and apply load

The loading point, loading area and restraint area should remain constent. In this study, 2.4 times human body weight (70kg) was applied to each model, which is equivalent to the load that the patient would be subjected to from standing to walking at a gentle pace. Fixed end-face constraints X, Y, Z, Ux, Uy, and Uz have six degrees of freedom.

Results

Overall deformation analysis of the structure

The structural stiffness curves for different degrees of proximal femur shortening are shown in Fig. 3. The stiffness of the non-shortening, mild-shortening, moderate-shortening and severe-shortening were 6491.8N/mm, 7264.8N/mm, 8168.0N /mm and 9222.8N/mm respectively. According to the numerical analysis, when the proximal femur was shortened by 1mm, the overall deformation resistance of the structure increased by 227.4N.

Bone stress

The maximum stress in the cancellous bone region of proximal femur was 4.39 MPa, 3.96 MPa, 3.63 MPa and 3.43MPa in the non-shortening, mild shortening, moderate shortening and severe shortening models respectively (Fig. 4).The maximum stress of fracture place was 134.2 MPa, 133.9 MPa, 133.5 MPa and 133.2 MPa respectively (Fig. 5).It can be seen from the figure that the stress around the helical blade does not change significantly, but by comparing the front and rear stresses to the upper stress of the lateral cortex near the helical blade, it can be found that the maximum stress on the front and rear sides of the helical blade is approximately three times that of the upper stress. The maximum upper stress values are 14.2 MPa, 14.3 MPa, 14.4 MPa and 14.6 MPa respectively. The maximum front stress values were 48.4 MPa, 48.2 MPa, 47.9 MPa and 47.6 MPa respectively (Fig. 6).

The data on the overall stress of the femur are presented in Table 2. The maximum stress was concentrated mainly on the dorsal side of the femur.

Table 2
Stress peaks of different proximal femur shortening femur (MPa)

	No shortening	Shortening of 4 mm	Shortening of 8 mm	Shortening of 12 mm
The ventral	18.75	17.43	16.31	15.19
The dorsal	25.27	25.18	25.09	24.99
The lateral	18.57	17.46	16.21	15.03
The medial	9.19	8.77	8.33	7.88

Stress of helical blade

The stress at the tail of the helical blade are 4.49MPa, 4.56MPa, 4.65MPa and 4.75MPa respectively, and the stress above the tip are 26.06MPa, 25.65MPa, 23.49MPa and 20.04MPa respectively, and the stress below are 7.07MPa, 6.65MPa,4.42MPa, 3.43MPa, respectively.(Fig. 7)

Discussion

Previously, a lower limb shortening of more than 2cm was considered to cause lower limb dysfunction and even claudication. However, continuous study by scholars found that shortening of the proximal femur exceeding 5mm causes the dysfunction of the patient's hip joint[7]. Intertrochanteric fractures are in the elderly. With continuous improvements in the internal fixation system, PFNA has obvious advantages in most types of intertrochanteric fractures. However, many scholars have found that proximal femoral shortening after intramedullary fixation of intertrochanteric fractures is common. Hou et al. found that the shortening rates of intertrochanteric fractures of the femur were 72.46% and 88.76% after treatment with a third generation gamma nail (TGN) and PFNA[8],respectively. Some scholars believe that due to the anteversion angle of the hip joint and the collodiaphyseal angle, gravity transmission from the pelvis to the lower limb occurs at a turning point[9]. Therefore, when the proximal femur is fractured, fretting and bone loss of the fracture plane occur easily, resulting in proximal femur shortening. However, strict biomechanical experiments to verify the biomechanical effects of proximal femoral shortening after PFNA internal fixation on the proximal femur and internal fixation are lacking.

In this study, models of proximal femur shortening of different degrees were established, and it was found that the overall femur stress was concentrated on the medial aspect of the dorsal side of the proximal femur, that is, near the calcar femur. The calcar femur is the internal weight-bearing system of the proximal femur, and plays an important role in the fracture of the proximal femur. By decreasing the force on the posterior and medial femur and increasing the force on the anterior and lateral femur[10,11], we found that with the gradual shortening of the proximal femur, the maximum stress on all four surfaces of the proximal femur decreased gradually. This suggests that the stability of the whole femur gradually increased with the shortening of the proximal femur.

According to the stiffness changes of different proximal femur shortening in Fig. 3, it was found that the overall deformation resistance of the structure increased by 227.4N for every 1mm shortening of the proximal femur. In addition, the stress in the cancellous bone region and fracture plane of the proximal femur decreased with a gradual increase in the shortening degree, indicating that the stability of the fracture plane gradually improved after shortening, which was in great contrast to the adverse effect of proximal femur shortening on hip joint function. This may be due to the helical blade of the PFNA fracture compression effect. Because, the head end of the control force is strong enough, the compression effect of the fracture plane will gradually increase with shortening aggravation, so that the fracture surface stress decreases, which is conducive for fracture healing, and is also consistent with the clinical results. In clinical practice, shortening of the proximal femur is often caused by continuous compression of the fracture end, which often promotes fracture healing[12].

Bone around the end of a helical blade stress changes as shown in Fig. 6, the stress variation in the shortening of the different groups is not obvious, it can be presumed that after the shortening, the lateral femoral wall stress effect is reduce, but it can be found that the maximum stress on the front and rear sides of the helical blade is about three times the upper stress. This may lead to forward displacement of the bone after separation, and this may be related to the model setup. In this study, the intertrochanteric fracture of the femur was set as Evans-Jensen type Ⅲ, and the fracture involved the lateral wall, which may lead to poor stability of the lateral wall in the front and rear directions. However, different degrees of shortening seem to have little effect on the lateral wall stress, but the specific reasons for this need to be explored further in the future.

By observing different degrees of proximal femoral shortening, the helical blade tip and the tail end, it can be found that with increase in shortening, the stress of the helical blade end increases gradually, while the stress of the helical blade tip decreases. At the same time, the shortening of the various groups of at top of the helical blade tip stress was significantly greater than that under stress. This could occur if shortening gradually increases, which may result in an increased chance of the helical blade pulling out the screw laterally and a decreased chance of cutting in the direction of the femoral head and acetabulum. This may be due to the fact that this experiment simulates a fracture involving the lateral wall. With an increase in shortening, the blocking effect on the tail end of the helical blade is weakened. Meanwhile, the stress difference between the tip and tail of the helical blade may indicate that if the helical blade cuts toward the femoral head, the probability of cutting toward the proximal end is very high. Helical blade cutting and nail removal are common complications of PFNA[13–17]. Previous studies have reported that the cutting rate of a helical blade after PFNA for intertrochanteric fracture is 0-

7.9%.There are many influencing factors, including fracture type, reduction quality, apex distance, helical blade position, osteoporosis, incorrect functional exercise, and design defects of the PFNA itself. At present, the tip apex distance(TAD) is considered to be the most important predictor of helical blade cutting[16,18].Additionally, the integrity of the lateral wall is an important factor. Previous studies have shown that the presence of the lateral wall provides lateral support for the proximal main nail and head and neck screw, preventing the removal and withdrawal of the head and neck screw[19].In this study, intertrochanteric fractures of the femur involving the lateral wall may increase the probability of screw-blade nail withdrawal after proximal femoral shortening, but the probability of cutting toward the femoral head and acetabulum may decrease.

In conclusion, through finite element analysis, it was theoretically found that the stability of intertrochanteric fractures would gradually increase with proximal femoral shortening after PFNA internal fixation. Also, when intertrochanteric fractures involve the lateral wall, the probability of screw blade disengagement may increase as shortening increases, and the probability of cutting toward the femoral head and acetabulum may decrease.

This experimental study has some limitations: First, it simulates the mechanical analysis of a static hip joint. If finite element analysis can be carried out in the walking state of the hip joint, the data obtained will be closer to the mechanical characteristics of the human body. Second, only one type of femoral trochanter was simulated in this experiment. Third, the fracture type is relatively simple. These limitations will need to be addressed in further research.

Declarations

Acknowledgements

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Conflict of interest

The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors. This study conforms to the provisions of the Declaration of Helsinki and has been reviewed and approved by the Institutional Review Board of Beilun People’s Hospital.

Informed consent

Informed consent to participate and publish was obtained from the volunteer individual in the study.

References

1. Quental C, Vasconcelos S, Folgado J, et al.Influence of the PFNA screw position on the risk of cut-out in an unstable intertrochanteric fracture: a computational analysis. Med Eng Phys. 2021;97: 70-6.
2. Li XP, Zhang P, Zhu SW, et al. All-cause mortality risk in aged femoral intertrochanteric fracture patients. J Orthop Surg Res. 2021; 16 (1):727.
3. Suh YS,Nho JH, Kim SM, et al.Clinical and Radiologic Outcomes among Bipolar Hemiarthroplasty, Compression Hip Screw and Proximal Femur Nail Antirotation in Treating Comminuted Intertrochanteric Fractures. Hip Pelvis. 2015; 27(1): 30-5.
4. Weil, YA. Khoury A, Zuaiter I, et al.Femoral neck shortening and varus collapse after navigated fixation of intracapsular femoral neck fractures. J Orthop Trauma. 2012; 26(1): 19-23.
5. Platzer P, Thalhammer G, Wozasek GE, et al.Femoral shortening after surgical treatment of trochanteric fractures in nongeriatric patients. J Trauma. 2008; 64 (4) : 982-9. .
6. Zlowodzki M,Ayeni O, Petrisor BA, et al.Femoral neck shortening after fracture fixation with multiple cancellous screws: incidence and effect on function. J Trauma. 2008; 64(1): 163-9.
7. Li WL,Yu X,Pang QJ, Advances on preventing femoral neck shortening after internal fixation of femoral neck fracture. Chinese Journal of Orthopaedics. 2016; 36(6): 378-84.
8. Hou Y ,Yao Q,Zhang Gen'ai,et al. Comparative study of proximal femoral shortening after the third generation of Gamma nail versus proximal femoral nail anti-rotation in treatment of intertrochanteric fracture. Zhongguo Xiu Fu Chong Jian Wai Ke Za Zhi. 2018; 32(3): 338-45.
9. Wang K, Wu D, Liu Q,et al. Advances in the research of proximal femoral shortening after intertrochanteric fracture surgery. Chinese Journal of Bone and Joint. 2020; 9(6): 435-9.
10. Hammer A, The calcar femorale: A new perspective. J Orthop Surg (Hong Kong). 2019; 27(2):2309499019848778.
11. Mei J, Pang L and Jiang Z.Strategies for managing the destruction of calcar femorale. BMC Musculoskelet Disord. 2021; 22 (1) : 460.
12. Park YC,Um KS, Kim DJ, et al.Comparison of femoral neck shortening and outcomes between in situ fixation and fixation after reduction for severe valgus-impacted femoral neck fractures. Injury. 2021, 52(3): 569-74.
13. Brunner A, Buttler M, Lehmann U, et al.What is the optimal salvage procedure for cut-out after surgical fixation of trochanteric fractures with the PFNA or TFN?: A multicentre study. Injury. 2016; 47(2): 432-8.
14. Turgut A,Kalenderer O, Karapinar L, et al.Which factor is most important for occurrence of cutout complications in patients treated with proximal femoral nail antirotation? Retrospective analysis of 298 patients. Arch Orthop Trauma Surg. 2016;136(5): 623-30.
15. Nikoloski AN, Osbrough AL and 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(1): 35.

16. Yu W, Zhang X, Zhu X, et al.A retrospective analysis of the InterTan nail and proximal femoral nail anti-rotation-Asia in the treatment of unstable intertrochanteric femur fractures in the elderly. J Orthop Surg Res. 2016; 11: 10.
17. Radaideh AM, Qudah HA, Audat ZA, et al. Functional and Radiological Results of Proximal Femoral Nail Antirotation (PFNA) Osteosynthesis in the Treatment of Unstable Pertrochanteric Fractures. J Clin Med, 2018; 7(4):78.
18. Karakus O,Ozdemir G,Karaca S,et al.The relationship between the type of unstable intertrochanteric femur fracture and mobility in the elderly. J Orthop Surg Res. 2018;13(1): 207.
19. Studer P, Suhm N, Wang Q, et al.Displaced trochanteric fragments lead to poor functional outcome in pertrochanteric fractures treated by cephalomedullary nails. Injury. 2015; 46(12): 2384-8.

Figures

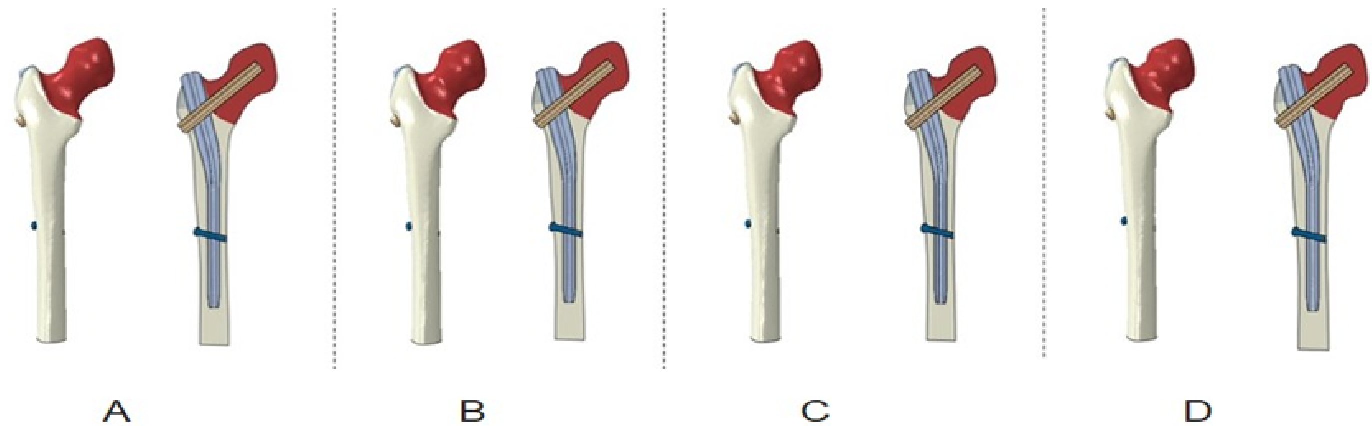

Figure 1

Comparison of finite element models of different degrees of shortening of proximal femur

A, B, C, and D represent non-shortening, mild-shortening (4 mm), moderate-shortening (8 mm), and severe-shortening (12 mm) models

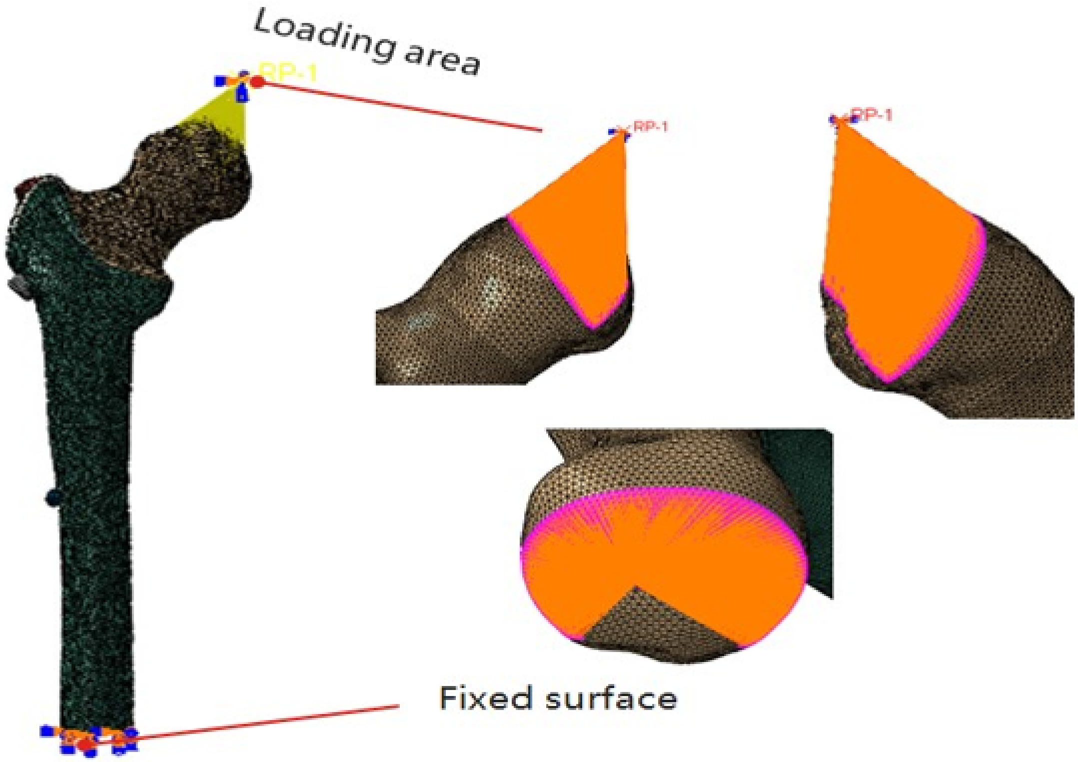

Figure 2

Loading and constraint regions in finite element analysis

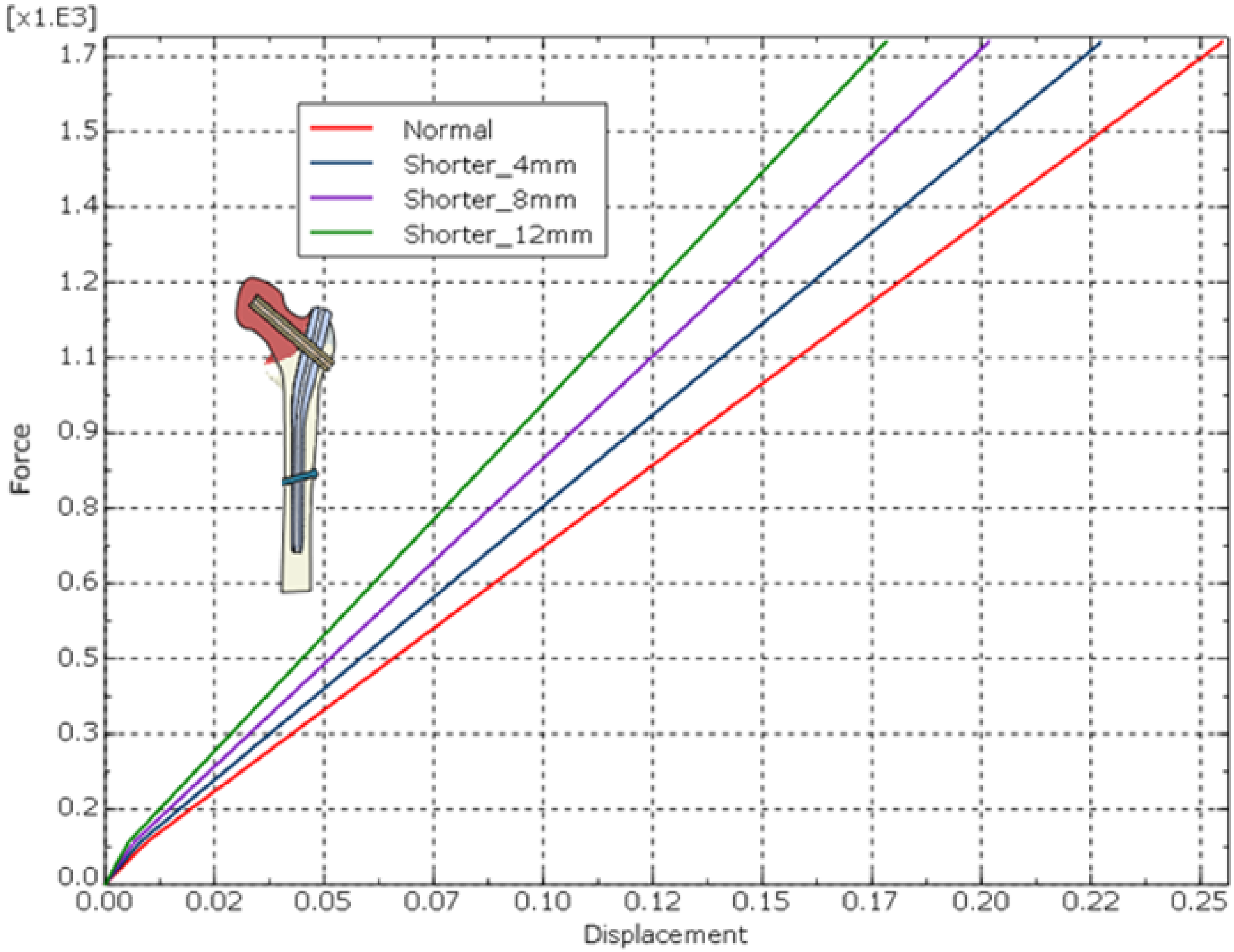

Figure 3

Comparison of structural stiffness of proximal femur with different degrees of shortening

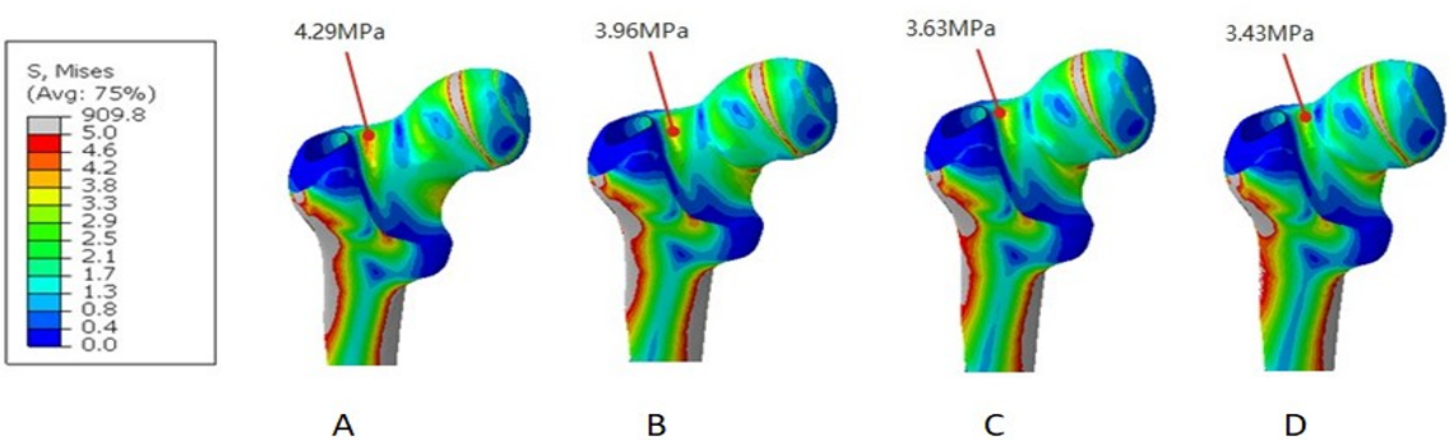

Figure 4

Von Mises stress pattern in the cancellous bone region of the proximal femur

A, B, C, and D represent non-shortening, mild-shortening (4 mm), moderate-shortening (8 mm), and severe-shortening (12 mm) models

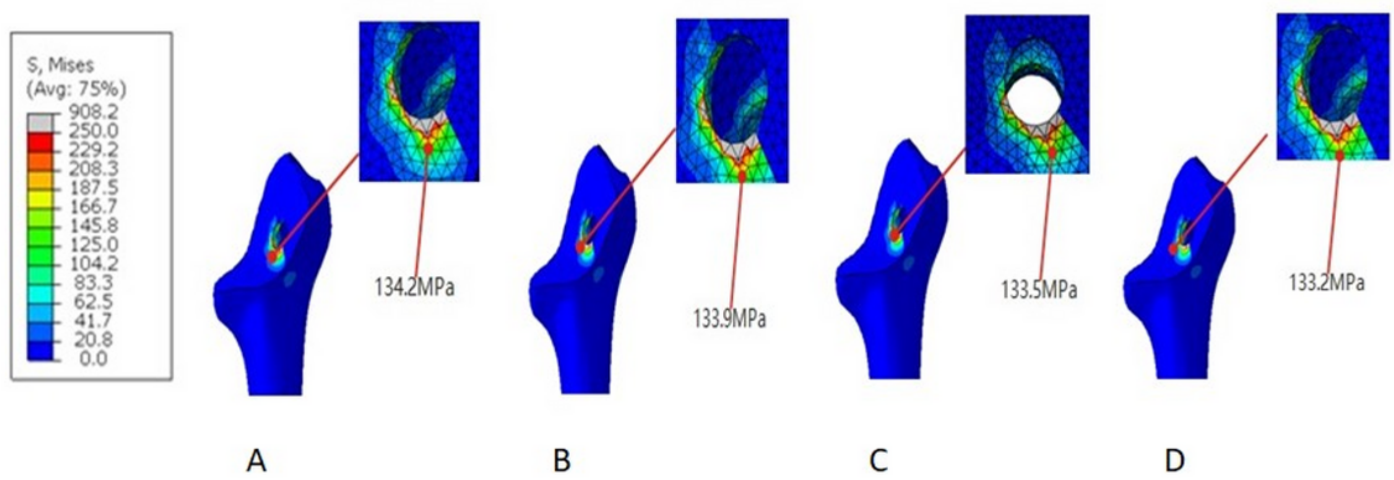

Figure 5

Stress cloud of fracture plane

A, B, C, and D represent non-shortening, mild-shortening (4 mm), moderate-shortening (8 mm), and severe-shortening (12 mm) models

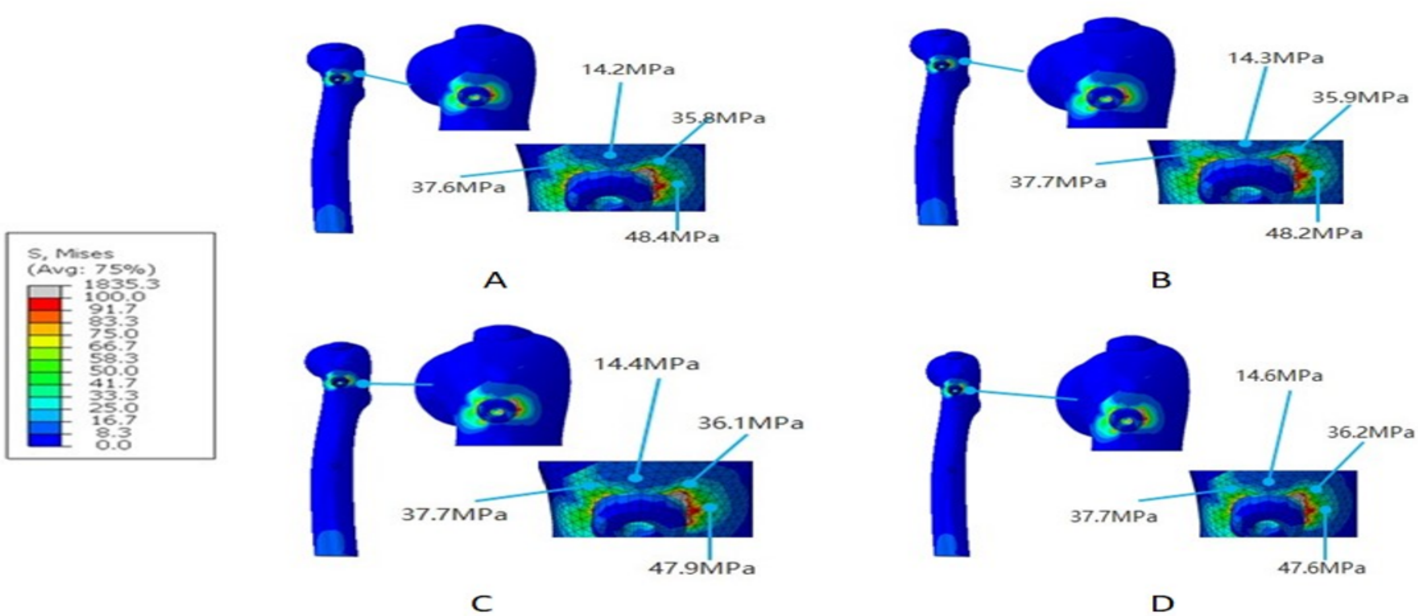

Figure 6

Cortical bone stress cloud around the end of spiral blade

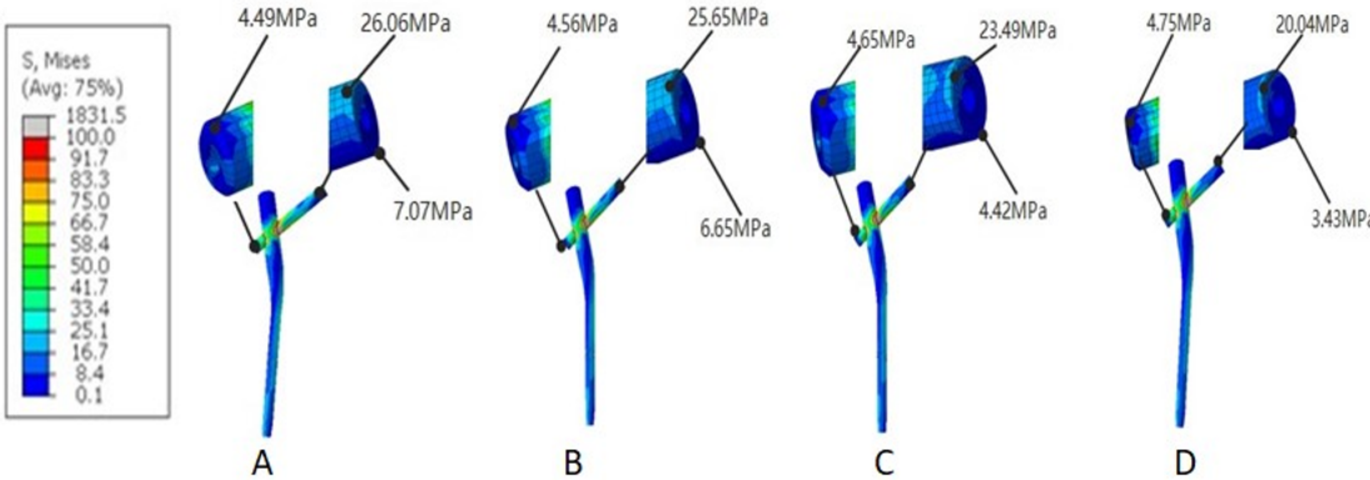

Figure 7

Stress cloud of helical blade

A, B, C, and D represent non-shortening, mild-shortening (4 mm), moderate-shortening (8 mm), and severe-shortening (12 mm) models