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Research article

Mechanical effect of changed femoral neck ante-version angles on the stability of an intertrochanteric fracture fixed with PFNA: A finite element analysis☆

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A R T I C L E I N F O

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A B S T R A C T

Objective: Change of femoral neck ante-version angle postoperatively due to inadequate reduction could result in unsatisfying treatment outcome of intertrochanteric fracture. However, the influence of increased or decreased femoral neck ante-version on the biomechanical stability of the bone-implant complex has rarely been studied.
Methods: A finite element model of a complete normal human femur with normal femoral neck ante-version as 13° was established accurately by scanning a 64 year old female femur. The models of 31-A1.1 intertrochanteric fractures with different femoral neck ante-version angles of 3°, 5.5°, 8°, 10.5°, 13°, 15.5°, 18°, 20.5°, 23° were created. They were assembled with a proximal femoral nail anti-rotation (PFNA) device. The biomechanical differences with varying femoral neck ante-version angles were compared using finite element analysis method.
Results: As the femoral neck ante-version angle gradually increased from 13° to 23°with a gradient of 2.5°, the peak von Mises stress was gradually increased from 137.82 MPa to 276.02 MPa. Similarly, the peak von Mises stress was gradually increased from 137.82 MPa to 360.12 MPa with the femoral neck ante-version angle decreased from 13° to 3°. When decreased ante-version angle of 7.5° and increased ante-version angle of 10° will exceed the yield strength of femoral (240.32 MPa), the risk of femoral fracture will increase significantly. The maximum displacement of the femur was significantly reduced for increased ante-version models than for decreased ante-version models, whether the changes of ante-version angles were 2.5°, 5°, 7.5° or 10°. The maximum stress of PFNA was found in the intersection of main nail and helical blade, and became greater gradually as the ante-version angle increased or decreased with a gradient of 2.5°. The maximum stress of PFNA was presented in the model 5.5° with the maximum stress of 724.42 MPa (near to the yield strength of titanium alloy of 700–1000 MPa), producing the breakage risk of PFNA. The maximum displacement of the PFNA was significantly reduced for increased ante-version models than for decreased ante-version models, whether the changes of ante-version angles were 2.5°, 5°, 7.5° or 10°.
Conclusion: Based on the results of present study, it was demonstrated that the anatomical reduction of femoral neck ante-version was vital to secure the optimal stability. Abnormal femoral ante-version could increase the potential risk of failure for intertrochanteric fracture after PFNA. The stability of increased femoral ante-version (less than 10°) was superior to the stability of

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decreased ante-version (less than 5°) for the cases of difficulty to acquire anatomical reduction. The clinical implication of the finding was that increased femoral neck ante-version had an advantage of mechanical stability towards the decreased femoral neck ante-version for the cases of comminuted intertrochanteric fracture and failure of anatomical reduction.

1. Introduction

Femoral intertrochanteric fracture is a major healthcare problem, presenting a huge challenge and burden to patients, healthcare systems and society. According to a recent systemic review, more than half of all hip fractures in the world will occur in Asia by the year 2050 with the advent of an old-aging population [1]. A recent study in Asia predicts that the number of hip fractures alone will increase from just over one million now to just over 2.5 million in 2050 [2]. The associated financial burden will increase from US$ 9.5 to US $15 billion, not including the cost of the social care needs of disabilities and the long-term nursing care [2,3]. For geriatric intertrochanteric fractures, the process of surgical treatment is firstly recommended for the reasons of getting patients off bed as early as possible. Published studies reported that early reduction and internal fixation for intertrochanteric fracture improved patient comfort, facilitated nursing care, and decreased the duration of hospitalization [4]. Satisfactory results of intertrochanteric fracture treated with proximal femoral nail anti-rotation (PFNA) have been reported [5,6]. In addition to accurate reduction, fracture type, bone quality, supply of blood and nutritional status of the patient also plays an important role in the stability of an intertrochanteric fracture after PFNA fixation [7–9].

Femoral neck ante-version (FNA) is the angle between the projections of two lines in the axial plane perpendicular to the femoral shaft. FNA affects the biomechanics of the hip, as moment arms and the line of action of muscles around the joint are altered. If the FNA alters, whether it is decreased or increased, it often means pathological changes, leading to the occurrence of early degenerative diseases. Eckhoff et al. [10] observed and investigated 110 femur specimens, and pointed out that the increase of knee osteoarthritis was related to the decreased femoral neck ante-version. Gokce et al. [11] reported that increased femoral ante-version could result in the lower-extremity functional problems and children with excessive femoral ante-version angle may be more vulnerable to injuries. Regarding femoroacetabular impingement (FAI), decreased femoral version has been reported as a predisposing factor in the pathomechanics of impingement [12]. Femoral version was often variable in both dysplastic and non-dysplastic hips, but in general, higher than average femoral ante-version was expected in the setting of hip dysplasia [13]. It was very important to secure accurate reduction of femoral ante-version for postoperative hip function and gait. Nowadays, the treatment of intertrochanteric fractures has undergone favorable evolution and revolution during the past 20 years, as manifested by new technical concepts of tip apex distance (TAD), lateral wall, cortex support reduction, and the success of intramedullary nailing [8,14]. Due to the limitation of C-arm image intensifier during the process of operation, it was difficult to judge precisely for femoral ante-version reduction, thus leading to increased (Fig. 1A–D) or decreased (Fig. 2 A - D) femoral ante-version after PFNA operation using CT scanning. Abnormal femoral version was crucial in determining inherent impingement, range of motion and pathology of the hip joint. Published studies reported that abnormal femoral version have been associated with lower limb dysfunctions of patellar instability, abnormal gait mechanics, slipped capital femoral epiphysis, femoroacetabular impingement (FAI), hip dysplasia and OA of the knee and hip [10,15]. Many studies reported the influence of abnormal femoral version on the FAI, and hip arthroscopy [16,17], while little information was found for the changed femoral version after PFNA in the intertrochanteric fracture. We aimed to evaluate the effects of abnormal femoral neck ante-version on the biomechanical stability of bone-implant complex using the method of finite element analysis (FEA).

2. Methods

A healthy femur of a female (64-year-old) without pathological fracture, tumor, infection, malformations, or coxitis was identified for computed tomography (CT) scan at Zhujiang Hospital, Southern Medical University. Informed consent was obtained from the patient. This study was approved by the institutional ethics committee (2022-KY-164-02). The CT scan (General Electric Company, Fairfield, USA) (protocol: voltage 120 kV, pitch 0.984, standard reconstruction kernel) was collected with slice thickness of 1.25 mm

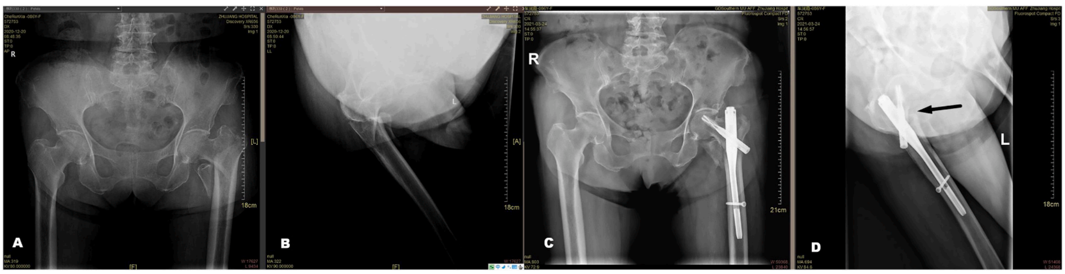

Fig. 1. Case presentation 1: Inadequate reduction with increased femoral neck ante-version. An 86-y old female patient was presented with left intertrochanteric fracture of 31-AO 2.1. A:The radiographical film of pelvis (A-P position) before PFNA, B: Lateral position of the hip before PFNA, C: Anteroposterior position after PFNA, D: Lateral position after PFNA (increased femoral neck ante-version was identified using arrow).

and 512 × 512 pixels per image. The segmentation of femur from proximal to distal ends was acquired, and each image was recorded in the Digital Imaging and Communications in Medicine (DICOM) format. Then these images were transferred to the software of MIMICS Research 20.0 (Materialise Interactive Medical Image Control System; Materialise, Antwerp, Belgium). With the help of Geomagic Studio 10 software (Raindrop Inc., USA), the surface errors such as spike and intersection of the femur model were corrected. After the correction of the surface roughness of the model, a solid model of femur cortical bone was developed and then the model of femur trabecular bone was developed by using the offset command in the software of Geomagic Studio 10. Both of the models were then imported into SolidWorks program (Dassault Systemes SolidWorks Corp., Massachusetts, USA) to assemble to be a complete femur bone model. According to our measurement with SolidWorks program, the original ante-version angle of the femur bone was 13.34°, and we took it for 13°.

We established an original model of intertrochanteric fracture corresponding to the Muller AO classification 31-A1.1 in the software of SolidWorks. And we assumed that the fracture surface was flat. By rotating the proximal fracture fragments, the change of femoral ante-version angles were increased or decreased by 0°, 2.5°, 5°, 7.5° and 10° respectively. Nine femoral models with ante-version angles of 3°, 5.5°, 8°, 10.5°, 13°, 15.5°, 18°, 20.5° and 23° were created. The 3D model of PFNA (Synthes, Solothurn, Switzerland) with a length of 170 mm and a caput-collum-diaphysis (CCD) angle of 125° was established in SolidWorks program according to the data of the PFNA measured with vernier calipers in vitro. Assemblage of the PFNA and nine bone fracture models was accomplished using SolidWorks program in accordance with clinical practice. The Tip-Apex distance (TAD) was controlled the range of 25~27 mm using the tool of measurement in the software of SolidWorks, which was known as the ideal position [18]. In total, nine fracture-implant models were generated and they were named as model 3°, 5.5°, 8°, 10.5°, 13°, 15.5°, 18°, 20.5° and 23°, respectively. The finite element fracture-implant models are shown in Fig. 3A.

Nine fracture-implant models were imported into the software of ANSYS 17.0 (ANSYS Inc., Canonsburg, PA, USA). The convergence of mesh refinement was checked with the "relevance" option in ANSYS Workbench with a value of −100 indicating a very coarse mesh and 100 corresponding to an extremely fine mesh. A set of simulations showed that a value of 75 will result in convergence, and thus further increasing the relevance will not change the strain values by more than 1 % [19–21]. The mesh of the models was generated using the tetrahedrons element type of C3D4. The mesh size was 2 mm, which was suitable for finite element analysis after convergence study.

The coordinate system for the femur adopted in this study was defined based on the definition by Bergmann et al. [22,23]. Frictional contact interactions were assumed between the different parts of the models. The femur was fixed from the distal end as shown in Fig. 3B. Friction coefficient is 0.46 for bone interactions, 0.3 for bone-implant interactions, and 0.23 for implant-implant interactions [24]. In particularly, the contact relationship between the front end of the helical blade and the femoral head is bonding. And the lock screw was closely connected with the femoral shaft and intramedullary nail [25]. Both the bone and the implant were assumed to be isotropic and linearly elastic. Bone was considered to be homogeneous material, and the femur bone was divided into four types of cortical bone of femur, cancellous bone of femoral head, cancellous bone of femoral neck and cancellous bone of femur shaft. The elastic modulus and Poisson's ratio values were showed in Table 1 [26].The prosthesis of PFNA was considered to be made of medical titanium alloy (Ti–6Al–7Nb) with an elastic modulus of 110 GPa and a Poisson's ratio of 0.33 [26]. Hip joints should meet the requirements of a wide range of activities required in physiological conditions, such as walking, sitting and squatting. Hip joint forces mostly led to higher joint forces than measured, especially for the second half of the stance phase [20,22]. Based on published paper, the models were loaded with a joint contact force and an abductor muscle force as shown in Fig. 3B. The vector force in the XYZ axis direction was listed concretely in Fig. 3B, to simulate the peak loads during the second stance phase of gait [20,22]. A resultant load vector of 1426.5 N corresponded to 238 % for a bodyweight of 60 kg was applied on the femoral head while the abductor force was exerted on the greater trochanter [27].

The maximum displacement of the femoral head and PFNA was often used to quantitatively evaluate the overall stability of the femoral internal fixation system, which can be divided into total displacement and partial displacement in all directions. The total displacement reflected the overall stability of the femoral head or PFNA in the finite element model. Published studies reported that the yield strength was 240.32 MPa for femoral cortical bone, and 700–1000 MPa for titanium alloy (Ti–6Al–7Nb) [28]. In present study,

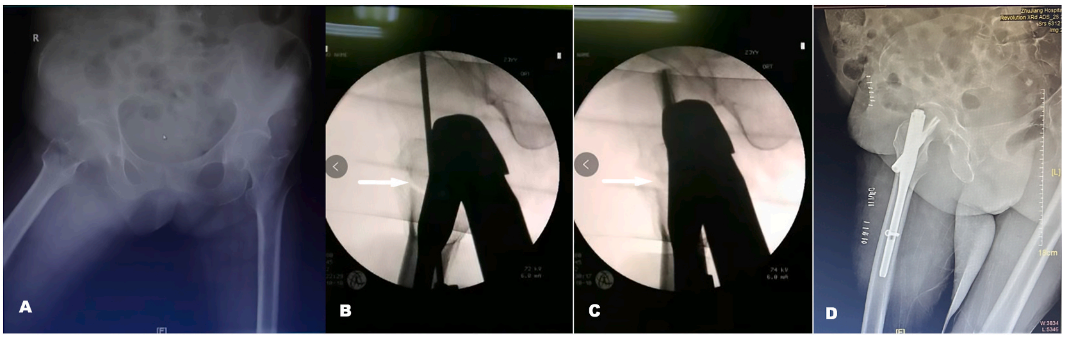

Fig. 2. Case presentation 2: Inadequate reduction with decreased femoral neck ante-version. An 81-y old female patient was presented with right intertrochanteric fracture of 31-AO 1.1. A: The radiographical film of pelvis before PFNA, B and C: Intraoperative fluoroscopy of the hip (decreased femoral neck ante-version was identified using arrow), D: Radiographical film of pelvis after PFNA.

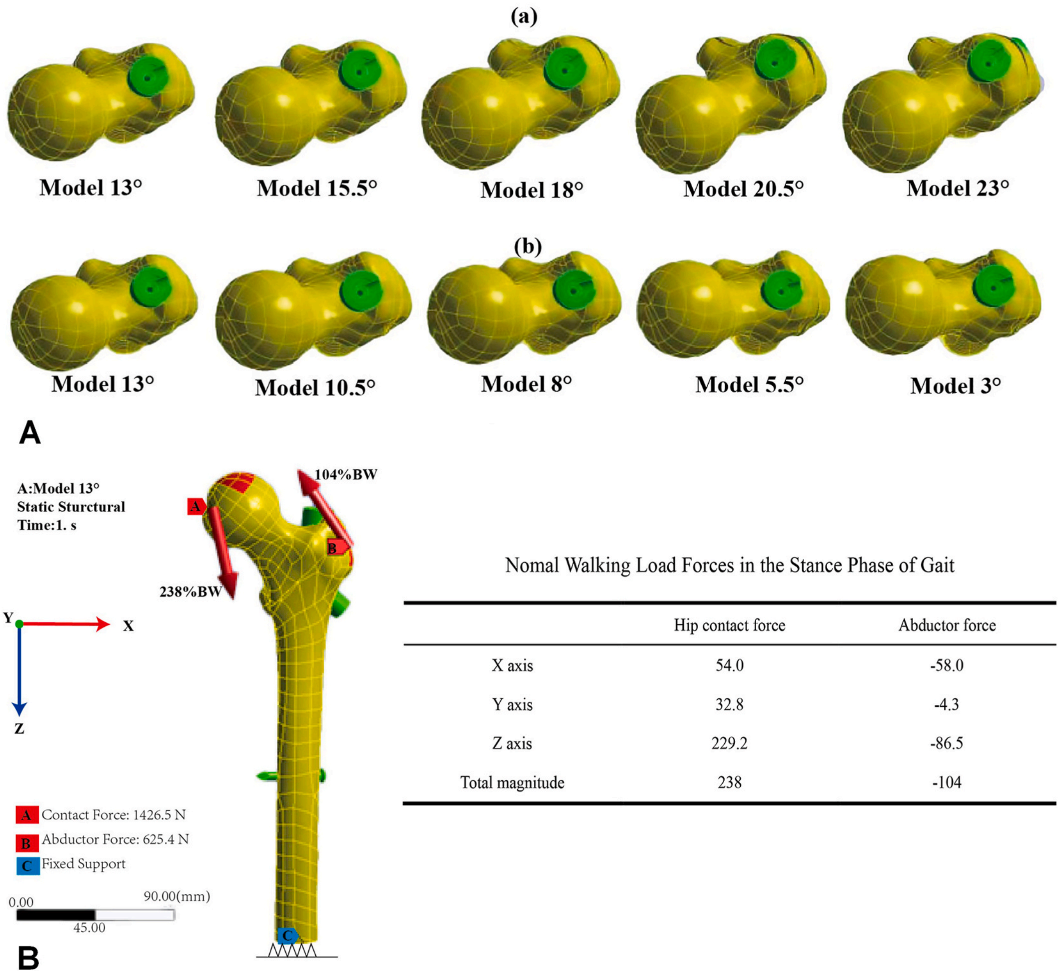

Fig. 3. Nine finite element models with different femoral neck ante-version (3A) and Loading condition and boundary conditions applied to all of the finite element models (3B).

Table 1
Material mechanical properties.

Material	Elastic modulus(MPa)	Poisson's ratio
Cancellous bone of femoral head	840	0.29
Cancellous bone of femoral neck	620	0.29
Cancellous bone of femoral shaft	620	0.29
Cortical bone	16800	0.30

the maximum displacement and the maximum stress were applied to explore the mechanical stability of intertrochanteric fracture treated with PFNA.

3. Results

3.1. Verification of finite element models

One normal femur specimen was selected for biomechanical test (Fig. 4A and B), and same loading and boundary conditions were set. The biomechanical testing machine (BOSE Company, USA) was used to detect and record principle stains of 9 marker points (Table 2). Comparison with the results, our finite model was conformed to the biomechanical study, with correlation coefficient of 0.861 (Fig. 4C and D) and the linear regression equation of $y = -11.01 + 0.91x$. y was defined as the strain values of the biomechanical study, and x was defined as the strain values of finite element method.

Our finite element model was further verified by the published data in the literature. The finite element model of medial wall defect

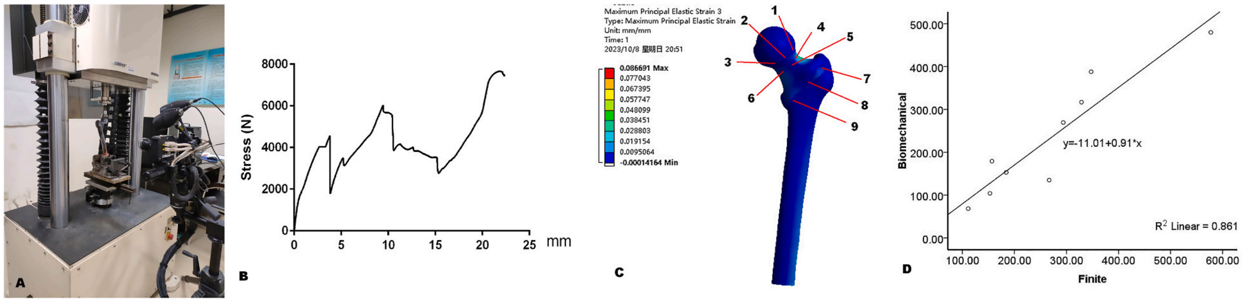

Fig. 4. The validation of the finite element models. A: the biomechanical test; B: The stress-displacement curve of the biomechanical study; C: Finite element model: the position of 9 maker points for correlation analysis; D: The results of correlation analysis between biomechanical study and finite element method.

Table 2
The strain values of the biomechanical test and finite element analysis (10^{-6}).

Make Points	1	2	3	4	5	6	7	8	9
Finite element analysis	293.9	184.2	328.8	347.4	153.1	577.3	266.8	111.3	156.9
Biomechanical study	269.4	153	316.9	387.9	104.1	479.9	135	68.4	179.1

was established, and the data was compared with published paper from femur specimens [29]. The results were comparable between our finite element model and published femur specimen (Table 3).

3.2. The distribution of von Mises stress and displacement of the femur

The distribution plots of the von Mises stress of femurs of nine models were shown in Fig. 5A. The maximum stress of the femurs was mainly concentrated on the medial and lower medial segment of the femoral shaft. As the femoral neck ante-version angle gradually increased from 13° to 23°with a gradient of 2.5°, the peak von Mises stress was gradually increased from 137.82 MPa to 276.02 MPa. Similarly, the peak von Mises stress was gradually increased from 137.82 MPa to 360.12 MPa with the femoral neck ante-version angle decreased from 13° to 3°. The yield strength was 240.32 MPa for femoral cortical bone [28], it was indicated that the decreased ante-version angle was less than 7.5° and increased ante-version angle was no more than 10° to avoid the further femoral fracture. The comparisons of the maximum displacement of the proximal femur head were shown in Fig. 5B. The maximum displacement was shown in the femoral head in all the nine femoral models. As the femoral neck ante-version increased or decreased, the maximum displacement showed a trend of gradual increase. It was indicated that the abnormal ante-version angle reduced the mechanical stability after PFNA fixation for intertrochanteric fracture. The maximum displacement was greater for model 3° (16.307 mm) than model 23° (15.267 mm). The comparison between increased and decreased ante-version angle was presented in Fig. 5C. Significant increased stress was found when the femoral ante-version angle was reduced from 5°(158.8 MPa) to 7.5° (282.03 MPa) (Fig. 5C). The maximum displacement of the femur was significantly reduced for increased ante-version angles than for decreased ante-version angles, whether the changes of ante-version angles were 2.5°, 5°, 7.5° or 10° (Fig. 5C). It was indicated that the mechanical stability of increased ante-version angle was superior to the decreased angle for the intertrochanteric fracture fixed with PFNA. The force-displacement curve of the femur was calculate and presented in Fig. 7A.

3.3. The distribution of von Mises stress and displacement of PFNA

The distribution maps of the von Mises stress of PFNA of nine models shown in Fig. 6A, the maximum von Mises stress was found around the intersection of main nail and helical blade. The stress of the intersection of main nail and helical blade became greater gradually as the ante-version angle increased or decreased with a gradient of 2.5°. For the increased ante-version angle models, the maximum von Mises stress was shown in the model 23°, and the minimum von Mises stress was in the model 13°. For the decreased angle models, the maximum von Mises stress was presented in the model 5.5° with the maximum stress of 724.42 MPa. It was indicated

Table 3
Comparison of the femoral surface strain between the medial femoral defect model and the in vitro specimen experiment (*10^{-6}).

	Our finite model	Published data	t value	p-value
Point a	215.98 ± 39.02	200.17 ± 67.24	0.906	0.416
Point b	646.07 ± 46.47	639.00 ± 93.94	0.340	0.751
Point c	453.07 ± 25.98	456.00 ± 164.06	−0.252	0.813
Point d	1380.38 ± 121.20	1464.17 ± 627.05	−1.546	0.197

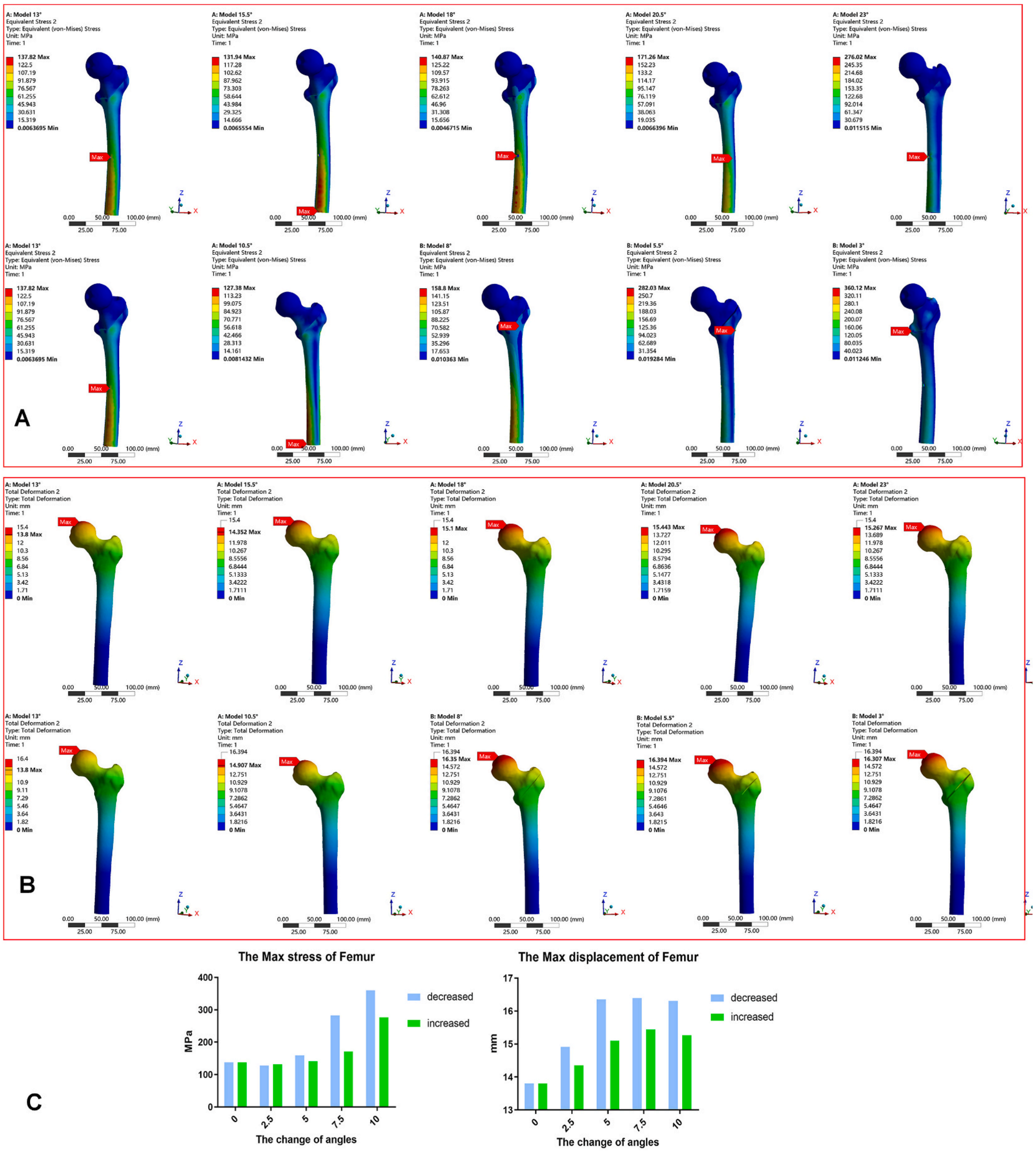

Fig. 5. Distribution plots of the von Mises stress (A) and displacement (B) of femurs of nine models. The comparison of the maximum von Mises stress and the maximum displacement of femur were presented in Figure C.

that the possible breakage of PFNA maybe happen under the ante-version angle decreased 5° as the limit stress of titanium alloy (Ti–6Al–7Nb) of 700–1000 MPa. The comparisons of the maximum displacement of PFNA were shown in Fig. 6B. The maximum displacement was presented in the tip of the blade in all the nine implant models. For the increased ante-version angle models, the maximum displacement was presented in the model 20.5°, and the minimum displacement was in the model 13°. For the decreased angle models, the maximum displacement was presented in the model 5.5° with the maximum displacement of 14.896 mm. The comparison data of nine PFNA models was presented in Fig. 6C. The results of the maximum stress and displacement of PFNA was significantly greater for decreased ante-version angle models than increased ante-version angle models. Significant increased stress was found when the femoral ante-version angle was reduced from 2.5° (456.72 MPa) to 5° (724.42 MPa) (Fig. 6C). The maximum displacement of the PFNA was significantly reduced for increased ante-version angles than for decreased ante-version angles, whether the changes of ante-version angles were 2.5°, 5°, 7.5° or 10°. The force-displacement curve of the PFNA was calculate and presented in Fig. 7B.

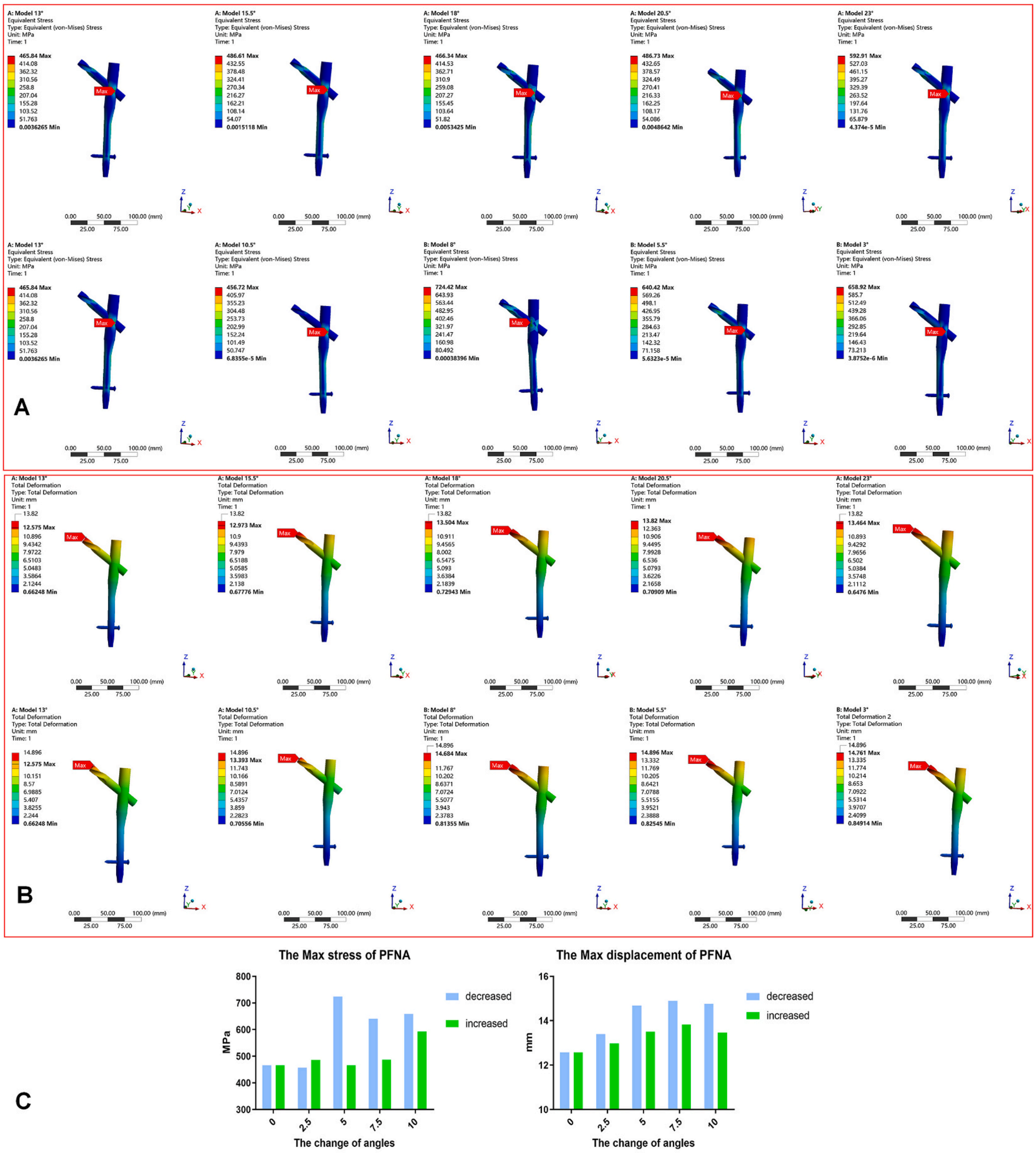

Fig. 6. Distribution plots of the von Mises stress (A) and displacement (B) of PFNA of nine models. The comparison of the maximum von Mises stress and the maximum displacement of femur were presented in Figure C.

4. Discussion

Normal femoral ante-version (FNA), which was the anatomic relationship between the femoral neck axis and the distal femoral condyles, typically ranges from 8∘to 20° in adults [30]. A change in FNA may affect the position of the trochanter and therefore the lever arms of the muscles action surrounding that region. From the point of biomechanical significance, the increased FNA results in a slightly shorter hip extension and abductor lever arm, a longer hip flexion and internal rotation moment arm, and higher hip contact forces during gait [31]. While reduced FNA results in higher shear forces on the junction of femoral neck and head, quantifiable as a 42 % increase of 0° and 86 % of −12.5° compared with the FNA of 12.5° [32]. In clinical practice, excessive femoral ante-version can be connected with hip instability, dislocation, and early degenerative arthritis [7,33,34]. While, decreased femoral version has also been identified as an important factor for femoroacetabular impingement (FAI) [31,35]. The inadequate reduction of femoral ante-version angles (increased femoral neck ante-version in Fig. 1 and decreased neck ante-version in Fig. 2) were found in the process of PFNA for intertrochanteric fracture. There has been little literature published regarding the effect of alterations of femoral neck ante-version angle on bone-implant stability after PFNA fixation for an intertrochanteric fracture.

The effectiveness of finite element model was verified based on the published study [36]; same loading and boundary conditions

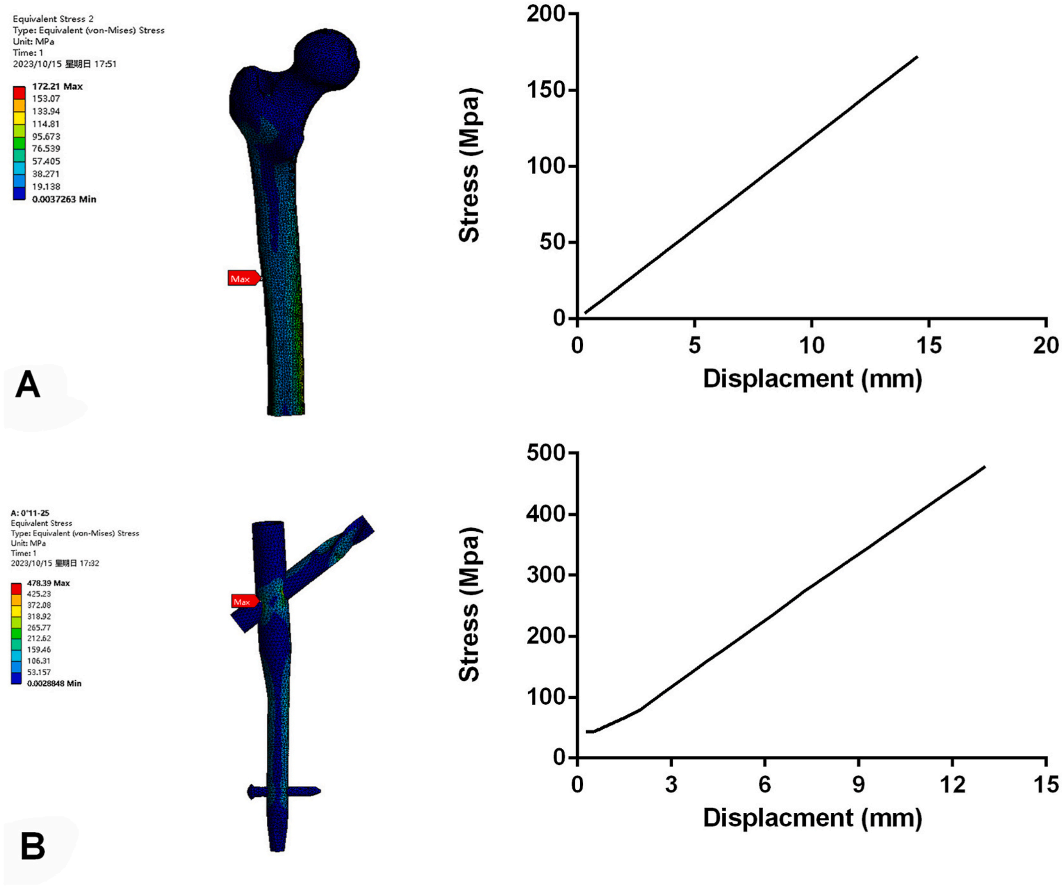

Fig. 7. The force-displacement curve of the femur (A) and PFNA (B) was calculate and presented.

were applied for biomechanical test. The results showed that our finite model was conformed to the biomechanical study, with correlation coefficient of 0.861 and the linear regression equation of $y = -11.1 + 0.91*x$. Also, our finite element model was further verified by the published data in the literature. The finite element model of medial wall defect was established, and the data was compared with published paper from femur specimens [29]. The results were comparable between our finite element model and published femur specimen. Based on the verified model, we aimed to explore the effect of increased or decreased femoral neck ante-version on the mechanical stability of the bone-implant complex. According to the previous studies, the yield strength of cortical bone of human femoral shaft was 240.32 MPa [28]. According to our finite element analysis, when the femoral neck ante-version increased by 10°(model 23°), the peak von Mises stress of medial femoral shaft reached 276.02 MPa; When the femoral ante-version reduced 7.5° (model 5.5°), the maximum von Mises stress of the femur was 282.03 MPa. Both of the two values exceed the yield strength (240.32 MPa) of femoral cortical bone. The results suggested that the decreased femoral ante-version angle should be less than 7.5° and increased femoral ante-version should be no more than 10° to avoid the potential risk of the fracture of femur. The ante-version of 10° was an important boundary data for surgical decision-making. Shu and Safran [37] revealed that variable femoral version (i.e., >10° normal range) can be independently associated with hip instability and degeneration, even in the absence of other conditions such as DDH. Also, Parker et al. [38] demonstrated that ante-version at least 1 standard deviation from the mean (i.e., >10° normal range) was associated with significantly greater Kellgrene Lawrence (KL) scores. The study of Ejnisman et al. [30] demonstrated that hips with femoral version greater than 15° were 2.2 times more likely to have labral tears that extended beyond the 3 o'clock position. In summary, the increased femoral ante-version angle of more than 10° may be associated with the stress concentration of medial femoral shaft, and increase the risk of hip degeneration and labral tears. Moreover, it was worth noting that when the femoral neck ante-version decreased by 5° (model 8°), the peak von Mises stress of 724.42 MPa was found in the intersection of intramedullary nail and helical blade. It was near to the yield strength of medical titanium alloy (700 MPa–1000 MPa) [39]. It was indicated that the decreased femoral neck ante-version should be less than 5° deviation from normal femoral neck ante-version angle for the cases of failure to anatomical reduction. Otherwise, there was potential risk for the breakage of intramedullary device. From the biomechanical viewpoint, if taking weight of patient into account, the potential risk of metal failure may be greater for those with obesity. Tomás-Hernández et al. [40] demonstrated that an insufficient reduction with varus and fracture gaps >5 mm can contribute to the development of delayed or nonunion with subsequent nail breakage. The retroversion of 5° was also an important boundary data in clinical decision-making. The study from Fabricant et al. [41] reported that the femoroacetabular impingement patients with relative femoral retroversion (<5° ante-version) may experience less improvement after arthroscopic surgery than those with normal or increased femoral version in clinical outcomes. To sum up, in terms of stress distribution of femur and PFNA, the mechanical stability of the model 13°with adequate reduction of femoral neck ante-version was optimal. This finding revealed that excessive ante-version reduction of femoral neck (more than 10°) was incline to increase the risk of femoral shaft breakage, and inadequate ante-version reduction of femoral neck (more than 5°) was tended to increase the risk of PFNA breakage. The difference of displacement with the same loading condition indicates the stability of fractured bone-implant construct [39]. Specifically, the maximum total bone deformation reflects the overall stability, while the maximum directional bone deformation along z axis in the coronal plane represents the ability of sustaining compressive pressure. Comparison of the displacement values for all nine models revealed that the mechanical stability of model 13°was optimal on the whole. It was indicated that adequate reduction of femoral neck ante-version was the most important for the intertrochanteric fracture. Also, the total displacement of femur and PFNA was less in the increased femoral neck ante-version compared with the decreased femoral neck ante-version. It was supposed that the increased ante-version of femoral neck had mechanical stability over the decreased ante-version of femoral neck for intertrochanteric fracture after PFNA fixation. The important interpretation of the finding was that increased femoral neck ante-version had an advantage of mechanical stability towards the decreased femoral neck ante-version for the cases of comminuted intertrochanteric fracture and failure of anatomical reduction.

The merit of present study was that the mechanical stability of inadequate reduction of an intertrochanteric fracture fixed with PFNA was systematically and innovatively studied. We proposed that the stability of femoral ante-version was superior to that of the femoral retroversion in the special range of value when the intertrochanteric fracture was fixed with PFNA. It was of great clinical significance to guide the decision-making for the comminuted intertrochanteric fracture and failure of anatomical reduction. This study had several limitations. Firstly, all materials involved in this analysis were deemed as isotropic, homogeneous and linear elastic, which is different from femurs in real life. Up to now, it has remained a problem for similar finite element experiments. However, the above models have been verified with small errors and are within the acceptable range. Secondly, a single healthy femur was selected as a representation of all patients, while in fact a large proportion of intertrochanteric fracture happened to the elderly [9,14]. Some researchers believed that osteoporotic bone could be simulated in finite element analysis software by changing the Young's modulus of bone used in the simulation [42,43]. Lastly, our study was conducted in static conditions to simulate the peak loads during the stance phase of gait. Published studies also reported that the reliability of 238 % body weight (BW) load to the femoral head and an abductor muscle force of 104 % BW, representing the peak loads during the stance phase of a level walking gait [21,23]. A more in-depth investigation would also take into consideration of the relationship between femur version and other more demanding load such as stair climbing and stumbling in future. Also, this study may open the future work to correlation with patient reported outcome measures at different levels of ante-version.

5. Conclusion

Based on the results of present study, it was vital to obtain anatomical reduction of femoral neck ante-version. Abnormal femoral ante-version could increase the potential risk of failure for intertrochanteric fracture after PFNA. It was seemed that increased femoral ante-version (less than 10°) was superior to the decreased ante-version (less than 5°) for the cases of comminuted intertrochanteric fracture and failure of anatomical reduction.

Ethics statement approval and consent to participate

The study was approved by the institutional ethics committee (2022-KY-164-02), and was performed in accordance with the Declaration of Helsinki. The participant has been previously informed about the study, decided to participate in the research and gave their written informed consent.

Data availability statement

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

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CRediT authorship contribution statement

Song-Jian Li: Formal analysis, Data curation. **Hua-Jian Huang:** Software. **Chen-Tian Li:** Formal analysis. **Guo-Ju Hu:** Methodology, Conceptualization. **Fei Yu:** Validation, Funding acquisition. **Yu-Bin Liu:** Writing – review & editing, Writing – original draft.

Declaration of competing 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.

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References

[1] J.A. Kanis, A. Odén, E.V. McCloskey, et al., A systematic review of hip fracture incidence and probability of fracture worldwide, Osteoporos. Int. 23 (9) (2012) 2239–2256.
[2] I. Tabu, E.L. Goh, D. Appelbe, et al., Service availability and readiness for hip fracture care in low- and middle-income countries in South and Southeast Asia, Bone Jt Open 4 (9) (2023) 676–681.
[3] C.L. Cheung, S.B. Ang, M. Chadha, et al., An updated hip fracture projection in Asia: the Asian Federation of Osteoporosis Societies study, Osteoporos Sarcopenia 4 (1) (2018) 16–21.
[4] D. Wirtz, H. Kohlhof, The geriatric patient: special aspects of peri-operative management, EFORT Open Rev 4 (6) (2019) 240–247.
[5] A. Arirachakaran, T. Amphansap, P. Thanindratarn, et al., Comparative outcome of PFNA, Gamma nails, PCCP, Medoff plate, LISS and dynamic hip screws for fixation in elderly trochanteric fractures: a systematic review and network meta-analysis of randomized controlled trials, Eur. J. Orthop. Surg. Traumatol. 27 (7) (2017) 937–952.
[6] R.K. Simmermacher, J. Ljungqvist, H. Bail, et al., The new proximal femoral nail antirotation (PFNA) in daily practice: results of a multicentre clinical study, Injury 39 (8) (2008) 932–939.
[7] C. Kn, N.S. Bhat, M. Zuber, et al., Evolution of different designs and wear studies in total hip prosthesis using finite element analysis, A review 9 (1) (2022) 2027081.
[8] Z. Wang, Y. Liu, S. Li, et al., How to get better TAD? Relationship between anteversion angle of nail and position of femoral neck guide pin during nailing of intertrochanteric fractures, BMC Musculoskelet Disord 21 (1) (2020) 512.
[9] C. Zhang, B. Xu, G. Liang, et al., Optimizing stability in AO/OTA 31-A2 intertrochanteric fracture fixation in older patients with osteoporosis, J. Int. Med. Res. 46 (5) (2018) 1767–1778.
[10] D.G. Eckhoff, R.C. Kramer, C.A. Alongi, et al., Femoral anteversion and arthritis of the knee, J. Pediatr. Orthop. 14 (5) (1994) 608–610.
[11] G. Leblebici, E. Akalan, A. Apti, et al., Increased femoral anteversion-related biomechanical abnormalities: lower extremity function, falling frequencies, and fatigue, Gait Posture 70 (2019) 336–340.
[12] M.J. Kraeutler, V. Chadayammuri, T. Garabekyan, et al., Femoral version abnormalities significantly outweigh effect of cam impingement on hip internal rotation, J Bone Joint Surg Am 100 (3) (2018) 205–210.
[13] J. Wells, J.J. Nepple, K. Crook, et al., Femoral morphology in the dysplastic hip: three-dimensional characterizations with CT, Clin. Orthop. Relat. Res. 475 (4) (2017) 1045–1054.
[14] S.M. Chang, Z.Y. Hou, S.J. Hu, et al., Intertrochanteric femur fracture treatment in Asia: what we know and what the world can learn, Orthop Clin North Am 51 (2) (2020) 189–205.
[15] C. Goldsmith, J. Cheng, D. Mintz, et al., Correlation of femoral version measurements between computed tomography and magnetic resonance imaging studies in patients presenting with a femoroacetabular impingement-related complaint, J Hip Preserv Surg 9 (4) (2022) 219–224.
[16] N.J. Murphy, J. Eyles, L. Spiers, et al., Combined femoral and acetabular version and synovitis are associated with dGEMRIC scores in people with femoroacetabular impingement (FAI) syndrome, J. Orthop. Res. 41 (11) (2023) 2484–2494.
[17] A.J. Curley, B.G. Domb, Editorial commentary: evaluate for the beighton score and additional radiographic signs of instability prior to proceeding with hip arthroscopy in patients with combined borderline hip dysplasia and excessive femoral anteversion, Arthroscopy 39 (4) (2023) 978–980.
[18] M.R. Baumgaertner, S.L. Curtin, D.M. Lindskog, et al., The value of the tip-apex distance in predicting failure of fixation of peritrochanteric fractures of the hip, J Bone Joint Surg Am 77 (7) (1995) 1058–1064.
[19] S. Samiezadeh, P. Tavakkoli Avval, Z. Fawaz, et al., Biomechanical assessment of composite versus metallic intramedullary nailing system in femoral shaft fractures: a finite element study, Clin. Biomech. 29 (7) (2014) 803–810.
[20] I.A. Radcliffe, M. Taylor, Investigation into the effect of varus-valgus orientation on load transfer in the resurfaced femoral head: a multi-femur finite element analysis, Clin. Biomech. 22 (7) (2007) 780–786.
[21] I.A. Radcliffe, P. Prescott, H.S. Man, et al., Determination of suitable sample sizes for multi-patient based finite element studies, Med. Eng. Phys. 29 (10) (2007) 1065–1072.
[22] G. Bergmann, F. Graichen, A. Rohlmann, Hip joint loading during walking and running, measured in two patients, J. Biomech. 26 (8) (1993) 969–990.
[23] G. Bergmann, G. Deuretzbacher, M. Heller, et al., Hip contact forces and gait patterns from routine activities, J. Biomech. 34 (7) (2001) 859–871.
[24] S. Eberle, C. Gerber, G. von Oldenburg, et al., A biomechanical evaluation of orthopaedic implants for hip fractures by finite element analysis and in-vitro tests, Proc. Inst. Mech. Eng. H 224 (10) (2010) 1141–1152.
[25] C. Liang, R. Peng, N. Jiang, et al., Intertrochanteric fracture: association between the coronal position of the lag screw and stress distribution, Asian J. Surg. 41 (3) (2018) 241–249.
[26] P. Helwig, G. Faust, U. Hindenlang, et al., [Biomechanical evaluation of the gliding nail in trochanteric fractures], Z. Orthop. Ihre Grenzgeb. 144 (6) (2006) 594–601.
[27] P.Y. Lee, K.J. Lin, H.W. Wei, et al., Biomechanical effect of different femoral neck blade position on the fixation of intertrochanteric fracture: a finite element analysis, Biomed. Tech. 61 (3) (2016) 331–336.
[28] K. Sitthiseripratip, H. Van Oosterwyck, Sloten J. Vander, et al., Finite element study of trochanteric gamma nail for trochanteric fracture, Med. Eng. Phys. 25 (2) (2003) 99–106.
[29] B. Nie, X. Chen, J. Li, et al., The medial femoral wall can play a more important role in unstable intertrochanteric fractures compared with lateral femoral wall: a biomechanical study, J. Orthop. Surg. Res. 12 (1) (2017) 197.
[30] L. Ejnisman, M.J. Philippon, P. Lertwanich, et al., Relationship between femoral anteversion and findings in hips with femoroacetabular impingement, Orthopedics 36 (3) (2013) e293–e300.
[31] M. Scorcelletti, N.D. Reeves, J. Rittweger, et al., Femoral anteversion: significance and measurement, J. Anat. 237 (5) (2020) 811–826.
[32] T.Q. Lee, G. Morris, R.P. Csintalan, The influence of tibial and femoral rotation on patellofemoral contact area and pressure, J. Orthop. Sports Phys. Ther. 33 (11) (2003) 686–693.
[33] K. Hong, Z. Yuan, J. Li, et al., Femoral anteversion does not predict redislocation in children with hip dysplasia treated by closed reduction, Int. Orthop. 43 (7) (2019) 1635–1642.
[34] K. Chethan, N.S. Bhat, Shenoy BsjijoE, et al., Biomechanics of hip joint, A systematic review 7 (3) (2018) 1672–1676.
[35] A.K. Bhawe, K.M. Shah, S. Somani, et al., Static structural analysis of the effect of change in femoral head sizes used in Total Hip Arthroplasty using finite element method 9 (1) (2022) 2027080.

[36] K. Ding, Y. Zhu, Y. Li, et al., Triangular support intramedullary nail: a new internal fixation innovation for treating intertrochanteric fracture and its finite element analysis, Injury 53 (6) (2022) 1796–1804.
[37] B. Shu, M.R. Safran, Hip instability: anatomic and clinical considerations of traumatic and atraumatic instability, Clin. Sports Med. 30 (2) (2011) 349–367.
[38] E.A. Parker, A.M. Meyer, M. Nasir, et al., Abnormal femoral anteversion is associated with the development of hip osteoarthritis: a systematic review and meta-analysis, Arthrosc Sports Med Rehabil 3 (6) (2021) e2047–e2058.
[39] F. Trevisan, F. Calignano, A. Aversa, et al., Additive manufacturing of titanium alloys in the biomedical field: processes, properties and applications, J. Appl. Biomater. Funct. Mater. 16 (2) (2018) 57–67.
[40] J. Tomás-Hernández, J. Núñez-Camarena, J. Teixidor-Serra, et al., Salvage for intramedullary nailing breakage after operative treatment of trochanteric fractures, Injury 49 (Suppl 2) (2018) S44–s50.
[41] P.D. Fabricant, K.G. Fields, S.A. Taylor, et al., The effect of femoral and acetabular version on clinical outcomes after arthroscopic femoroacetabular impingement surgery, J Bone Joint Surg Am 97 (7) (2015) 537–543.
[42] M. Papini, R. Zdero, E.H. Schemitsch, et al., The biomechanics of human femurs in axial and torsional loading: comparison of finite element analysis, human cadaveric femurs, and synthetic femurs, J. Biomech. Eng. 129 (1) (2007) 12–19.
[43] J.M. Goffin, P. Pankaj, A.H. Simpson, et al., Does bone compaction around the helical blade of a proximal femoral nail anti-rotation (PFNA) decrease the risk of cut-out?: a subject-specific computational study, Bone Joint Res 2 (5) (2013) 79–83.