Fixation effects of different types of cannulated screws on vertical femoral neck fracture
A finite element analysis and experimental study

Zhan, Shi; Jiang, Dajun; Ling, Ming; Ding, Jian; Yang, Kai; Duan, Lei; Tsai, Tsung Yuan; Feng, Yong; van Trigt, Bart; Jia, Weitao

DOI
10.1016/j.medengphy.2021.09.007

Publication date
2021

Document Version
Accepted author manuscript

Published in
Medical Engineering and Physics

Fixation Effects of Different Types of Cannulated Screws on vertical Femoral Neck Fracture: A Finite Element Analysis and Experimental Study

Shi Zhan[a,#], Dajun Jiang[a,#], Ming Ling[a], Jian Ding[b], Kai Yang[c], Lei Duan[d], Tsung-Yuan Tsai[e], Yong Feng[a], Bart van Trigt [f], Weitao Jia[b,*], Changqing Zhang[a,*], Hai Hu[a,*]

[a] Department of Orthopedic Surgery and Orthopedic Biomechanical Laboratory, Shanghai Jiao Tong University Affiliated Sixth People's Hospital, Shanghai, 200233, P.R.China.

[b] Department of Orthopedic Surgery, Shanghai Jiaotong University Affiliated Sixth People's Hospital, Shanghai, 200233, P.R.China.

[c] Radiology Department, Shanghai Jiaotong University Affiliated Sixth People's Hospital, Shanghai, 200233, P.R.China.

[d] State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean & Civil Engineering, Shanghai Jiao Tong University, Shanghai, 200240, P. R. China

[e] Engineering Research Center of Clinical Translational Digital Medicine, Ministry of Education of P.R. China, School of Biomedical Engineering, Shanghai Jiao Tong University, Shanghai, 200030, China.

[f] Department of Biomechanical Engineering, Delft University of Technology, Mekelweg 4, 2628 CD Delft, The Netherlands.

[#] These two authors contributed equally to this work and should be considered co-first authors.

*Corresponding author at: Department of Orthopedic Surgery and Orthopedic Biomechanical Laboratory, Shanghai Jiao Tong University Affiliated Sixth People's Hospital, NO. 600, Yishan Rd., Shanghai, China. Tel: +86 21 24058161. E-mail: xmhuhai@hotmail.com (Hai Hu), jiaweitao@shsmu.edu.cn (Weitao Jia) and zhangcq@sjtu.edu.cn (Changqing Zhang).

Abstract

Femoral neck fractures (FNFs) in young patients usually result from high-energy violence, and the vertical transcervical type is typically challenging for its instability. FNFs are commonly treated with three cannulated screws (CS), but the role of screws type on fixation effects (FE) is unclear. The purpose of this study was to evaluate the FE of ten types of CS with different diameters, lengths, depths, and pitches of thread via finite element analysis which was validated by a biomechanical test. Ten vertical FNF models were grouped, fixed by ten types of CS, respectively, all in a parallel, inverted triangular configuration. Their FE were scored comprehensively from six aspects via an entropy evaluation method, as higher scores showed better results. For partial-thread screws, thread length and thread shape factor (TSF) are determinative factors on stability of FNF only if thread depth is not too thick, and they have less cut-out risk, better compression effects and better detached resistance of fracture than full-thread screws, whereas full-thread screws appear to have better shear and shortening resistance. A combination of two superior partial-thread screws and one inferior full-thread screw for vertical FNF may get optimal biomechanical outcomes. The type of cannulated screw is important to consider when treating vertical FNF.

Keywords:

Vertical femoral neck fracture

Types of screws

Finite element analysis

Biomechanics

Introduction

Femoral neck fractures (FNFs) in young patients usually result from high-energy violence, and the vertical transcervical type is typically challenging for its instability [1, 2]. For these young patients, without osteoporotic bones like elderly patients, internal fixation with multiple cannulated screws (CSs) is often preferred due to several advantages, such as less damage to soft tissue, lower amount of bone removal, less blood loss, ease of operation, and lower cost [3, 4]. Although the clinical outcomes have demonstrated the approach’s efficiency for bone healing [5, 6], the surgical failure rate for vertical FNFs remains high [7, 8]. Surgeons have attempted to modify multiple-screw fixation with regard to the direction, number of screws and configuration to improve its biomechanical properties [9-11]. However, the role of screws type on fixation effects is unclear, and the question of how the use of different types of screws affects the vertical FNF’s biomechanical stability is still open and has increasingly attracted attention [12, 13]. The sliding mechanism of a partial-thread screw (PS) allows linear intraoperative and postoperative compression in the treatment of vFNFs and facilitates fracture healing [14]. However, sliding implants can lead to femoral neck shortening which has been shown to be correlated with reduced quality of life and impaired gait pattern [15]. Consequently, some researchers chose to use full-thread screws in the inferior position to defend against shear stress and to prevent femoral neck shortening [4, 15, 16].

Screws used for vertical FNF are generally cancellous screws, but these vary in diameter, thread length, thread depth, and thread pitch, without a standard clinical guideline. Thus, selecting appropriate screws is crucial for each individual patient, and a biomechanical evaluation of the screws is needed. The purpose of this study is to evaluate the biomechanical fixation effects of different types of screws via

Finite Element Analysis (FEA) and to validate the modelling method by an experimental test. Ten commonly-used types of cannulated screws were employed, including PS and FS. Our goal was to find the pros and cons of different types of screws and help surgeons to better understand the biomechanical properties of screws to make a suitable choice when treating vertical FNF.

Methods

Screw Models

Three-dimensional (3D) models of 10 Synthes and Stryker screws with different lengths, diameters, and threads (Figure 1, Synthes Depuy-Synthes, West Chester, PA, USA; Stryker, Stryker Corporation, Kalamazoo, MI, USA) were created using Solid Works 14.0 (Solid Works Corp, Dassault Systèmes, Concord, MA, USA). Their geometric details were obtained from the manufacturer's surgical guide brochures (Table 1 and Figure 1). These parameters are usually used in screw pull-out study. Among them, thread depth and thread shape factor (TSF) were calculated by the equations as follows [17, 18]:

$$Thead\ depth = \frac{Major\ diameter - Minor\ diameter}{2}$$

$$TSF = 0.5 + 0.57735 \times \frac{Thread\ depth}{pitch}$$

Three parallel screws with inverted triangular configuration were selected for fixation of FNF [9], among which, two cannulated screws (90 mm in length) were in the proximal region, and one screw (100 mm in length) was in the distal region. The distance between the anterior end of the screw and the subchondral bone was approximately 5 mm. The models of all screws were stored in IGES format.

Femur Model

The model of a Sawbone femur (Model 3402, 4th Generation Sawbone, Vashon, WA, USA) was created from computed tomography (CT) scans [2]. CT data (0.6 mm in thickness, DICOM format) were imported into Mimics 20.0 (Materialise NV, Leuven, Belgium) to create a 3D model. The model was then imported into Hypermesh 14.0 (Altair Engineering, Inc., Detroit, MI, USA) for meshing (1 mm in length). Based on the meshed model (Figure 2a), the characteristics of the proximal femur--including the femoral head center (FHC), femoral neck axis (FNA), femoral shaft axis (FSA) [20], and narrowest surface (NS)--were calculated using customised Matlab programs (MathWorks, Natick, MA, USA). The narrowest surface was defined as the smallest area across the femoral neck (Figure 2b). The femoral neck axis and thread center (defined as the point at which the screw axis intersected with the narrowest surface) were used to determine the proper orientation and location for the three screws. The femoral head center, femoral shaft axis, femoral medial condyle, and lateral condyle were used to create a vertical FNF surface with a modified Pauwels angle of 70° (Figure 2c) [2, 21, 22]. The Pauwels angle was measured by using a modified method described in the previous study [21].

Assembly of Components

Three same types of screws were inserted into the fractural femur along the direction of the femoral neck axis and were ensured not to pass through the neck cortex. Ten FNF structures fixed with 10 types of screws were created from the femur model via a Boolean operation in 3-Matic 11.0 ((Materialise NV, Leuven, Belgium). The distal parts of femur were cut off, leaving the proximal parts for further analysis [2].

FEA Meshing and Material Properties

The screws and femur model were imported into Hypermesh 14.0 for meshing with a mesh size of 1 mm, based on the convergence test of the proximal femur in the previous article [22, 23]. The number of nodes (ranging from 174,389 to 272,700) and elements (ranging from 800,108 to 1,242,898) for all models was recorded. A 4-node tetrahedron body element (C3D4) was used for the bone and screws according to previous studies [2, 22]. The properties of the Sawbone femur were linear, elastic, and isotropic. Young's moduli (E) was 16.7 and 0.155 GPa for cortical and cancellous bones, respectively, and Poisson's ratio (v) of 0.3 was assumed for both of them, while the screws were modelled as medical grade titanium steel (E = 110 GPa, v = 0.33) [2].

FEA Boundary Conditions

The combined models were imported into Abaqus 6.14 (Dassault Systemes Simulia Corp., Johnstone, RI, USA) for static simulation. The slipping friction factor of the bone-block interface was set to 0.46 while the corresponding factor for the interface of the bone and screws was set to 0.3 [2, 22]. To ensure consistency with later validation experiments, the contact zone between the axial loading platen and the femur head was set as one reference point, together with a small zone of nodes on the head. Freedom of the distal femur (108 mm in length) was restrained in the simulation tool, which is the same as the setup in the validation experiments. Movement restrictions were assigned for the cortical faces of the femoral distal region (Figure 2d). A force of 2000 N along the femoral shaft, similar to the previous study [2], was applied to the face of the loading platen. To simulate the compression effects (CE) of partial-thread screws in FNF fixation, a pre-tension force of 230 N [19, 22] was applied to each screw. Full-thread screws do not add pre-tension force because of their non-pressurising capacity.

Validation Experiments

A Sawbone femur as same as that in the FE model was fixed with three parallel screws (6.5 mm in diameter) in an inverted triangular configuration. A 3D printing guide plate, as in previous studies [4, 12 22], was employed to ensure the fracture line was created exactly from the femoral neck to the lesser trochanter and the screws were inserted in the appropriate position (Figure 3a). Screws' anteroposterior and lateral views were obtained by using fluoroscopy to validate they were in the right position (Figure 3b and c). The femoral distal end was trimmed with a band saw on the medial, lateral, and posterior sides to keep the final working length of the distal femur within 108 mm, and then potted into a square steel cube filled with anchoring cement (Die-Stone, Heraeus Kulzer Dental Ltd Company, Hanau, Germany). The strain on femur surface during compression was measured via VIC-3D (XR-9M, Correlated Solutions Company, Westford, MA, USA), based on the theory of digital image correlation [22, 24, 25]. And then, stress on femur outface was calculated from strain via inputting femur cortical Young's moduli and Poisson's ratio (16.7GPa &0.3) into VIC-3D [26] for validating FEA modelling method. The fixed femur was positioned with 15° of adduction in the frontal plane and aligned vertically in the sagittal plane to replicate the single-legged mid-stance phase of gait (Figure 3d) [27, 28]. As in a previous study [29], an axial force (i.e. vertical force, similar to the FE models) was applied to the top of the femur head utilising displacement control (linear waveform, max force=2000N, rate=2mm/min, preload=10N). The force was approximately three times the body weight of an adult (70 kg), which reflects the situation during daily walking activities. Testing was performed three times in an Instron 5569 mechanical tester (Instron Corp., Canton, MA, USA), and the VIC-3D camera began capturing as soon as the loading platen contacted the femur head.

FEA and Statistical Analysis

Six parameters, reflecting six biomechanical aspects, were calculated to analyse the fixation effects of FNF with regard to the major internal fixation failure risk [30] as follow: stiffness, bone cutting rate (BCR), cut-out risk (COR), compression effects (CE), shear resistance of fracture (FSR), and detached resistance of fracture (FDR) (Table 2).

The fixation effects of the models were rated based on these six parameters (the best model of a certain parameter rated 10, the worst rated 1). These six parameters might be all important to estimate the fixation effects of FNF, but in different aspects. Thus, an objective entropy evaluation method (EEM) [31, 32] was adopted to assess the weight coefficients (WC) of each parameter according to their entropy redundancy (ER) in this study. 10 models need to be evaluated and 6 evaluation parameters need to be weighted; thus, the original data matrix is:

$$X = \left(x_{ij}\right)_{m \times n}$$

Where m = 10 and n = 6.

The WC of each parameter can be calculated by the following formula according to a previous study [32]:

$$WC_j = \frac{1 - ER_j}{\sum_{j=1}^{n}\left(1 - ER_j\right)} (j = 1,2, \dots n)$$

Where the ER_j is calculated as follows:

$$ER_j = -\frac{1}{\ln m}\sum_{i=1}^{m} p_{ij} \ln p_{ij}$$

$$p_{ij} = r_{ij} / \sum_{i=1}^{m} r_{ij}$$

Where the p_{ij} is the probability of each parameter. If $p_{ij} = 0$, we can define $\lim_{p_{ij} \to 0} p_{ij} \ln p_{ij} = 0$. r_{ij} is the standard values of each parameter of ith sample, which can be calculated as follows:

$$r_{ij} = \frac{x_{ij} - \min_i\{x_{ij}\}}{\max_i\{x_{ij}\} - \min_i\{x_{ij}\}}$$

The scores for all models were then multiplied by the WC to obtain the total score (EEM Score). The EEM Score and the Average Score (WC of each parameter assumed to be equal) for all parameters were used to determine the fixation effects of FNF.

The models were divided into two groups according to their compression ability: the partial-thread

Group (PG) and full-thread Group (FG). For statistical analysis, linear regression was used to evaluate the presence of a linear correlation between the experimental and FEA results, and independent sample T-tests were used to compare the fixation effects between PG and FG. P-values less than 0.05 was considered as statistically significant.

Please attach Figure 1 here

Please attach Figure 2 here

Please attach Figure 3 here

Please attach Table 1 here

Please attach Table 2 here

Results

Validation of the Modelling Method

To validate the modelling method for 2000N of axial force on the femur with 15° of adduction, the Von Mises stress of FEA and the experimental results were compared with linear regression (Figure 4). The slope was 0.45 and the linear correlation coefficient was 0.90, indicating a strong correlation between FEA and the experimental results. Therefore, the FE modelling method is reliable for comparing the fixation effects among different screws.

FEA Results

Among the 10 screw models (Table 3), Model S1 was the most stiff (1993.5 N/mm, rated 10), whereas Model A4 was the least stiff (1566.4 N/mm, rated 1). The average stiffness of the PG models (Figure 5) was 1810.70±141.66 N/mm, greater than that of the FG models (1710.88±73.41 N/mm), but without statistical significance ($p = 0.25$).

The lowest BCR was found in Model A5 (4.44%, rated 10) and the highest was in Model A4 (8.76%, rated 1). The average BCR in PG (6.39±0.79%) was not statistically different ($p = 0.63$) from that in FG (5.95±1.59%).

Model S2 had the lowest COR (6.79 MPa, rated 10), whereas Model S3 had the highest (17.14 MPa, rated 1). The average COR in PG (8.87±1.52 MPa) was significantly lower than that in FG (16.08±0.61 MPa) ($p < 0.01$).

The CE for Model A3 was the best (5.40 MPa) with a score of 10, whereas that for Model A5 was the worst (0.87 MPa, rated 1). The average CE in PG (4.81±0.89 MPa) was much better than that in FG (1.77±0.67 MPa) ($p < 0.01$).

The FSR for Model S4 (1.07E-01 mm) was the smallest among the models (rated 10), whereas the FSR for Model A1 (2.40E-01 mm) was the largest (rated 1). The average FSR in PG was 1.96E-01±3.01E-02 mm, significantly larger than that in FG (1.29E-01±1.78E-02 mm) ($p < 0.01$).

Model S1 had the strongest FDR (6.36E-03 mm, rated 10), while Model A4 had the weakest (5.11E-02 mm, rated 1). The average FDR in PG (6.93E-03±3.53E-04 mm) was significantly ($p < 0.01$) less than that in FG (3.96E-02±6.35E-03 mm).

Model S1 had the highest EEM Score (8.23) in PG as well as the highest score across all models (Figure 6a). Model A1 had the lowest EEM Score in PG (5.07), which was inferior to Model S4 and A6 (5.79 & 5.22) and better than those of the other models in FG. The average EEM Score in PG (6.57±1.05) was significantly larger ($p = 0.03$) than that in FG (4.43±1.24) (Figure 6b). After adjusting the weight coefficient of each parameter to equal, the Average Score for Model S1 remained the highest (8.00) across all models. Model A1 still had the lowest score in PG (4.50), which was better than scores of A4 and S3 and worse than those of the other screws in FG. Although the Average Score of PG (6.37±1.21) was greater than that of FG (4.63±1.25), there were no significant differences between them ($p = 0.08$) (Table 4).

Please attach Figure 4 here

Please attach Figure 5 here

Please attach Figure 6 here

Please attach Table 3 here

Please attach Table 4 here

Discussion

Despite previous studies mostly focused on the direction, number and the configuration of screws for vertical femoral neck fractures (FNFs) of young patients, the types of screws used on fixation is also an important factor which could affect the biomechanical characters and clinical outcomes. However, there still lacks of consensus on types of screws in clinical practice [4]. Our study has shown that different type of screws had its cons and pros biomechanically (Figure 6), and suggested that a better choice of screw types may improve the biomechanics of the bone-screw composite structure for vertical FNF in young patients.

Ten commonly-used types of screws including partial-thread screws and full-thread screws were chosen in this study, which had diameters ranging from 6.5 mm to 8.0 mm with thread lengths, thread depths, and pitches varied, representing most commonly-used screws in clinical practice. And six biomechanical parameters were employed in this study, namely stiffness, BCR, COR, CE, FSR and FDR (Table 2), representing different biomechanical aspects of the fixation effects [30]. In order to evaluate fixation effects thoroughly, we attempted to combine these six parameters together. However, to the best of our knowledge, there are no previous studies weighting the importance of these parameters. Therefore, entropy evaluation method (EEM) [31, 32] was chosen in this study to objectively weight importance of each parameter. This method was originally a concept of thermodynamics, which was first added into the information theory by C.E.S Hannon, and it is now applied widely in the fields of engineering technology [32]. Based on the basic principle of information theory, the information is a measure of system orderly degree, but the entropy is a measure of the system's disorder. The smaller the information entropy of the indicators (ER, entropy redundancy) is, the larger the amount of information provided by indicators. This will also make the role played in the comprehensive evaluation more important and mean the weight coefficient should be higher. The opposite is also true. To confirm whether EEM was suitable to represent the weight coefficients of each parameter, the Average Score with all six parameters given equal weight was also calculated. The results based on Average Score showed that the best two screws were S1 and A3 and the worst was A4, same to results based on EEM (Table3), though the Average Score in the partial-thread screws Group (PG) was not significantly higher than that of the full-thread screws Group (FG) (Table4).

Based on EEM, the fixation performance of PG (6.57±1.05) was significantly ($p = 0.03$) better than that of FG (4.43±1.24) (Figure 6b). The advantage of partial-thread screws was evidenced by lower COR, higher CE, and better FDR, as shown in Figure 5. However, FG showed excellent performance in protecting the FNF from shear movement. The different advantages of the PG and FG indicated that combination of both screw types would be beneficial. According to previous studies [4, 33], for unstable femoral neck fractures (Pauwels Type III), optimal results were obtained by stabilizing the fracture with a combination of inferior full-thread screws and superior partial-thread screws due to their distinct biomechanical characters. In addition, cannulated screws in an inverted triangle configuration can achieve better clinical outcomes compared to the regular triangle one [9]. Consequently, we hypothesized that the combination of one full-thread screw positioned inferiorly to resist shear deforming force and two partial-thread screws placed superiorly to provide adequate compression and eliminate the gap between fragments may get optimal fixation effects. In clinical practice, partial-thread screws are usually used first and then full-thread screws so that the compressive effects will not be affected. This hypothesis will be tested in the future. Furthermore, Screw S1 had the highest EEM Score of 8.23, with the best stiffness (1993.5 N/mm, rated 10) and FDR (6.36E-03 mm, rated 10); excellent CE (5.31 MPa, rated 9), BCR (5.54%, rated 7), and COR (10.12 MPa, rated 7); and moderate FSR (1.62E-01 mm, rated 5). With these rates, Screw S1 showed the best fixation effect in the PG, and even across all models (Figure 5), while Screw A3 rated second. In contrast, Screw A1, with the shortest thread and thinnest diameter, had the lowest EEM Score of 5.07, indicating the poorest fixation performance for vertical FNF in the PG.

Why S1 performed better fixation effect than A2 and A3 within the PG? We found S1 had longer thread length (20mm) than A2 and A3 (16mm), although TSF of S1 (0.68) is smaller than that of A2 and A3 (0.76), which indicated sufficient thread length without crossing the fracture line can increase the surface area of the threads in contact with the cancellous bone of the femoral head [32] and lead to a better fixation effect. Comparing A1, A2, and A3, all in the same thread lengths, A2 and A3 with bigger TSF of 0.76, show better fixation performance than A1 (TSF of 0.68). However, the thread length and TSF are determinative factors on stability of FNF only if the thread depth of the screw is not too thick. For instance, although S2 has the longest thread length (25mm) and largest thread shape factor (0.81), which should have had the best pull-out strength [17, 18], it did not achieve the best fixation performance for FNF in the PG with only a score of 6.49 (Table 3). This could be explained by the fact that the too thick thread depth (1.50mm) kept the screw's stem far from the support of the cortical layer, which are very important for supporting the screws biomechanically [35], and eventually reducing the fixation effect of FNF. On the other hand, within the FG, Screw S4, whose geometrical parameter (TSF of 0.81) should be associated with the best pull-out strength, indeed had the best performance in vertical FNF fixation (score 5.79) with the best FSR and relative better BCR, COR and FDR. Unlike S2 in the PG, for full-thread screws, the support from the cortical layer was not negatively affected by the thread depth because the thread covers the entire stem in the FG and lead to the screws always receive support from the cortical layer. Furthermore, the COR of S3 and A4 who had the smallest diameters (6.5mm), were the worst (rated 1&2), implying that a thinner full-thread screw may enhance the risk of cutting out from the femoral head. All screws in the FG had better FSR and lower CE than those in the PG (Table3), which provides evidence supporting the recent suggestion to include full-thread screws during multiple-screw fixation in vertical FNF [12, 15, 33].

As to the method in this study, we chose Finite Element Analysis (FEA) because it has advantages to achieve ideal reduction of fragments and put screws in a specific position which is hard in reality. Also, direct comparison could be done in the same femur in this way [2]. An experimental test was designed to validate our modelling method, in which a 3D printing guide template was used to keep three screws in same direction, at same location and with same configuration. Thus, variation between FEA and test was minimised. Comparison between FEA and experimental test (Figure 4) showed that the Von Mises stress value obtained with FEA was lower than that obtained with the experimental tests (slope = 0.45), but the correlation coefficients were consistent (R = 0.9). The lower slope may be due to the C3D4 mesh type we used, as reported by Simonovski [36], and be due to the simplification of bone material properties and inhomogeneity in FEA. However, the correlation coefficient between results of FEA and the experimental test was nearly the same as the values in other studies (R = 0.78-0.96) [22, 37]. Thus, the modelling method is effective for comparing the biomechanical fixation effects of FNF models. Moreover, the reason we used Sawbone but not cadaver in the validated experiment is because Sawbone has been confirmed to be a suitable replacement of cadaver [38].

There are still some limitations in this study. One is that we used 4-node linear tetrahedron body element (C3D4) instead of 10-node quadratic tetrahedron body element (C3D10) to save analysis time. However, it is reliable enough in this study, as it showed a higher correlation with the experimental test (R = 0.9). The other limitation is that we were unable to obtain more types of screws from the market. For instance, we lack screws with thread length of 16 mm and major diameters of 8.0mm, and screws with thread length of 25 mm and major diameters of 7.3/7.0/6.5 mm, which could have been employed for better comparisons. Nonetheless, the current study had uncovered enough biomechanical properties for the different types of screws evaluated. In addition, the material property of synthetic bone is relatively simplified compared to human bone, which could lead to a few differences in real-world applications. However, since Sawbone femora were commonly used in previous studies for being highly consistent with human bones [2, 38], the analysis of this study could still reflect the real-world clinical biomechanical conditions.

Conclusions

The fixation performance of partial-thread screws was significantly better than that of full-thread screws. However, full-thread screws showed excellent performance in protecting the FNF from shear and shortening movement. A combination of two superior partial-thread screws and one inferior full-thread screw for vertical FNF may get optimal biomechanical outcomes. For partial-thread screws, the thread length and TSF are determinative factors on stability of FNF only if the thread depth of the screw is not too thick. Whereas, the thread depth of full-thread screws does not affect the fixation effects on FNF significantly. Moreover, thinner full-thread screws may be associated with high cut-out risk from the femoral head. The type of cannulated screw is important to consider when treating vertical FNF.

Conflicts of interests: The authors are not compensated and there are no other institutional subsidies, corporate affiliations, or funding sources supporting this work unless clearly documented and disclosed.

Funding: This study was sponsored by the National Natural Science Key Foundation of China (61731009); National Natural Science Foundation of China(81572105, 31270996); Project introduction Shanghai Municipal Education Commission-Gaofeng Clinical Medicine Grant Support (20172026); Funding project for talent development in Shanghai (2017035); Interdisciplinary Program of Shanghai Jiao Tong University (YG2017QN14); Funding project of Shanghai Sixth People's Hospital (ynlc201617).

Ethics approval and consent to participate: Not required

Acknowledgements: The authors gratefully acknowledge for language polishing support from Dr. Peter B. Shull who is an Associate Professor in mechanical engineering with Shanghai Jiao Tong University.

References

[1] Kyle, Richard F. Operative techniques of fixation for femoral neck fractures in young adults. Tech Orthop 1986; 1(1):33-8. https://doi.org/10.1097/00013611-198604000-00008.

[2] Zhan S, Jiang D, Xu J, Ling M, Yang K, Li Y, et al. Influence of the proximal screws of buttress plates on the stability of vertical femoral neck fractures: a finite element analysis. BMC Musculoskelet Disord 2020; 21(1):842. https://doi.org/ 10.1186/s12891-020-03853-7.

[3] Duffin M, Pilson HT. Technologies for Young Femoral Neck Fracture Fixation. J Orthop Trauma 2019; 33:S20-6. https://doi.org/10.1097/BOT.0000000000001367.

[4] Zhang B, Liu J, Zhu Y, Zhang W. A new configuration of cannulated screw fixation in the treatment of vertical femoral neck fractures. Int Orthop 2018; 42(8):1949-55. https://doi.org/ 10.1007/s00264-018-3798-x.

[5] Guimarães JAM, Rocha LR, Noronha Rocha TH, Bonfim DC, Costa, R, Amanda, D. Vertical femoral neck fractures in young adults: a closed fixation strategy using a transverse cancellous lag screw. Injury 2017; 48:S10-6. https://doi.org/10.1016/S0020-1383(17)30769-6.

[6] Ma JX, Kuang MJ, Xing F, Zhao Yl, Chen HT, Zhang LK, et al. Sliding hip screw versus cannulated cancellous screws for fixation of femoral neck fracture in adults: A systematic review. Int J Surg 2018; 52:89-97. https://doi.org/10.1016/j.ijsu.2018.01.050.

[7] Liporace, Frank. Results of Internal Fixation of Pauwels Type-3 Vertical Femoral Neck Fractures. J Bone Joint Surg Am 2008; 90(8):1654-9. https://doi.org/10.2106/00004623-199401000-00003.

[8] Lu-Yao GL, Keller RB, Littenberg B, Wennberg JE. Outcomes after displaced fractures of the femoral neck. A meta-analysis of one hundred and six published reports. J Bone Joint Surg Am 1994; 76(1):15-25. https://doi.org/10.1055/s-2005-919113.

[9] Yang JJ, Lin LC, Chao KH, Chuang SY, Wu CC, Yeh TT, et al. Risk factors for nonunion in patients with intracapsular femoral neck fractures treated with three cannulated screws placed in either a triangle or an inverted triangle configuration. J Bone Joint Surg Am 2013; 95(1):61-9. https:// 10.2106/JBJS.K.01081.

[10] Jiang D, Zhan S, Cai Q, Hu H, Jia W. Long-term differences in clinical prognosis between crossed- and parallel-cannulated screw fixation in vertical femoral neck fractures of non-geriatric patients. Injury 2021. https://doi.org/10.1016/j.injury.2021.07.014.

[11] Jiang D, Zhan S, Cai Q, Hu H, Jia W. Enhanced interfragmentary stability and improved clinical prognosis with use of the off-axis screw technique to treat vertical femoral neck fractures in nongeriatric patients. J Orthop Surg Res 2021; 16(1):473. https://doi.org/10.1186/s13018-021-02619-8.

[12] Zhang B, Jingwen L, Wei Z. Ordinary Cannulated Compression Screws or Headless Cannulated Compression Screws? A Synthetic Bone Biomechanical Research in the Internal Fixation of Vertical Femoral Neck Fracture. Biomed Res Int 2018; 2018:4898301. https://doi.org/10.1155/2018/4898301

[13] Parker MJ, Ali SM. Short versus long thread cannulated cancellous screws for intracapsular hip fractures: A randomised trial of 432 patients. Injury 2010; 41(4):382-4. https://doi.org/10.1016/j.injury.2009.10.008.

[14] Nishiyama D, Matsumoto T, Hamazaki H: The treatment of femoral neck fractures: results using cephalocervical screws with sliding mechanism. Eur J Orthop Surg Traumatol 2013; 23(8):907-11. https://doi.org/10.1007/s00590-012-1103-z.

[15] Weil YA, Qawasmi F, Liebergall M, Mosheiff R, Khoury A: Use of fully threaded cannulated screws decreases femoral neck shortening after fixation of femoral neck fractures. Arch Orthop Trauma Surg 2018; 138(5):661-7. https://doi.org/10.1007/s00402-018-2896-y

[16] Boraiah S, Paul O, Hammoud S, Gardner MJ, Helfet D L, Lorich DG. Predictable Healing of Femoral Neck Fractures Treated With Intraoperative Compression and Length-Stable Implants. J Trauma 2010; 69(1):142-7. https://doi.org/10.1097/ta.0b013e3181bba236.

[17] Chapman JR, Harrington RM, Lee KM, Anderson PA, Tencer AF, Kowalski D. Factors affecting the pullout strength of cancellous bone screws. J Biomech Eng 1996;118(3):391-8. https://doi.org/10.1115/1.2796022.

[18] Asnis SE, Ernberg JJ, Bostrom MPG, Wright TM, Peterson M. Cancellous Bone Screw Thread Design and Holding Power. J Orthop Trauma 1996;10(7):462-9. https://doi.org/10.1097/00005131-199610000-00003.

[19] Taylor BC, Litsky AS, Pugh KJ, Fowler TT: Biomechanical Evaluation of 6.5-mm Cannulated Screws. J Surg Orthop Adv 2016; 25(1):8-12.

[20] Dimitriou DTT, Yue B, Rubash HE, Kwon YM, Li G. Side-to-side variation in normal femoral morphology: 3D CT analysis of 122 femurs. Orthop Traumatol Surg Res 2016; 102(1): 91-7. https://doi.org/10.1016/j.otsr.2015.11.004.

[21] Wang SH YJ, Shen HC, Lin LC, Lee MS, Pan RY. Using a modified Pauwels method to predict the outcome of femoral neck fracture in relatively young patients. Injury 2015; 46(10):1969-74. https://doi.org/10.1016/j.injury.2015.06.016.
[22] Jiang D, Zhan S, Wang L, Shi LL, Ling M, Hu H, et al. Biomechanical comparison of five cannulated screw fixation strategies for young vertical femoral neck fractures. J Orthop Res 2020. https://doi.org/ 10.1002/jor.24881.
[23] Hölzer A, Schröder C, Woiczinski M, Sadoghi P, Scharpf A, Heimkes B, et al. Subject-specific finite element simulation of the human femur considering inhomogeneous material properties: a straightforward method and convergence study. Comput Methods Programs Biomed 2013; 110(1):82-8. https://doi.org/ 10.1016/j.cmpb.2012.09.010.
[24] Grassi L, Väänänen SP, Ristinmaa M, Jurvelin JS, Isaksson H. How accurately can subject-specific finite element models predict strains and strength of human femora? Investigation using full-field measurements. J Biomech 2016; 49(5):802-6. https://doi.org/ 10.1016/j.jbiomech.2016.02.032.
[25] Grassi L, Väänänen SP, Yavari SA, Jurvelin JS, Weinans H, Ristinmaa M, et al. Full-field strain measurement during mechanical testing of the human femur at physiologically relevant strain rates. J Biomech Eng 2014;136(11):111010. https://doi.org/10.1115/1.4028415.
[26] Sadd MH. Elasticity: Theory, applications, and numerics. Aaee 2014; 191(9):1843–60. https://doi.org/10.1119/1.2341427.
[27] Talbot M, Zdero R, Garneau D, Cole PA, Schemitsch EH. Fixation of long bone segmental defects: A biomechanical study. Injury 2008; 39(2):181-6. https://doi.org/10.1016/j.injury.2007.08.026.
[28] Heiner AD. Structural properties of fourth-generation composite femurs and tibias. J Biomech 2008; 41(15):3282-4. https://doi.org/10.1016/j.jbiomech.2008.08.013.
[29] Goffin JM, Pankaj P, Simpson AHRW, Seil R, Gerich T. Does bone compaction around the helical blade of a proximal femoral nail anti-rotation (PFNA) decrease the risk of cut-out?. Bone Joint Res 2013; 2(5):79-83. https://doi.org/10.1302/2046-3758.25.2000150.
[30] Estrada LS, Volgas DA, Stannard JP, Alonso JE. Fixation Failure in Femoral Neck Fractures. Clin Orthop Relat Res 2002; 399:110-8. https://doi.org/10.1097/00003086-200206000-00013.
[31] Zou ZH, Yi Y, Sun JN. Entropy method for determination of weight of evaluating indicators in fuzzy synthetic evaluation for water quality assessment. J Environ Sci 2006; 18(5):1020-3. https://doi.org/10.1016/s1001-0742(06)60032-6.
[32] Zhang H. Application on the entropy method for determination of weight of evaluating index in fuzzy mathematics for wine quality assessment. Adv J Food Sci Technol 2015; 7(3):195-8. https://doi.org/ 10.19026/ajfst.7.1293.
[33] Li J, Wang M, Li L, Zhang H, Hao M, Li C, et al. Finite element analysis of different configurations of fully threaded cannulated screw in the treatment of unstable femoral neck fractures. J Orthop Surg Res 2018; 13(1):272. https://doi.org/ 10.1186/s13018-018-0970-3.
[34] Liu C, Keudell AV, McTague M, Rodriguez kE, Weaver MJ. Ideal length of thread forms for screws used in screw fixation of nondisplaced femoral neck fractures. Injury 2019; 50(3):727-32. https://doi.org/10.1016/j.injury.2019.01.036.
[35] Hoffmann JC, Kellam J, Kumaravel M, Clark K, Gary JL. Is the Cranial and Posterior Screw of the "Inverted Triangle" Configuration for Femoral Neck Fractures Safe? J Orthop Trauma 2019; 33(7):331-4. https://doi.org/10.1097/BOT.0000000000001461.
[36] Simonovski I, Cizelj L, Jaki N. The influence of finite element meshes on the results of a spatial polycrystalline aggregate model[J]. Nuclear Engineering & Design, 2011; 241(4):1184-90.

https://doi.org/10.1016/j.nucengdes.2010.05.063.
[37] Coquim J, Clemenzi J, Salahi M, Sherif A, Avval PT, Shah S, et al. Biomechanical analysis using FEA and experiments of metal plate and bone strut repair of a femur midshaft segmental defect. BioMed Res Int 2018; 2018:1-11. https://doi.org/10.1155/2018/4650308.
[38] Papini M, Zdero R, Schemitsch EH, Zalzal P. The biomechanics of human femurs in axial and torsional loading: comparison of finite element analysis, human cadaveric femurs, and synthetic femurs. J Biomech Eng 2007; 129(1):12-9. https://doi.org/10.1115/1.2401178.

Figure 1. Ten types of cannulated screws models.

Figure 2. The process of placing screws and analyzing. (a) Anatomical feature point of femur. (b) Locating femoral head center (FHC), femoral neck axial (FNA), femoral shaft axial (FSA), femoral mechanics shaft (FMS) and the narrowest surface (NS) according to anatomical feature point. All types of screws were inserted to femoral neck in parallel inverted triangle configuration so that their thread centers (TC) were on the same line and their major diameter (MD = 6.5mm (orange), 7.0mm (green), 7.3mm (yellow) and 8.0mm (red)) were tangent at cortical sides. (c) Screws were inserted to femoral neck fracture (FNF) of modified Pauwels 70 degree at a certain place according to the location of FNA and thread center. (d) Fixed models were converted to 3D mesh and calculated in Abaqus. (e) The shear and detached direction of fracture.

Figure 3. (a) Inserting the screws in accurate position by using 3D printing guide template. ‘(b)’and ‘(c)’ Anteroposterior and lateral view of screws in fluoroscopy. (d) The setup of biomechanical test.

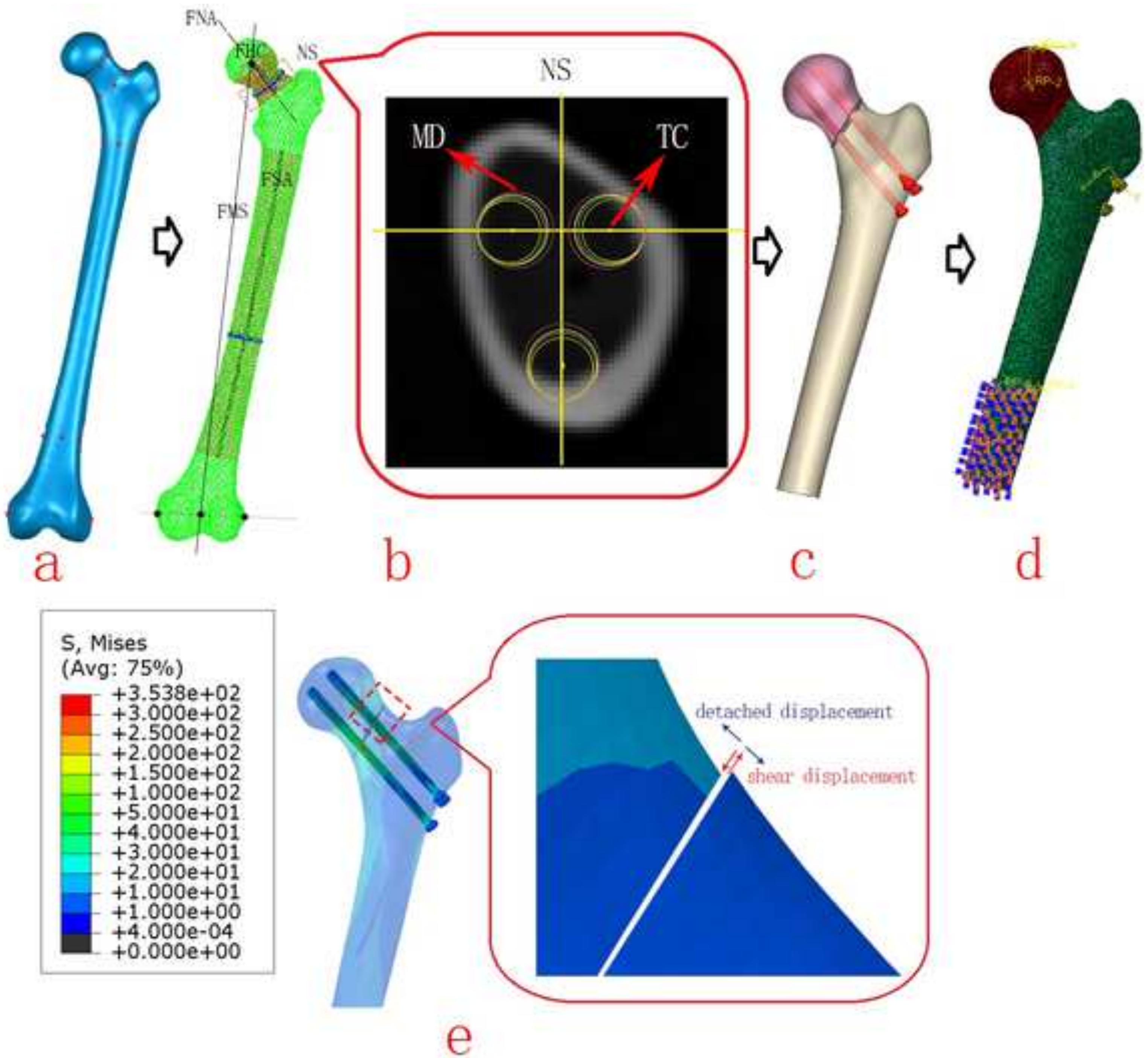
Figure 4. Linear regressing of FEA and Experiment, the stress of experiment was calculated from strain via inputting femur cortical Young’s moduli (16.7GPa) and Poisson's ratios (0.3) into VIC-3D.

Figure 5. The comparison of six parameters of fixation effects between PG and FG.

Figure 6. The fixation effects of ten types of screws (a) and the comparison between PG and FG (b).

Figure1

Figure2



FNA
FHC
NS
FSA
FMS
NS
MD
TC
a
b
c
d
S, Mises
(Avg: 75%)
+3.538e+02
+3.000e+02
+2.500e+02
+2.000e+02
+1.500e+02
+1.000e+02
+5.000e+01
+4.000e+01
+3.000e+01
+2.000e+01
+1.000e+01
+1.000e+00
+4.000e-04
+0.000e+00
detached displacement
shear displacement
e

Figure3

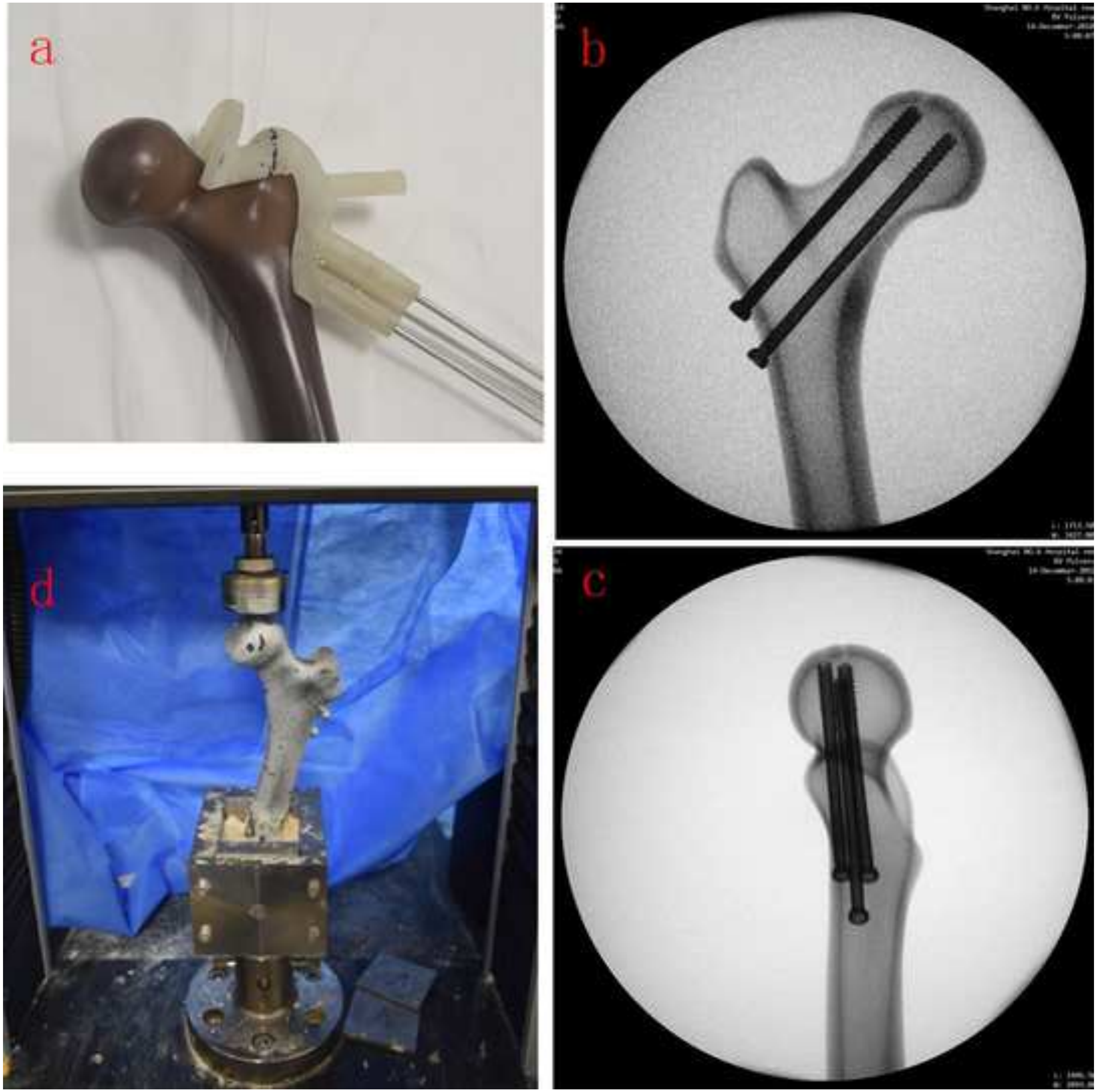


Figure4

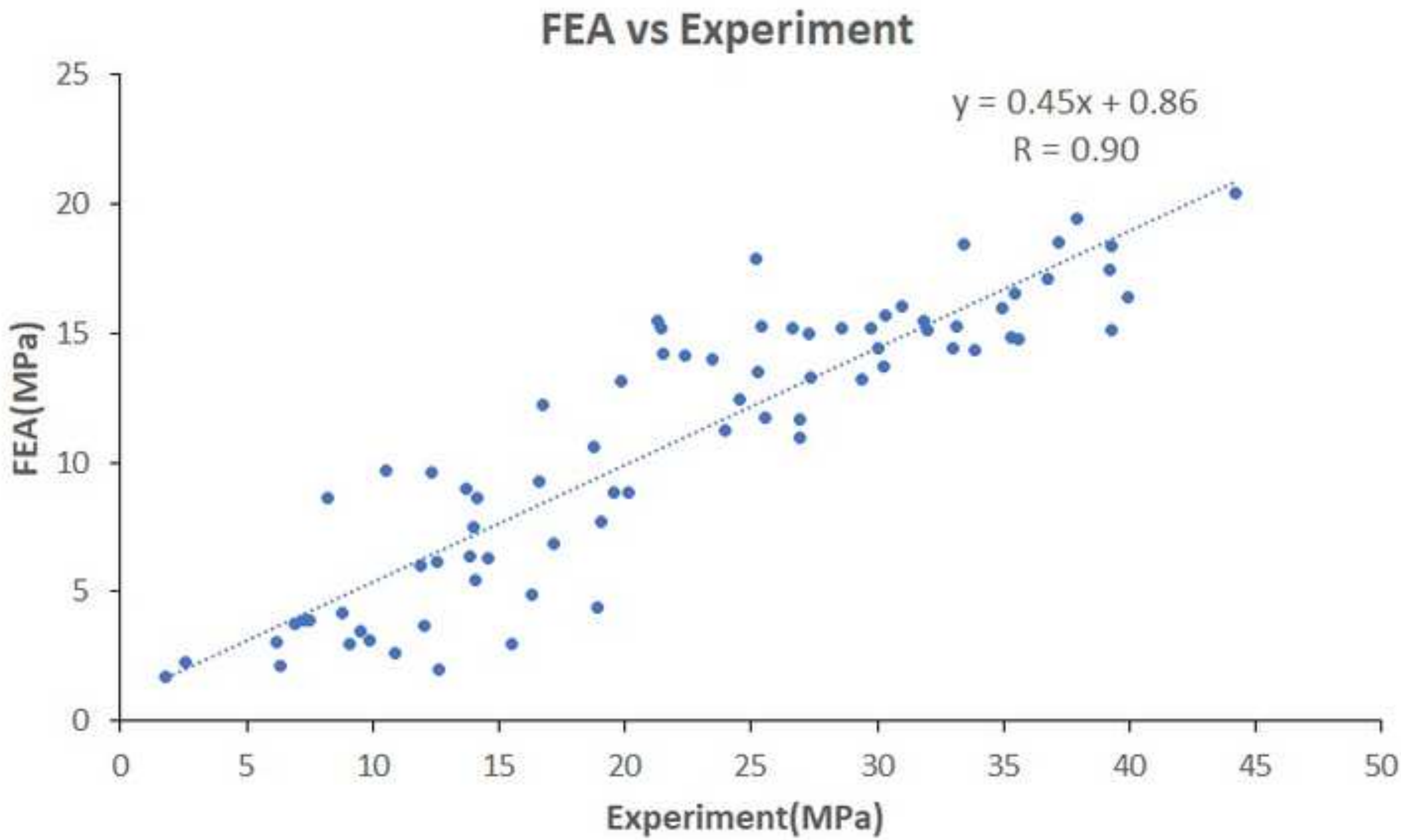
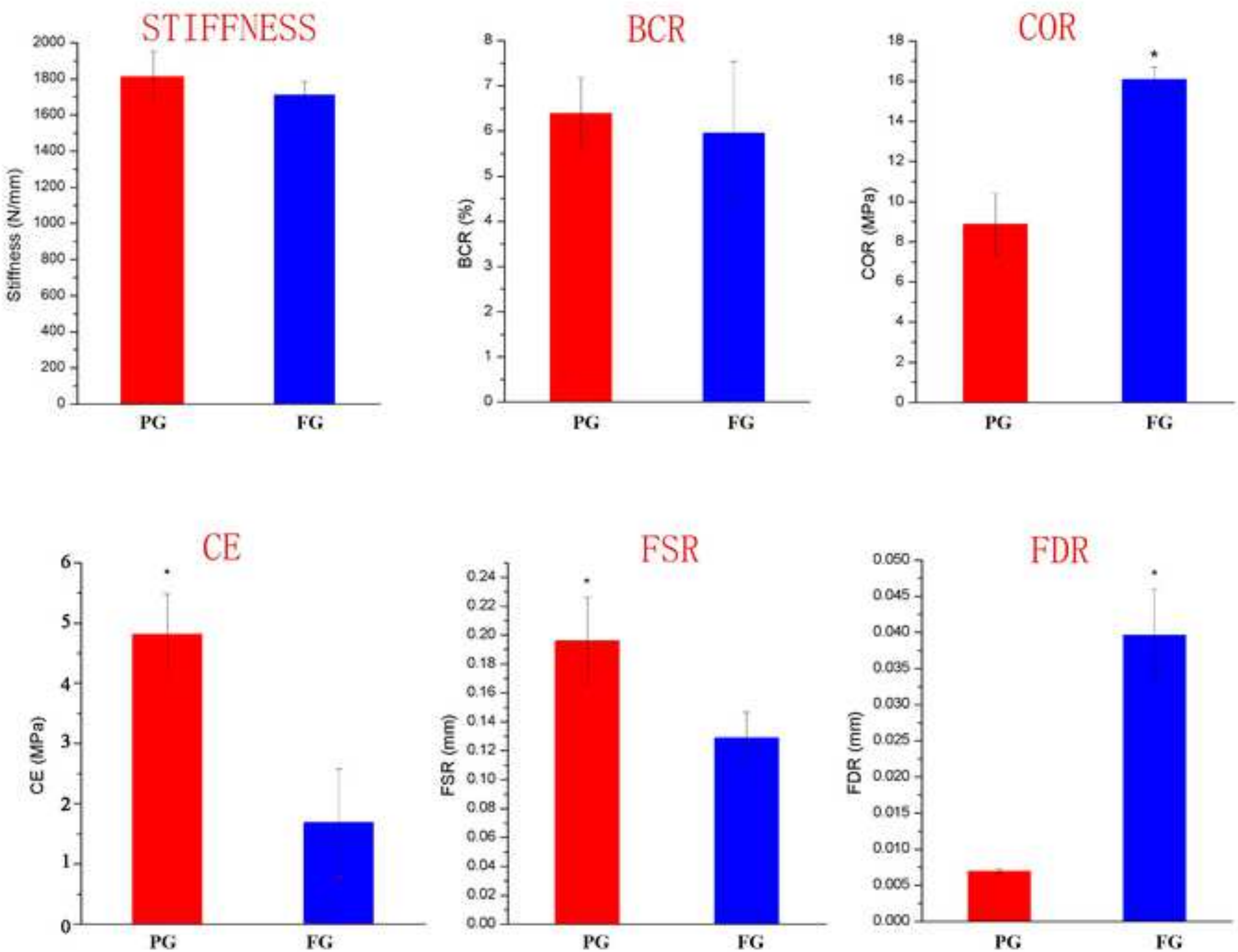

FEA vs Experiment
y = 0.45x + 0.86
R = 0.90
FEA(MPa)
Experiment(MPa)
0
5
10
15
20
25
30
35
40
45
50

Figure5



STIFFNESS
Stiffness (N/mm)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
PG
FG
BCR
BCR (%)
0
1
2
3
4
5
6
7
8
PG
FG
COR
COR (MPa)
0
2
4
6
8
10
12
14
16
18
*
PG
FG
CE
CE (MPa)
0
1
2
3
4
5
6
*
PG
FG
FSR
FSR (mm)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
*
PG
FG
FDR
FDR (mm)
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
0.050
*
PG
FG

Figure6

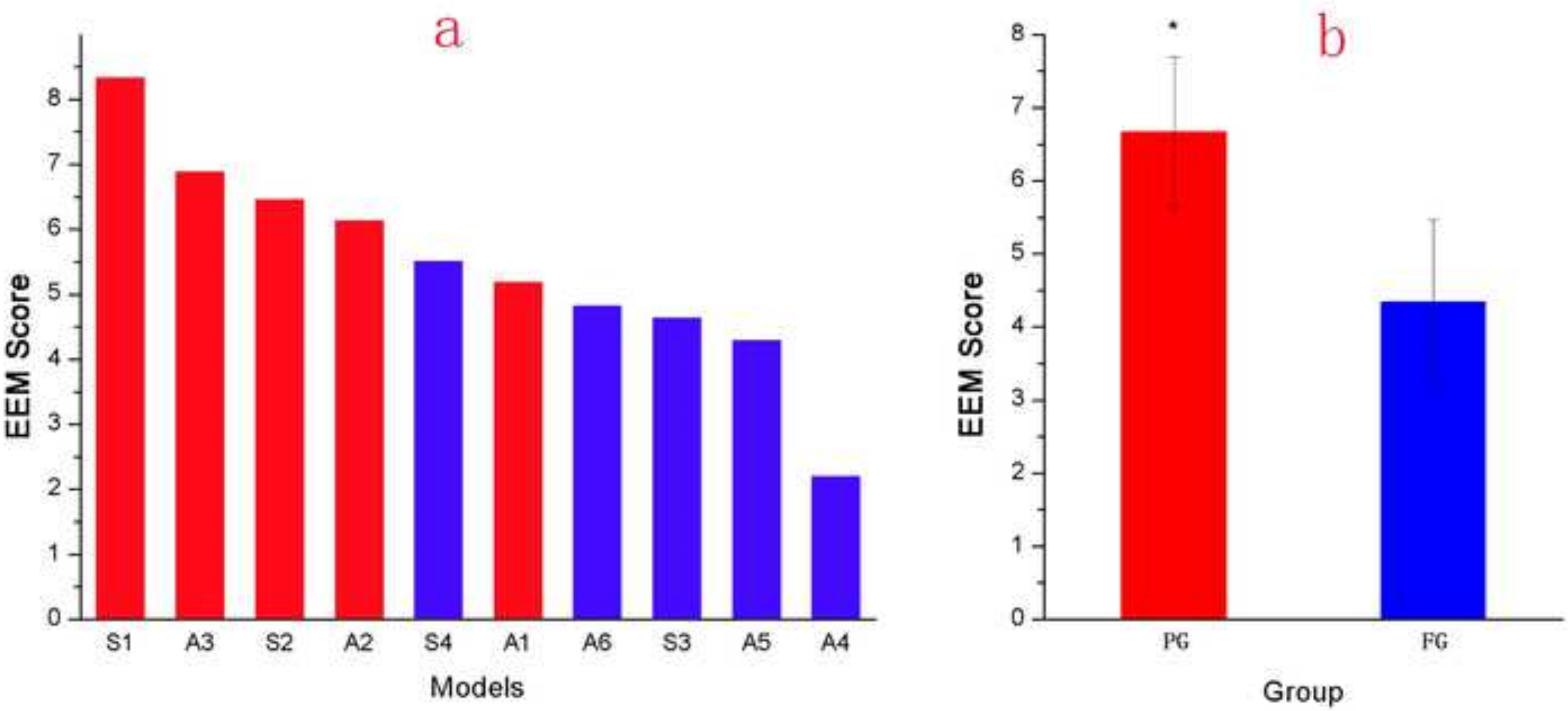

a
EEM Score
0
1
2
3
4
5
6
7
8
S1
A3
S2
A2
S4
A1
A6
S3
A5
A4
Models
b
*
EEM Score
0
1
2
3
4
5
6
7
8
PG
FG
Group

Table 1

Geomatical parameter of screws.

Models	Thread length	Major dia	Minor dia	Thread depth	Pitch	TSF
A1	16	6.5	4.8	0.85	2.75	0.68
A2	16	7.0	4.5	1.25	2.75	0.76
A3	16	7.3	4.8	1.25	2.75	0.76
A4	full	6.5	4.8	0.85	2.75	0.68
A5	full	7.0	4.5	1.25	2.75	0.76
A6	full	7.3	4.8	1.25	2.75	0.76
S1	20	6.5	5.0	0.75	2.22	0.70
S2	25	8.0	5.0	1.50	2.75	0.81
S3	full	6.5	5.0	0.75	2.22	0.70
S4	full	8.0	5.0	1.50	2.75	0.81

*Thread shape factor (TSF) = 0.5 + 0.57735 d/p, dia=diameter.

Table 2

The fixation value of ten types of screws.

Group	Models	Stiffness (N/mm)	BCR (%)	COR (MPa)	CE(MPa)	FSR (mm)	FDR (mm)	EEM Score	Average Score
PG	A1	1620.8 (2)	7.87 (2)	10.31(6)	5.16 (8)	2.40E-01 (1)	7.08E-03 (8)	5.07	4.50
	A2	1877.6 (8)	6.38 (4)	9.86(8)	3.05 (6)	1.87E-01 (3)	7.16E-03 (7)	6.05	6.00
	A3	1891.7 (9)	5.92 (6)	7.27(9)	5.40 (10)	1.70E-01 (4)	7.35E-03 (6)	7.03	7.33
	S1	1993.5 (10)	5.54 (7)	10.12(7)	5.31 (9)	1.62E-01 (5)	6.36E-03 (10)	8.23	8.00
	S2	1669.9 (3)	6.25 (5)	6.79(10)	5.14 (7)	2.21E-01 (2)	6.70E-03 (9)	6.49	6.00
FG	A4	1566.4 (1)	8.76 (1)	16.38(2)	1.54 (3)	1.61E-01 (6)	5.11E-02 (1)	2.19	2.33
	A5	1768.0 (7)	4.44 (10)	15.52(5)	0.87 (1)	1.28E-01 (7)	4.13E-02 (2)	4.80	5.33
	A6	1728.1 (4)	5.48 (8)	15.77(3)	2.41 (4)	1.22E-01 (9)	3.61E-02 (4)	5.22	5.33
	S3	1751.0 (6)	6.49 (3)	17.14(1)	2.67 (5)	1.24E-01 (8)	3.69E-02 (3)	4.12	4.33
	S4	1740.9 (5)	4.56 (9)	15.59(4)	1.36 (2)	1.07E-01 (10)	3.27E-02 (5)	5.79	5.83
	ER	0.896	0.865	0.875	0.869	0.861	0.727		
	WC	11.5%	14.9%	13.8%	14.4%	15.3%	30.1%		

PG Partial-thread Group; FG Full-thread Group; BCR bone cutting rate; COR cut-out risk; CE compression effects; FSR shear resistance of fracture; FDR detached resistance of fracture; EEM entropy evaluation method; ER entropy redundancy; WC weight coefficient. From second row on, the value in bracket was Models' scores in certain fixation category. ER was calculated by EEM according to all these six types of fixation effects value and used to determine the WC. EEM Score were equal to the sum of each score multiplied by each WC. Average Score was average value of six parameters with assumption that each parameter has the same WC.

Table 3

Comparison of Partial-thread Group (PG) and Full-thread Group (FG)

Types	PG	FG	P value
Stiffness (N/mm)	1810.70±141.66	1710.88±73.41	0.25
BCR (%)	6.39±0.79	5.95±1.59	0.63
COR (MPa)	8.87±1.52	16.08±0.61	0.00
CE(MPa)	4.81±0.89	1.77±0.67	0.00
FSR (mm)	1.96E-01±3.01E-02	1.29E-01±1.78E-02	0.00

FDR (mm)	6.93E-03±3.53E-04	3.96E-02±6.35E-03	0.00
EEM Score	6.57±1.05	4.43±1.24	0.03
Average Score	6.37±1.21	4.63±1.25	0.08

Author contributions

SZ: Study design, data analysis, interpretation, finite element analysis, and manuscript preparation. D-JJ: Study design, manuscript preparation. SZ and D-JJ are co-first authors. ML, JD, KY and LD: Data acquisition, format checking. T-Y T, YF and B-V T: review & editing. W-TJ, HH, and C-QZ designed and approved the manuscript and should be considered as corresponding authors. The author (s) read and approved the final manuscript.

Explanation of why more than 8 authors are justified

In this study, ten types of screws were analyzed by FEA method as well as a validating experiment, which need more than 8 authors to work together to finish this quite a lot work.