



# Biomechanical Study of Three Cannulated Screws Configurations for Femur Neck Fracture: A Finite Element Analysis

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## Abstract

**Background:** To improve the performance of cannulated screws (CSs) in the treatment of femoral neck fractures (FNF), a number of new screw configurations have been proposed. However, most of the studies have only analyzed the biomechanical performance of different screw configurations under static conditions. This study aimed to investigate the biomechanical performance of three cannulated screws configurations under different loadings through finite element analysis. **Methods:** In this FEA study, nine numerical models of proximal femur were employed to analyze the mechanical response of various fracture types and different fixation strategies (three inverted triangular parallel cannulated screws (TCS), four non-parallel cannulated screws (FCS) and biplane double-supported screw fixation (BDSF) respectively). The maximum principal strain (MPS) on the proximal femur and the von Mises stress on the screws were compared for different models. **Results:** In Pauwels I and II fractures, FCS had the lowest peak MPS on the proximal femur and the BDSF had highest peak MPS value. In Pauwels III fractures, BDSF performance in MPS is improved and better than FCS under partial loading conditions. FCS exhibits the lowest von Mises stress in all load conditions for all fracture types, demonstrating minimal risk of screws breakage. **Conclusions:** FCS is an ideal screw configuration for the treatment of FNF. And BDSF has shown potential in the treatment of Pauwels type III FNF.

## Keywords

femoral neck fracture, cannulated screw, Pauwels type, finite element analysis, Limit slide

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## Introduction

There are currently more than 1.6 million hip fractures worldwide each year, and by 2050, these figures are predicted to reach 6.5 million.<sup>1-3</sup> Femoral neck fractures (FNF) account for 44% of hip fractures.<sup>4</sup> The average age of patients with hip fracture is over 80 years,<sup>5</sup> and the risk factors of hip fractures include decreased bone mineral density, decreased activity levels, and medication for chronic conditions.<sup>6</sup> The huge number of patients with FNF, the associated high complication rates and high mortality<sup>7-9</sup> place a heavy financial burden on the health-care system.

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Among many approaches for treating FNF, three inverted triangular parallel cannulated screws (TCS) is still a widely accepted and preferred procedure for many surgeons<sup>10-12</sup> because of its economics, low invasiveness, and low impact on the blood supply to the femoral head.<sup>13-16</sup>

However, there are still many problems in the TCS treatment of FNF. For example, the sliding compression after TCS fixation ensures continuous tight contact of the fracture end to facilitate the healing process.<sup>17,18</sup> Nevertheless, this process can also result in excessive shortening of the femoral neck and consequently affect the patient's postoperative hip function.<sup>19-21</sup> In addition, previous studies have shown that TCS is inferior to other methods such as dynamic hip screws and FNS in terms of stability, especially in the treatment of unstable FNF.<sup>22,23</sup> In response to these shortcomings, scholars have developed many new usages of cannulated screws (CSs) to improve their performance while retaining the advantages, such as four non-parallel cannulated screws (FCS), biplane double-supported screw fixation (BDSF, F-technique) and so on.<sup>24-28</sup>

In present, many studies have been conducted to analyze the different screw fixation methods in the treatment of FNF. The majority of current researches have focused on unstable fractures, such as Pauwels III fractures.<sup>29-31</sup> However, the femoral neck shortening also exists after internal fixation surgery for stable femoral neck fractures.<sup>32,33</sup> In the treatment of stable FNF with TCS, it may also be necessary to change the configuration to reduce the sliding effect and inhibit the excessive shortening of the femoral neck. In addition, most of the current biomechanical studies have only analyzed the performance of different screw configurations under static conditions without concerning the dynamic processes of daily activities.<sup>34,35</sup> We barely understand the biomechanical performance of different screw configurations of different FNF types in postoperative activity settings. Finite element analysis can assign various biomechanical material properties, accurately build 3D finite element models of bones, ligaments and other tissues, and calculate the stress, strain distribution, and deformation under different loads. Therefore, the purpose of this study is to compare the biomechanical performance of three different screws configurations under dynamic conditions in the treatment of FNF by finite element analysis.

## Methods

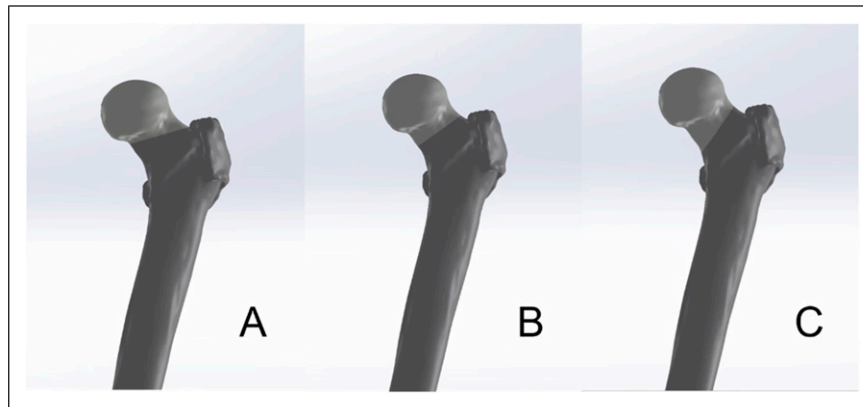
### *The Establishment of FNF Modes*

A healthy male volunteer who had no history of hip or systemic disease was chosen: age 65 years old, weight 70 kg, height 170 cm. A GE 64-slice spiral CT scanner was used to scan the proximal femur, and the CT images

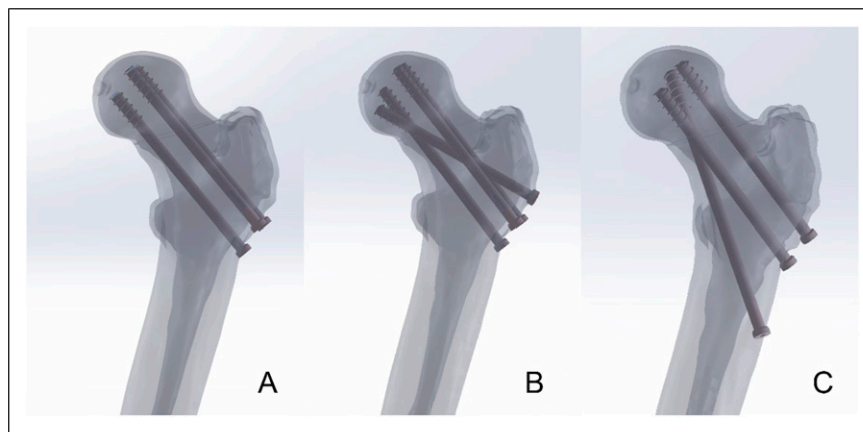
were stored in Digital Imaging and Communications in Medicine (DICOM) format. Then, the femur data was imported into Mimics 17.0 software (materialise, Belgium) and the appropriate gray value was selected to distinguish the bone and tissue. Establish the three-dimensional model of the proximal femur, and then output as an STL format file. The 3D model of the proximal femur was then loaded into Geomagic Studio 12.0 software (Raindrop Inc., USA) to correct the surface errors. After the correction of the surface roughness of the model, the model was then imported into SolidWorks program (Dassault Systems SolidWorks Corp., USA) where models of Pauwels I, II, III FNF were established. The Pauwels angles are set to type I 25°, type II 45° and type III 65° respectively (Figure 1).

### *The Building of Internal Fixation Model*

The 3D model of cannulated screws was established according to DePuy-Synthes lag screws via the SolidWorks software. The length of parallel screws was 85 mm, the Pauwels screw was 78 mm and the inferior screw of BDSF was 110 mm. The diameter of all screws is 6.5 mm, the thread length was 16 mm and the number of threads was 5 turns. The geometric model of the bone and the components of each implant were imported to Solidworks software, and Boolean operations were performed to assemble them together. In the TCS model, three parallel CSs were placed in an inverted triangular configuration from the lateral cortex of the proximal femur. The screws were parallel to the femoral neck axis. The insertion point of the lower screw was at the level of the lesser trochanter and was placed close to the femoral calcar.<sup>36</sup> The upper two screws are located anteriorly and posteriorly above the femoral neck close to the femoral neck cortex. The screws were dispersed as far as possible within the femoral neck. In the FCS model, three parallel CSs were inserted as described previously. The fourth Pauwels screw was inserted at the greater trochanter, being fixed inside the femoral head through the anti-stress bone trabeculae.<sup>34</sup> In the BDSF model, the entry point of the distal CS is located in the anterior one-third of the femur approximately 5 cm distally from the basis of the trochanter, with the tip of the screw entering the dorsal half of the femur head with inclination from anteriorly–distally to posteriorly–proximally. The entry point of the middle CS is at about 2 cm proximally from the entry point of the distal CS, and the proximal CS is at about 1 cm proximally from the middle CS, in the dorsal one-third of the femur. These two parallel CSs entering the front half of the femur head with inclination from posteriorly–distally to anteriorly–proximally.<sup>24</sup> The tips of all CSs were less than 5 mm from the femoral head cortex (Figure 2).



**Figure 1.** Three models of FNF with different Pauwels angle were established. (A) The model of the Pauwels I FNF, Pauwels angle 25°. (B) The model of the Pauwels II FNF, Pauwels angle 45°. (C) The model of the Pauwels III FNF, Pauwels angle 65°.



**Figure 2.** Three models of FNF were implanted with different screw configurations. (A) The model of TCS. (B) The model of FCS. (C) The model of BDSF.

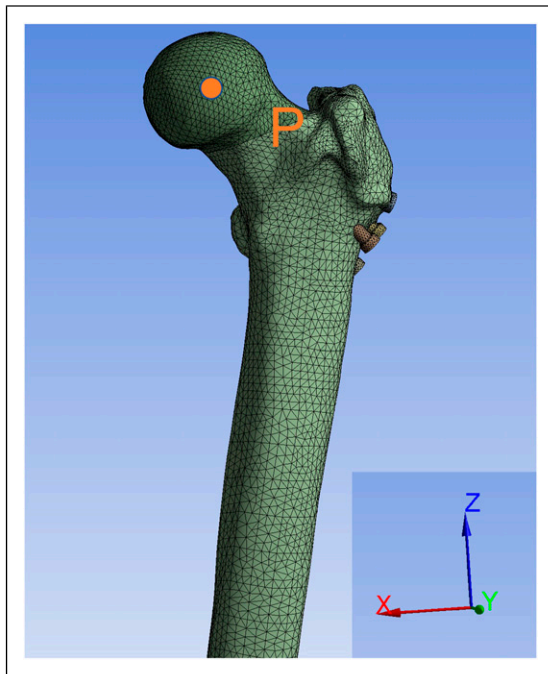
### *The Settings of Material Parameter and Contacts*

The proximal femur models with screws implants were imported into ANSYS Workbench 17.0 (ANSYS Inc., Canonsburg, PA) for analysis. The solid models were discretized into quadratic tetrahedral elements (C3D10) using ANSYS Workbench. To evaluate the accuracy of finite element models, convergence tests were performed to determine the optimum maximum element size. After the convergence measurement, the mesh size was determined to be 3 mm for the proximal femur and 1 mm for the screws. (Figure 3) The mesh at the contact surfaces between the femur model and the screws was encrypted to 1 mm for better convergence. All models are considered to be linear elastic materials that are continuous, isotropic, and homogenous.<sup>37</sup> Table 1 shows the material properties of the femur and implant materials used in the models.<sup>38,39</sup> The relationship between threaded surfaces of screws and bone was considered to be bonded. A frictional contact was used for describing the contact interactions between bone fragments and

between bone and implants. The friction coefficient between the fracture surfaces is set as 0.46,<sup>40</sup> and the friction coefficient between the femur and the implant is set as 0.3.<sup>41</sup>

### *The Boundary and Loading Conditions*

The patient was assumed to have recovered to a state of complete weight-bearing after surgery, the patient can complete daily exercises independently. The distal end of femur was restrained in all degrees of freedom to prevent rigid body movement. In order to simulate the effect of compression on the fracture end after internal fixation surgery, a bolt pretension force of 224N was added axially to the middle of the parallel CSs in each model in Ansys workbench software.<sup>34</sup> Considering that the compression process of is largely completed before the placement of the Pauwels screw and the distal CS of BDSF, no pretension is added to these screws.<sup>42</sup> The magnitude of dynamic hip contact force is shown in Figure 4 for walking, climbing stairs, knee bending



**Figure 3.** The meshed model of proximal femur and the loading acted on the model.

**Table 1.** The Material Parameters of Models.

Material	Young's Modulus (MPa)	Poisson's Ratio
Cortical bone	17 000	0.33
Cancellous bone	1000	0.3
CSs (Ti-6Al-7Nb)	110 000	0.35

and chair down/up condition respectively.<sup>43,44</sup> The hip contact force is introduced to the center of the femoral head, the point P in the [Figure 3](#).

### The Standard of Evaluation

In the finite element analysis, the peak maximum principal strains and the maximum von Mises stress were selected indicators of the stability of a fractured femur stabilized by CSs and of the risk of implant failure, respectively.<sup>43</sup> The von Mises stress on the internal fixations and the peak maximum principal strains on the proximal femur were evaluated and compared for three different CSs configurations model (TCS, FCS and BDSF) under four dynamic loadings.

## Results

### Strain on the Proximal Femur

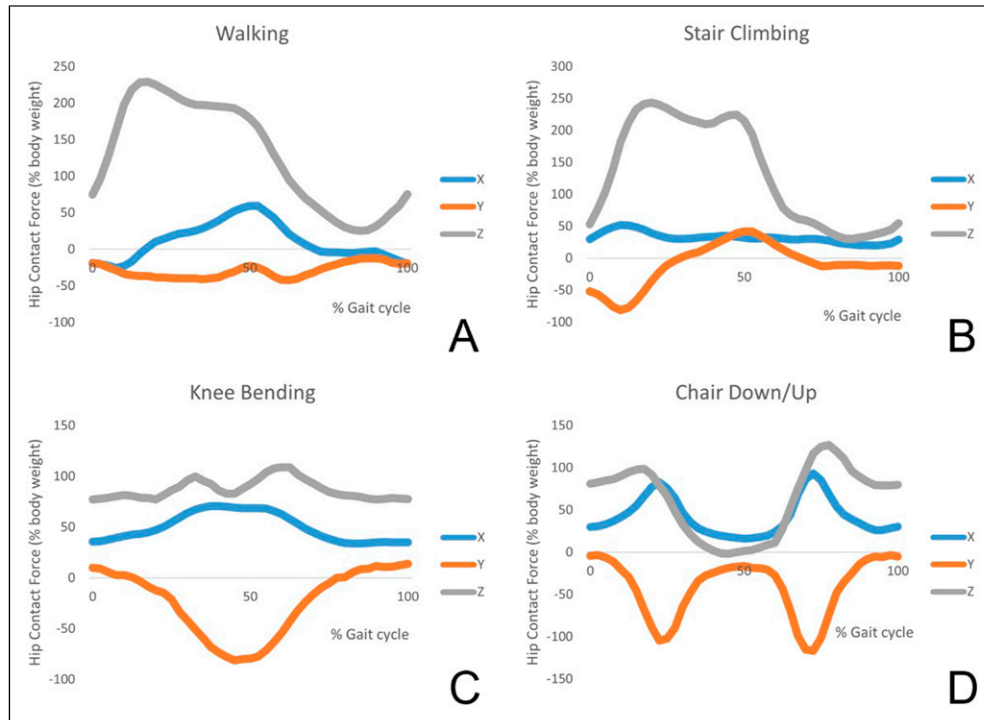
[Figure 5](#) compared the peak values of maximum principal strains (MPS) of femur in the three CSs configurations. For

all dynamic loads in Pauwels I and II fractures, FCS had the lowest peak MPS on the femur and the BDSF had highest peak MPS value with MPS values greater than 1% in walking, climbing and chair down/up. In contrast, in Pauwels III fractures, it was the TCS that showed the highest peak MPS and during knee bending and chair down/up, BDSF shows smaller peak MPS than FCS. In most loadings of the TCS model, the peak MPS on the proximal femur increases with increasing Pauwels angle in addition to the comparison of Pauwels I and II fractures during chair down/up. This trend is also reflected during the walking and climbing loadings of the FCS model. And in the BDSF model, the peak MPS during knee bending and chair down/up decreases with the increase of Pauwels angle. The knee bending caused the least peak MPS in the proximal femur among the four dynamic loadings.

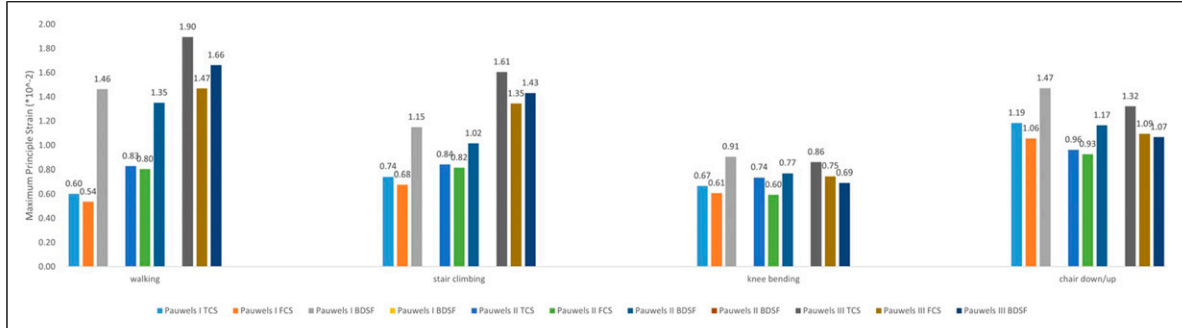
### Stress on the Screws

[Figure 6](#) compared maximum von Mises (equivalent) stress for three fixation styles under four different loading conditions. Among the three fracture types for all four loading conditions, BDSF exhibited the largest maximum von Mises stress, TCS the second, and FCS the smallest. As the Pauwels angle increasing, the TCS and BDSF models exhibit increased maximum von Mises stress under most loading conditions. This trend can also be found in the walking and climbing load process of the FCS model. The peak stress of the internal fixation device was greater in Pauwels III fractures than in Pauwels I and II for all load cases of the three screw configurations. Under the four load conditions, the maximum von Mises stress generated on the internal fixation during knee bending is the smallest. Under the majority of loading conditions, the maximum von Mises stress during chair down/up is less than during walking and climbing, but the difference is smaller in Pauwels I fractures, and the maximum von Mises stress during chair down/up is slightly greater than during walking and climbing in TCS-fixed Pauwels I fractures. With the exception of Pauwels III fractures with BDSF, the maximum Von Mises stress generated during climbing is less than during walking.

[Figure 7](#) depicted the von Mises stress distribution on the screws. The concentration of von Mises stress was showed on the middle regions of the screws, which was also around the bone fracture site. The stress nephogram showed that the addition of the Pauwels screws did not significantly change the stress distribution on the TCS and FCS parallel screws. The stress concentration was also found in the middle of the rear upper and lower parallel screws. However, the Pauwels screws did reduce the peak stresses at the screw stress concentrations. In the BDSF model, the von Mises stresses were mainly concentrated on the superior and intermediate screws, but with the increase



**Figure 4.** The hip contact forces in different conditions. (A) forces occurring in the walking cycle. (B) forces occurring in the stair climbing cycle. (C) forces occurring in the knee bending cycle. (D) forces occurring in the chair down/up cycle.



**Figure 5.** The maximal principal strains on the femur for three different screw configurations under four different loading condition.

of Pauwels angle, the stress concentration range of the superior two screws gradually decreased, and the maximum stress concentration of Pauwels III fracture internal fixation shifted from the superior two screws to the inferior screws during the walking and stair climbing process compared with Pauwels I and II types.

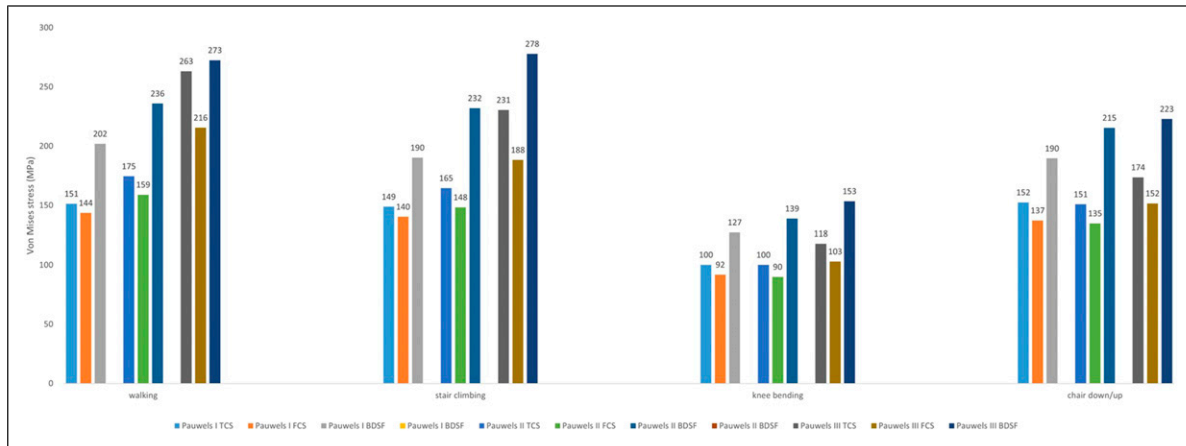
**Discussion**

In the treatment of femoral neck fractures, CSs occupy a very important place due to their advantages such as minimal trauma, although there are many other fixation methods that have shown better stability.<sup>13,14,45</sup> In this

study, we created 36 finite element models to evaluate and compare the biomechanical performance of three different screw configurations for the treatment of FNF under dynamic conditions.

Strain can be both a friend and an enemy of the post-operative bone healing process, it is both a relevant signal for triggering bone remodeling, yet it is also the major determinant of the failure at the tissue level through the induction of cracks.<sup>46</sup> For cortical bones, typical yield strain values are about 1.5%.<sup>43</sup> In the present study, the strain of proximal femur in the FCS group was less than 1.5% under all loading conditions. In contrast, in the TCS and BDSF groups, strain exceeds 1.5% under partial load





**Figure 6.** The maximum von Mises stress on the fixations under four different loading conditions.

conditions, which are all found in Pauwels III fractures. This suggests a higher risk of localized yielding and failure risk of the bone in the TCS and BDSF models. The reduction of the peak von Mises stress in the screws could decrease the risk of implant failure during daily loading. The yield strength of Ti-6Al-7Nb alloy was 921 MPa and the stress values on the screws are less than this value in all models.<sup>47</sup> However, under all loading conditions, we found that the stresses in the FCS model were minimal, which may reduce the risk of screws breakage.

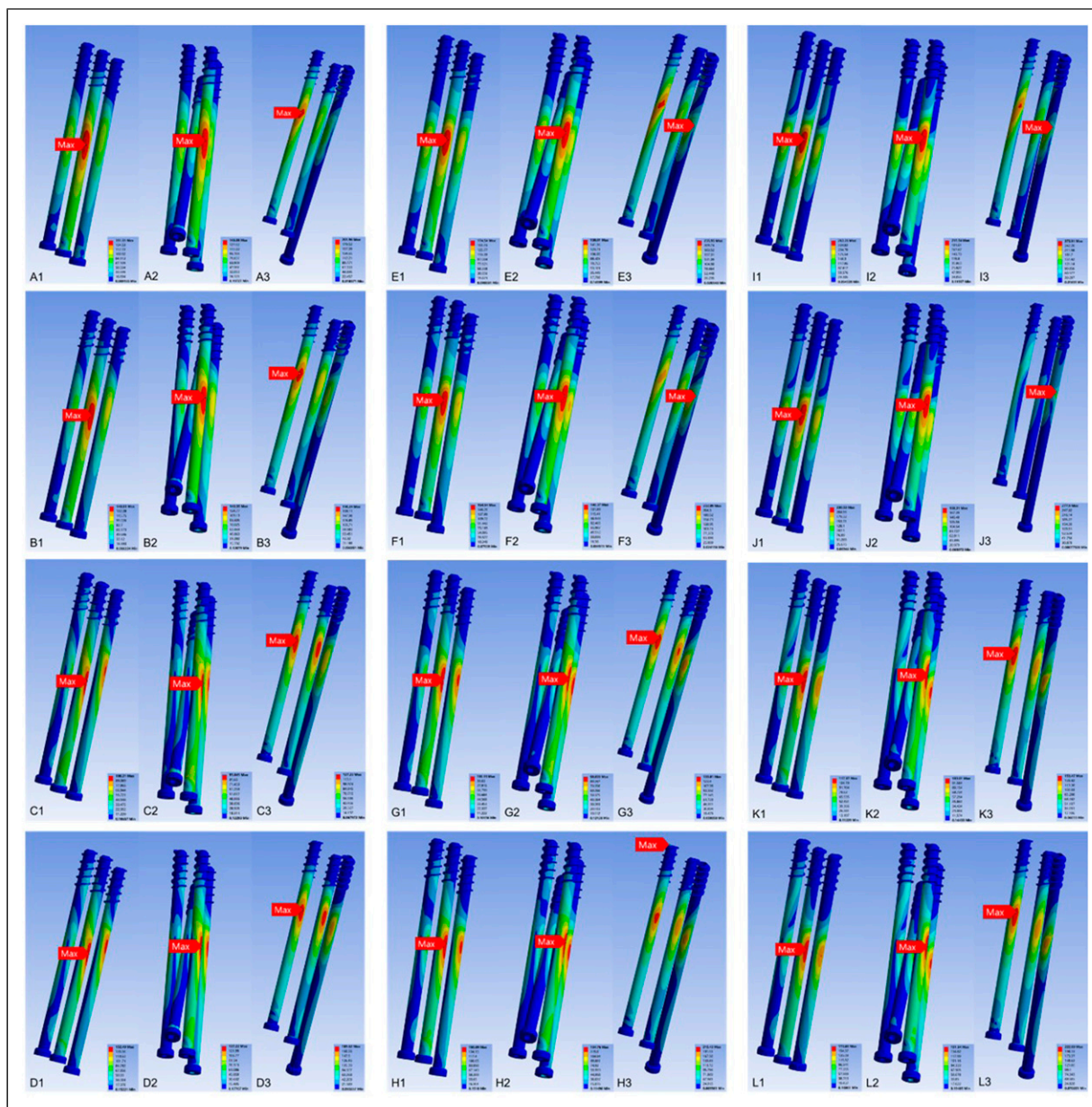
In all three models, the stress concentration area of the screw is in the middle of the screw, near the fracture line. Although the von Mises stress in the BDSF model for internal fixation in this study is the maximum in the equivalent case, the maximum stress is much less than the yield stress threshold for internal fixation. However, it is interesting to note that in Pauwels type III fractures, the MPS of the BDSF model was smaller than that of the TCS model, and it was also smaller than that of the FCS model during knee bending and chair down/up. And the stress distribution of BDSF changes with the change of Pauwels angle, as the angle increases, the distal screw gradually better shares the stress concentration on the proximal screws.

The console-like proximal femur demands the fixation screws have to support the weight-bearing head fragment. In Pauwels III FNF, shear forces are dominant due to the large angle of inclination of the fracture line, which can easily lead to fracture displacement and flexion collapse.<sup>48</sup> The position of the distal screw as well as the middle screw of BDSF turns them into a simple beam bearing the body weight and transferring it to the diaphysis. The position of the screw entrances farther apart allows the tension to be distributed to a larger lateral cortical surface during weight bearing, which may account for the smaller proximal femoral MPS shown in BDSF models in Pauwels III fractures. The steeper inferior BDSF screw's axial bearing

capacity is manifested under rather vertical loads. The closer working direction to the loading force ensures a better effect of the distal screw in playing the role of the beam. Compared to TCS, the reduced MPS of the proximal femur with BDSF may be more clinically significant than the greater screw stress concentration because the MPS values are closer to the yield strain values, and BDSF may therefore have a lower failure risk of the bone in Pauwels III fractures.

In our study, FCS exhibited minimal von Mises stress and also showed minimal proximal femoral MPS in Pauwels I and II fractures and a relatively small MPS in Pauwels III fractures. However, we found that the addition of Pauwels screws did not significantly change the trend of stress distribution on the parallel screws, and the area of stress concentration was similar to that of the TCS group. Previous study has suggested that Pauwels screws provide a higher holding force because the bone quality around the femoral calcar is superior to the bone quality around the Ward's triangle of the femur.<sup>26</sup> However, in our study, we assigned the same material parameter to the cancellous bone, suggesting that other possible explanations for the biomechanical advantage of FCS are also important. We speculate that the additional Pauwels screws share the stress on the remaining three parallel screws compared to the TCS, thus reducing the stress concentration on each screw. In FCS, the entry points of all four screws were at or near the thin and fragile lateral cortex of greater trochanteric, and the lack of cortical support may account for the greater MPS than BDSF in the partially loading conditions of Pauwels III fracture.

Currently, comparisons of the efficacy between BDSF and other screw configurations are mostly limited to the field of biomechanics, and large-scale clinical studies are lacking. Orlin Filipov, et al analyzed 207 patients with displaced Garden III, IV FNFs treated with BDSF and found that bone union occurred in 96.6% of patients, with a



**Figure 7.** The maximum von Mises stress distribution diagram on the screws. A-D showed the results of Pauwels I FNF, E-H showed the results of Pauwels II FNF, I-L showed the results of Pauwels III FNF. I-3 represent TCS, FCS and BDSF respectively. A,E,I showed the results under walking cycle, B,F,J showed the results under stair climbing cycle, C,G,K showed the results under knee bending cycle, D,H,L showed the results under chair down/up cycle.

nonunion rate of 3.4% and a femoral head avascular necrosis rate of 12.1%.<sup>49</sup> Sherif Galal, et al reported a 5% nonunion rate in 41 patients with FNFs treated with BDSF, 71% of whom had femoral neck shortening of less than 5 mm, 21% shortening of 5-10 mm and 8% shortening >10 mm.<sup>50</sup> However, the above studies did not set up other fixation methods as control groups, and the efficacy of BDSF needs to be verified by larger controlled clinical studies. Xiangyu Xu, et al analyzed 102 patients

with FNF treated with TCS and FCS and reported no significant difference in the rate of internal fixation failure in the treatment of Garden III and IV fractures, but FCS reduced femoral neck shortening and improved the post-operative Harris hip score.<sup>21</sup> Dajun Jiang, et al reported that FCS had a significantly lower rate of femoral neck shortening (8.3% vs 28.9%) than that of TCS.<sup>26</sup>

The novelty of this study is that we analyzed the biomechanical performance of three screw

configurations for FNF under dynamic conditions. However, there are still some limitations in this study. First, the proximal femur is treated as a isotropic and homogeneous material in the finite element model, which does not exactly correspond to the real situation. Second, we only performed the analysis under dynamic loading. However, in the studies by Wei Zeng et al and Xianbao Jiang et al dynamic loading produced greater strains and stresses than static loading.<sup>43,51</sup> Therefore, analysis under dynamic loading only can still reflect the maximum strains and stresses on the femur and CSs. Finally, one advantage of using TCS and BDSF for FNF is that the non-parallel placement of the screws limits the postoperative shortening of the femoral neck due to excessive sliding of the fracture ends thereby improving postoperative hip function. However, finite element analysis only reflects the mechanical characteristics of postoperative fixation and cannot assess the resorption and shortening of the femoral neck fracture in the long term.

## Conclusion

This study provides a biomechanical evaluation of TCS, FCS and BDSF for FNF with different Pauwels type under dynamic loads. Compared to TCS and BDSF, the finite element modeling of FCS shows better stability and lower risk of screw breakage in the treatment of FNF. BDSF shows better biomechanical properties in the Pauwels type III fracture model due to its resistance to shear forces. From the biomechanical perspective, FCS is an ideal screw configuration for the treatment of FNF. And BDSF has shown potential in the treatment of Pauwels type III FNF. The findings of this study provide a reference for the postoperative selection of internal fixations in FNF.

## Appendix

### List of abbreviations

CSs	Cannulated screws
FNF	Femoral neck fractures
TCS	Three inverted triangular parallel cannulated screws
FCS	Four non-parallel cannulated screws
BDSF	Biplane double-supported screw fixation
MPS	Maximum principal strain

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Preprint available on Research Square: <https://www.researchsquare.com/article/rs-2702523/v1>.

### Author contributions

ZC, YL, and JF formulated the study hypothesis. ZC and YL designed the study. ZC, YC, YF and LB completed the analysis of the model and write the manuscript. YL and JF review the manuscript. All authors contributed to the article and approved the submitted version.

### Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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### Ethical Statement

#### Ethical Approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the Ethical Committee of Peking University Third Hospital and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. This study was approved by the Ethical Committee of Peking University Third Hospital (M2020330).

#### Informed Consent

Written informed consent was obtained from the volunteer for the publication of any identifiable images included in this article.

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### Data Availability Statement

The datasets used and analysed during the current study available from the corresponding author on reasonable request.

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