Finite element analysis of a new internal fixation implant for Pauwels type III femoral neck fractures

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Research article

Keywords: femoral neck fracture, femoral neck system, cannulated screw, finite element analysis

Posted Date: June 3rd, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-31309/v1>

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Abstract

Background

The optimal treatment strategy for Pauwels type III femoral neck fractures remains controversial. A new internal fixation femoral neck system (FNS) for the treatment of femoral neck fractures was developed, and we compared the mechanical efficiency of the internal fixation FNS with that of two cannulated screw configurations for the treatment of Pauwels type III femoral neck fractures.

Method:

In this study, we constructed models of Pauwels type III femoral neck fractures with angles of 50°, 60°, and 70°. Moreover, a fixation model with the FNS and two fixation models with cannulated screws were developed. Under two axial loads, 1400 N and 2100 N, the von Mises stress distributions, maximum von Mises stress, and displacements of the femur and internal fixation components were measured for each fracture group.

Result

The maximum von Mises stress of internal fixation in the three models was mostly located near the fracture line, and the femoral head region closest to the femoral calcar experienced the maximum amount of stress. As the Pauwels angle and axial loads increased, the stress and displacement of the proximal femoral head and internal fixation component increased in each group. Compared with cannulated screw configurations, the internal fixation FNS showed lower values of peak stress at the femoral head and smaller displacements of the femur and internal implant in the treatment of Pauwels type III femoral neck fractures with Pauwels angles of 50°, 60°, and 70°.

Conclusion

The newly developed internal fixation FNS provided improved biomechanical stability for the treatment of Pauwels type III femoral neck fractures, which indicated that the internal fixation FNS may be a new option for the treatment of vertical femoral neck fractures.

Introduction

It is estimated that the worldwide incidence of hip fractures is 1.6 million annually¹. This incidence is expected to increase to 2.6 million by 2025 and to 4.5 million by 2050 globally since the elderly population is growing rapidly²⁻⁴. Femoral neck fractures account for almost half of all hip fractures⁵. On the basis of the angle of the fracture line in the coronal plane and the upper edge of the acetabulum,

Pauwels classified these fractures as Pauwels type I, type II and type III fractures, which have angles of up to 30 degrees, between 30 and 50 degrees, and greater than 50 degrees, respectively^{6,7}. Pauwels type III femoral neck fractures that occur in young and middle-aged patients are often caused by high-energy trauma^{8,9}. Because of the high shear stress incurred with these fractures, it is difficult to obtain adequate stability to resist vertical shear forces around the hip, thereby increasing the risk of complications such as fracture displacement, bone nonunion, and avascular necrosis (AVN) of the femoral head¹⁰. In previous studies, the incidence of the nonunion of Pauwels type III femoral neck fractures was between 16% and 59%, and the incidence of AVN was between 11% and 86%⁸.

At present, the most common internal fixation methods for femoral neck fractures are cancellous screw fixation, dynamic hip screw (DHS) fixation and intramedullary system fixation^{11–13}. Cancellous lag screws remain the most common treatment for femoral neck fractures in young and middle-aged people. However, previous studies, including biomechanical studies and randomized controlled trials, have reported that this procedure has a high risk of postoperative internal fixation failure, femoral neck shortening, varus deformity, femoral head necrosis and nonunion due to the shear forces mentioned above, especially in the treatment of type III fractures^{14–17}. To date, the optimal internal fixation technique for Pauwels type III femoral neck fractures is still controversial. Consequently, clinicians continue to explore the next generation of effective fixation implants¹⁸. Therefore, we performed finite element analysis to explore the biomechanical stability of a new internal fixation femoral neck system (FNS) for treating Pauwels type III femoral neck fractures (Fig. 1). Moreover, two cannulated screw configurations, which are used most commonly in clinical practice, were used for comparisons in our study. Thus, the purpose of our study was to evaluate the biomechanical stability of the new system and provide a theoretical reference for the application of the new internal fixation system in clinical practice.

Materials And Methods

Three-dimensional modeling of the femoral neck fracture

A 26-year-old healthy male volunteer was recruited, and the upper and middle part of the volunteer's femur was scanned using a Siemens 64-row CT scanner with a layer thickness of 0.5 mm. The CT image was stored in the Digital Imaging and Communications in Medicine (DICOM) format and was outputted to the three-dimensional reconstruction medical software Mimics 21.0 (Materialise, Belgium). A three-dimensional model of the upper part of the femur was built on the basis of the gray value of the tissue and segmentation of the region and was then exported in the stereolithography (STL) format. This model was imported into Geomagic Wrap 2017 software (Geomagic, USA) for smoothing, meshing, noise reduction and surface fitting and also imported into SolidWorks 2017 software (Dassault, France). The three-dimensional model of the cortical bone and cancellous bone was developed by Boolean operations, and the proximal femoral bone model was built for reassembly.

Building the Pauwels III femoral neck fracture model

The proximal femoral bone model was developed in SolidWorks 2017 software(Dassault, France). We first created the center of the femoral head, and a cross in the transverse plane was created. Then, we created cutting plates that intersected the center of the femoral neck at angles of 50°, 60° and 70° with respect to the transverse plane. The femoral neck was cut by the cutting planes, simulating Pauwels type III fractures (Figure 2).

Building the internal fixation model

Using SolidWorks 2017 software, we built three kinds of internal fixation models (FNS, triangular cannulated screw configuration, inverted cannulated screw configuration) according to the clinical fixation and engineering geometric data modeling programs. In the construction of the FNS model, a sliding hip screw with a diameter of 10 mm was placed at an angle of 130° to the locking plate, and one antirotational screw with a diameter of 6.4 mm was placed at an angle of 7.5° to the main screw at the proximal end of the FNS. At the distal end, two holes were made for a 5-mm locking screw (Figure 3). In the other two models, three cannulated screws were placed in positive triangular and inverted triangular configurations that were parallel to each other. Cannulated screws with a diameter of 7.3 mm were fabricated using SolidWorks software according to clinical Synthes screw data. Since the focus of this study was not related to the thread, threaded screw sections were modeled as solid cylinders to simplify the model. The plates and screws were composed of the titanium alloy Ti6Al4V. Subsequently, the models were imported into Abaqus 2017 software((Simulia, France) for meshing (Figure 4). Each assembly was meshed by tetrahedral elements.

Material parameters

For modeling purposes, it was assumed that the models were continuous, isotropic and uniform linear elastic materials. The number of nodes and elements of the three fixation models and the elastic modulus of the bones and implants are listed in Tables 1 and 2.

Table 1
Material properties used in the present study (titanium alloy, cortical, and cancellous bone)

Titanium alloy		Cortical bone		Cancellous bone	
E (GPa)	Poisson’s ratio	E (GPa)	Poisson’s ratio	E (GPa)	Poisson’s ratio
105	0.35	16.8	0.3	0.84	0.2

Table 2
The details of three assembly units and the total amount of nodes

Case group	Pauwels 50°	Pauwels 60°	Pauwels 70°
FNS model			
Node	290383	356534	438892
Unit	251421	228606	284567
Mesh size	Maximum: 2 mm; minimum: 0.8 mm		
inverted configuration			
Node	351189	343782	458356
Unit	225337	220419	299455
Mesh size	Maximum: 2 mm, minimum: 1.5 mm		
Triangular configuration			
Node	357169	360575	343539
Unit	229446	231574	220136
Mesh size	Maximum: 2 mm, minimum: 1.5 mm		

Boundary conditions and loading force settings

This study simulated the forces on the hip during the stance phase of walking. For calculation purposes, the distal end of the femur was completely fixed. In the finite element models, loads of 1400 N and 2100 N, equivalent to double and triple the body weight of the subject, were applied to the center of the femoral head. The force vector pointed laterally at an angle of 13° to the axis of the femoral shaft in the coronal plane and posteriorly at an angle of 8° to the shaft in the sagittal plane¹⁹.

Contact settings

According to the contact method described in previous studies²⁰⁻²², contact binding was created between the internal fixation screw and the femur, and friction contact was added to the fracture surface, with a friction coefficient of 0.46.

Evaluation criteria

In finite element analysis, the stress distributions, peak stresses, and displacements of the femur and internal fixations were measured in each group. The variation in each parameter was observed in each group.

Results

Von Mises stress (VMS) distributions and maximum stresses in the femoral neck and internal fixation

The VMS distributions for the three internal fixation models with Pauwels angles of 50°, 60°, and 70° were assessed. In the femur, the stresses appeared to be concentrated at the site closest to the femoral calcar in each group, and the peak VMSs of the femoral head in the two cannulated screw groups were higher than that in the FNS group (Figure 5, 6). In the internal fixation components, the stresses appeared to be concentrated at the middle surface of the screw near the fracture line in each group. The peak VMS of internal fixation components in the FNS group was higher than that in the PCS group (Figure 8, 9). However, the stress distribution was more uniform in the FNS model than in the other two models. Moreover, as the Pauwels angle and axial load increased, the maximum VMSs of the femoral head and internal fixation components increased in each group (Figure 7, 10).

Displacement in the femur and internal fixation

According to the displacement contours of the femurs with Pauwels fractures at angles of 50°, 60°, and 70°, the maximum displacement occurs at the upper of the femoral head and is shown in Figures 11 and 12. The femur displacement was smaller in the FNS group than in the cannulated screw groups. Moreover, the displacement of internal fixation components were observed for all three internal fixation methods (Figures 14 and 15). The displacement of internal fixation component was smaller in the FNS group than in the other two groups, which indicated that FNS fixation may reduce the risk of postoperative internal failure. Moreover, as the Pauwels angle and axial loads increased, the displacements of the femur and internal fixation component in each group increased (Figure 13, 16).

Discussion

In the present study, we compared the biomechanical stability of a newly developed internal fixation FNS to that of the cannulated screw method in the treatment of Pauwels type III femoral neck fractures by finite element analysis. Compared with the two cannulated screw configurations, the internal fixation FNS showed lower peak stresses of the femoral head and smaller displacements of the femur and internal implant in the treatment of Pauwels type III femoral neck fractures. In addition, when the Pauwels angle and loads increased, the stresses and displacements of the femoral head and internal fixation system also increased, which demonstrated that a stable internal fixation system is essential for the treatment of vertical femoral neck fractures. Compared with traditional cannulated screws used for fixation, the internal fixation FNS showed improved biomechanical stability in the treatment of Pauwels type III femoral neck fractures.

Currently, various strategies are used for the treatment of femoral neck fractures, including cannulated screw fixation, DHS fixation, intramedullary system fixation, locked plate fixation, dynamic condylar screw fixation and hip arthroplasty. However, the optimal fixation method for Pauwels type III femoral neck fractures remains controversial, especially for adult patients 65 years of age or younger. We do not consider arthroplasty for young patients unless it is necessary, given that arthroplasty implant prostheses generally last no more than 20 years and can lead to multiple complications, including infections and

dislocations^{23,24}. Unfortunately, commonly used internal fixation instrumentation, including cannulated screws and sliding hip screws, often result in poor outcomes, such as fixation failure, nonunion and AVN. Liporace et al.⁸ reported that the nonunion rate was 19% for fractures treated with cannulated screws alone. Duckworth et al.²⁵ retrospectively analyzed 122 patients with femoral neck fractures and found that the rates of fixation failure, nonunion and AVN were 13.1%, 7.4% and 11.5%, respectively. A recent meta-analysis reported complications of femoral neck fractures in patients 60 years of age or younger, and the rates of operation, implant failure, nonunion and AVN were 18%, 9.7%, 9.3% and 14.3%, respectively²⁶. Several biomechanical studies^{21,27,28} have revealed that the cannulated screw method of fixation is not the best choice for vertical femoral neck fractures in young adults. Because single DHS fixation has been shown to have a lower capacity to resist rotational forces compared with multiple cannulated screw fixation, many scholars suggest inserting a derotational screw in parallel to the main DHS to overcome this limitation at the cost of a larger skin incision and the dissection of more soft tissue. However, a long-term follow-up cohort study indicated that the reoperation rate for DHS + DS remained as high as 18%, and displaced fractures (22%) are associated with a higher risk for reoperation than are nondisplaced fractures (3%)²⁹. Therefore, the treatment principle for this type of fracture is to provide stable support to counter the shear force of the vertical fracture to prevent the displacement of the bone and preserve the blood supply of the femoral head because the occurrence of either issue could adversely affect the blood supply to the femoral head, which may lead to nonunion and necrosis of the femoral head. To address this issue, a new internal fixation FNS was recently developed and used in clinical practice; the FNS is advantageous because it is a relatively minimally invasive technique, leads to less tissue damage, less blood loss, a shorter hospital stay, and a shorter operation time.

Several studies have compared the use of different cannulated screw configurations for the fixation of femoral neck fractures^{20,27,30-32}, but no published studies have compared the mechanical stability of the FNSs used for unstable femoral neck fractures. Some researchers have assessed the mechanical strength of locking plates in the fixation of vertical femoral neck fractures. Aminian et al.³³ examined the fixation strength of vertical femoral neck fractures with cancellous screws, sliding hip screws, dynamic condylar screws, and proximal femoral locking plates in a mechanical study in fresh cadaveric specimens. Their results showed that proximal femoral locking plates were the strongest construct for stabilizing vertical shear femoral neck fractures, followed by dynamic condylar screws and sliding hip screws and three cancellous screws. In another femoral neck cadaver study, Basso et al.³⁴ found that the combination of one locking plate with three common cancellous screws reduced the magnitude of micromovement of the femoral neck and prevented rotation of the bone surrounding the proximal fracture. Several finite element analyses have indicated that a medial support plate can effectively resist the shear force of a Pauwels III femoral neck fracture and create an excellent mechanical environment for fracture healing^{21,35}. In a clinical study, Ye et al.³⁶ also explored three cannulated screws augmented with a medial buttress plate for the treatment of Pauwels type III femoral neck fractures, and their results showed that this surgical method improved the fracture healing rate. In a recent study by Wang et al.³⁷, a new femoral neck plate with four screws (a 7.3-mm partially threaded cancellous compression screw, two

7.3-mm half-screw locking compression screws, and a 5-mm locking screw) was designed by an orthopedic surgeon and a design engineer, and they found that the new plate is superior to the Pauwels screw with regard to biomechanical stability in Pauwels type III femoral neck fracture models with three different fracture angles. Despite the many advantages of those studies, proximal femoral locking plates or a medial buttress plate with cannulated screws require a large surgical incision, which undoubtedly damages the surrounding tissue and impairs the blood supply of the femoral head. To address this challenge, a new internal fixation FNS system was developed, and it is advantageous because it is a more minimally invasive technique, leads to less tissue damage, and protects the blood supply to a greater extent, yielding greater stability in the femoral head. Although several studies have compared the use of different plates for the fixation of femoral neck fractures, no studies examining the mechanical stability of the internal fixation FNS system used in Pauwels type III femoral neck fractures have been published. This is the first study to explore the mechanical stability of the internal fixation FNS for the treatment of unstable femoral neck fractures. Despite the disadvantage of cannulate screw fixation, it is still the most commonly used strategy for treating femoral neck fractures, especially in younger patients. Therefore, we used two types of cannulated screw configurations for comparison in our study.

Our study may provide some guidance for clinical practice, as finite element analysis was conducted. In terms of stress, Figs. 5 to 10 illustrate that the FNS fixation model resulted in a higher maximum stress but a lower femoral head stress than did the other models, and this result can be attributed to the natural internal fixation junction structure created by the junction between the sliding hip screw and antirotational screw. When axial loading is performed, the stress inevitably becomes concentrated at the junction of the two screws. Thus, machinery manufacturers and orthopedists should pay attention to the increased stress at the gap of the internal fixation component and reinforce the stiffness of the gap during the production process. However, apart from the junction of the internal fixation components, the integral part of the FNS has similar or even lower stresses than do the integral parts of the other models. Moreover, the stress distribution was more uniform in the FNS model than in the cannulate screw models. With respect to fracture displacement, Figs. 11 to 16 show that the FNS group is superior to the other two screw configuration groups in terms of the maximum displacement of the femur and internal fixation components, which indicates that the FNS fixation may reduce the risk of postoperative internal fixation failure compared with cannulated screw fixation. The triangular configuration was favorable compared with the inverted configuration. This result is consistent with those in previous studies^{32,38} showing that triangular configuration fixation is slightly better than inverted configuration fixation. This result can be explained by the main nail and the antirotational screw providing excellent angular support and effectively maintaining the fracture in the appropriate position. On the other hand, when two locking screws with a diameter of 5 mm are inserted at the distal end of the new plate, the internal fixation FNS plate can be connected and fixed to the femoral shaft and the femoral neck. Therefore, in terms of biomechanics, the internal fixation FNS serves as a better anchor than do the two types of cannulated fixation and contributes to a lower peak stress of the femoral head and smaller displacements of the femur and internal implant.

Limitation

A limitation of our study is that our results have not been verified by animal experiments or clinical experiments. However, our objective was to explore trends rather than absolute measurements. In this respect, the lack of experimental validation is rational. In the future, we expect that more realistic biomechanical experiments and clinical trials are conducted and verify our results. Despite this limitations, the novelty of this study is that it is the first finite element analysis study to explore the mechanical efficiency of the internal fixation FNS and compare it with cannulated screw configurations by measuring some important parameters that are difficult to experimentally measure and are rarely measured, such as the stress distribution and displacement within the bone and implant, for the treatment of unstable Pauwels type III femoral neck fractures.

Conclusion

In conclusion, using finite element analysis methods, we investigated the mechanical efficiency of an internal fixation FNS and compared it with that of different cannulated screw configurations for the treatment of unstable Pauwels type III femoral neck fractures. We found that the FNS internal fixation is superior to cannulated screw fixation with regard to biomechanical stability, which indicated that the internal fixation FNS may be a new option for the treatment of vertical femoral neck fractures.

Abbreviations

femoral neck system(FNS); von Mises stress(VMS); avascular necrosis (AVN); dynamic hip screw (DHS).

Declarations

Acknowledgements

We thank AJE (www.aje.com) for linguistic assistance during the preparation of this manuscript.

Funding:

There is no funding to this study.

Availability of data and materials:

Data and materials were accessible in the case system at our department.

Authors' contributions:

ZRF, HTS, and LZ conceived the study and wrote the manuscript. JDZ and HDH reconstructed the models and performed the finite element analysis. JJP, and WWH contributed to the data collection and

interpretation of the results. All authors read and approved the final manuscript and consented to publish this manuscript.

Ethics approval and consent to participate:

Not applicable.

Ethics approval and consent to participate:

This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication:

Not applicable

Competing interests:

The authors declare that they have no competing interests.

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Figures

For Fixation of Femoral Neck Fractures

Femoral Neck System

Surgical Technique

Figure 1

Internal fixation model of new internal fixation femoral neck system (FNS)

Figure 2

Pauwels III femoral neck fracture model with Pauwels angles of 50°, 60°, 70°

Figure 3

Geometric modeling of three internal fixation methods. (a) FNS model. (b) triangular cannulated screw configuration model. (c) triangular cannulated screw configuration model.

Figure 4

The mesh distribution appearance diagram in the FNS model with Pauwels angles of 70°.

Figure 5

Von Mises stress (VMS) of the proximal femoral neck under an axial load of 2100N: (A) FNS, (B) Triangular configuration, (C) Inverted configuration at Pauwels angles of 50°. (D) FNS, (E) Triangular configuration, (F) Inverted configuration at Pauwels angles of 60°. (G) FNS, (H) Triangular configuration, (I) Inverted configuration at Pauwels angles of 70°.

Figure 6

Von Mises stress (VMS) of the proximal femoral neck under an axial load of 1400N: (A) FNS, (B) Triangular configuration, (C) Inverted configuration at Pauwels angles of 50°. (D) FNS, (E) Triangular configuration, (F) Inverted configuration at Pauwels angles of 60°. (G) FNS, (H) Triangular configuration, (I) Inverted configuration at Pauwels angles of 70°.

Figure 7

Graphic demonstration of the maximum femur head stress (MPa) in three models.

Figure 8

Von Mises stress (VMS) of the internal fixation under an axial load of 2100N: (A) FNS, (B) Triangular configuration, (C) Inverted configuration at Pauwels angles of 50°. (D) FNS, (E) Triangular configuration, (F) Inverted configuration at Pauwels angles of 60°. (G) FNS, (H) Triangular configuration, (I) Inverted configuration at Pauwels angles of 70°.

Figure 10

Graphic demonstration of the maximum internal fixation stress(MPa) in three models.

Figure 11

The displacement of the femur under an axial load of 2100N: (A) FNS, (B) Triangular configuration, (C) Inverted configuration at Pauwels angles of 50°. (D) FNS, (E) Triangular configuration, (F) Inverted configuration at Pauwels angles of 60°. (G) FNS, (H) Triangular configuration, (I) Inverted configuration at Pauwels angles of 70°.

Figure 12

The displacement of the femur under an axial load of 1400N: (A) FNS, (B) Triangular configuration, (C) Inverted configuration at Pauwels angles of 50°. (D) FNS, (E) Triangular configuration, (F) Inverted configuration at Pauwels angles of 60°. (G) FNS, (H) Triangular configuration, (I) Inverted configuration at Pauwels angles of 70°.

Figure 13

Graphic demonstration of the maximum displacement of the femur (mm) in three models.

Figure 14

The displacement of the internal fixation(mm) under an axial load of 2100N: (A) FNS, (B)Triangular configuration, (C)Inverted configuration at Pauwels angles of 50°. (D) FNS, (E)Triangular configuration, (F)Inverted configuration at Pauwels angles of 60°. (G) FNS, (H)Triangular configuration, (I)Inverted configuration at Pauwels angles of 70°.

Figure 15

The displacement of the internal fixation(mm) under an axial load of 1400N: (A) FNS, (B)Triangular configuration, (C)Inverted configuration at Pauwels angles of 50°. (D) FNS, (E)Triangular configuration, (F)Inverted configuration at Pauwels angles of 60°. (G) FNS, (H)Triangular configuration, (I)Inverted configuration at Pauwels angles of 70°.

Figure 16

Graphic demonstration of the maximum displacement of the Internal fixation (mm) in three models.