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ORIGINAL ARTICLE

Comparative finite element analysis of four different internal fixation implants for Pauwels type III femoral neck fractures in various fracture angles in the sagittal plane

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ABSTRACT

Objectives: This study aimed to evaluate the performance of four different fixation techniques for Pauwels type III femoral neck fractures considering the fracture morphology in the sagittal plane.

Materials and methods: We constructed three different fracture morphologies in the sagittal plane in Pauwels type III femoral neck fractures: posteriorly angled at 20°, neutral, and anteriorly angled at 20°. We set up four fixation devices, including three cannulated screws (3CS), a dynamic hip screw with an antirotational screw (DHS+CS), a proximal femoral locking plate (PFLP), and three cannulated screws with a medial buttress plate (3CS+MBP). The twelve models were created and analyzed using the finite element analysis.

Results: The finite element analysis revealed that 3CS+MBP yields better results in total vertical and rotational displacements, regardless of the fracture angle in the sagittal plane. For the anterior and posterior angled fractures in the sagittal plane, the PFLP was superior to the DHS+CS. However, the DHS+CS exhibited less displacement than the PFLP in the neutral fracture line in the sagittal plane. The 3CS group demonstrated poor mechanical stability for Pauwels type III fractures.

Conclusion: Regardless of the fracture line in the sagittal plane, the 3CS+MBP showed better biomechanical behaviors than the 3CS, DHS+CS, and PFLP. In addition, in contrast to the DHS+CS, the PFLP displayed less vertical and rotational displacement in the anterior and posterior fracture lines in the sagittal plane.

Keywords: Femoral neck fractures, finite element analysis, dynamic hip screw plate, three cannulated screws.

The management of femoral neck fractures remains a challenge for trauma surgeons. Many treatment methods have been proposed with good results, including three cannulated screws (3CS), dynamic hip screw (DHS), and proximal femoral locking plate (PFLP).[1-3] Increased rates of fixation failure are observed in Pauwels type III femoral neck fractures due to higher shearing stress. Varus displacement, femoral neck shortening, and screw back-out are common complications after fixation. These have led the surgeons to evolve several technical modifications, such as adding a medial buttress plate (MBP), a transverse calcar screw, or an antirotation screw.[4,5] However, the optimal implant type and fixation technique are still controversial.

Pauwels angle and moment-arm length are well-known radiologic parameters affecting the fate of the femoral neck fractures.[6] Recently, the importance of fracture morphology in the sagittal plane has also been highlighted.[7,8] Wang et al.[8] emphasized the

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biomechanical differences across the sagittal subtypes and reported that the Pauwels type III fractures were mostly posterior oriented. While an increase in Pauwels angle leads to increases in the vertical shear forces, it may be argued that the anterior or posterior fracture line in the sagittal plane also affects the rotational or horizontal shear stress.

Finite element analysis (FEA) is a reliable and practical method for analyzing mechanical parameters that is becoming more widely used in orthopedic research.[4,9,10] This study aimed to compare the mechanical performance of the four different fixation techniques (3CS, DHS with an antirotational screw [DHS+CS], PFLP, and 3CS+MBP) in Pauwels type III femoral neck fractures with different fracture patterns in the sagittal plane and evaluate the vertical and rotational displacements using FEA (Figures 1-5). We hypothesized that the PFLP would provide better mechanical stability than 3CS, DHS+CS, and 3CS+MBP fixations due to its three-point fixation in the femoral neck and fixed angle function on the locking plate.

MATERIALS AND METHODS

Finite element modeling

The computed tomography (CT) scan images of the femur were obtained from a 30-year-old healthy male for other medical reasons using a Somatom CT scanner (Siemens Healthcare GmbH, Forchheim, Germany) with a 1.0 mm slice thickness. The geometry of the cortical and medullary femoral surfaces was reconstructed with a three-dimensional femur model using Materialise Mimics Innovation Suite 21 software (Materialise, Leuven, Belgium). Pauwels type III femoral neck fractures with an angle of 60° in the coronal plane were constructed. To stimulate three different fracture angles in the sagittal plane, we drew a straight line from the center of the femoral head to the center of the femoral neck, and then we determined a line perpendicular to this line. The fracture angle in the sagittal plane forms an angle of 20° anterior, neutral, and 20° posterior with the perpendicular line.[8] The geometry of the 3CS, PFLP, DHS+CS, and 3CS+MBP was modeled using SolidWorks (Dassault Systems, Paris, France). Twelve models were created and transferred to the Ansys Workbench program. Von Mises stress (VMS) distribution and rotational and vertical displacements were evaluated in all models. Von Mises stress (also called equivalent stress) is used to express maximum stress value in design work.

Material properties

All bone and other implant models were assumed to behave as linear elastic and isotropic material.

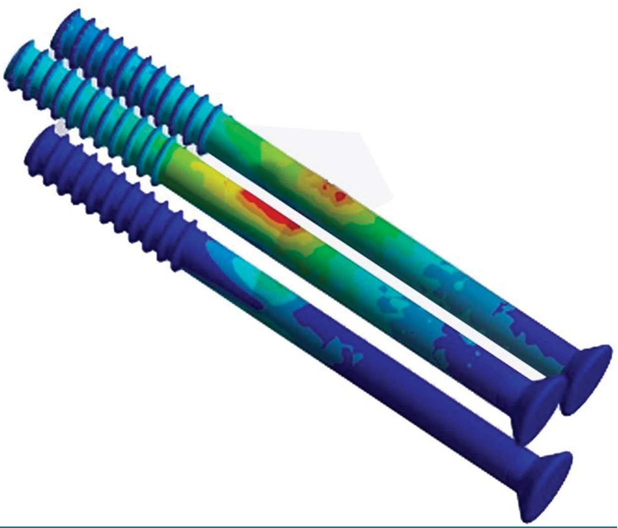

FIGURE 1. Three Dimensional (3D) Model and Von Mises Stress Distribution of 3CS.
CS: Cannulated screws.

FIGURE 2. Three Dimensional (3D) Model and Von Mises Stress Distribution of DHS+CS.
DHS: Dynamic hip screw; CS: Cannulated screws.

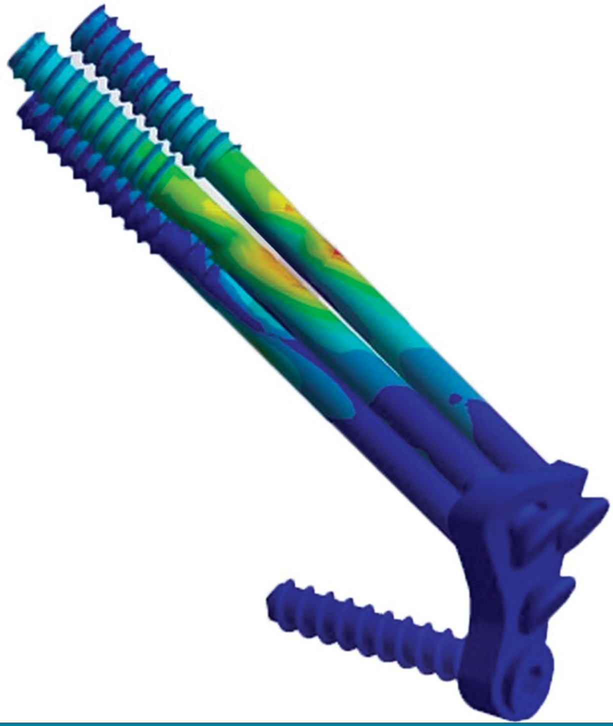

FIGURE 3. Three Dimensional (3D) Model and Von Mises Stress Distribution of PFLP.
PFLP: Proximal femoral locking plate.

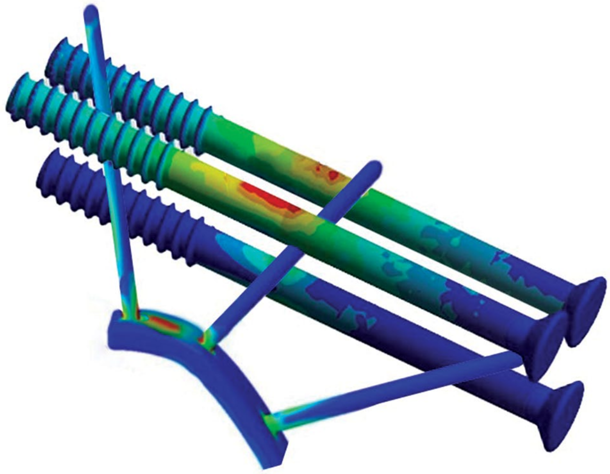

FIGURE 4. Three Dimensional (3D) Model and Von Mises Stress Distribution of 3CS+MBP.
CS: Cannulated screws; MBP: Medial buttress plate.

Cortical bone, cancellous bone, and titanium alloys were modeled with an assumed Young's elastic modulus of 16.8, 0.84, and 110 GPa, respectively.[5] The coefficient of friction of the bone-to-bone interface at the fracture line and bone-to-titanium interface were assigned 0.3 and 0.46, respectively.[5] The cannulated screw diameter was 7.3 mm with optimal length. The DHS plate thickness and its lag screw diameter were 5.8 mm and 12.7 mm. The PFLP thickness and its shaft screw diameter were 5.0 mm and 4.5 mm. The MBP thickness and its screw diameter were 1.2 mm and 3.0 mm.

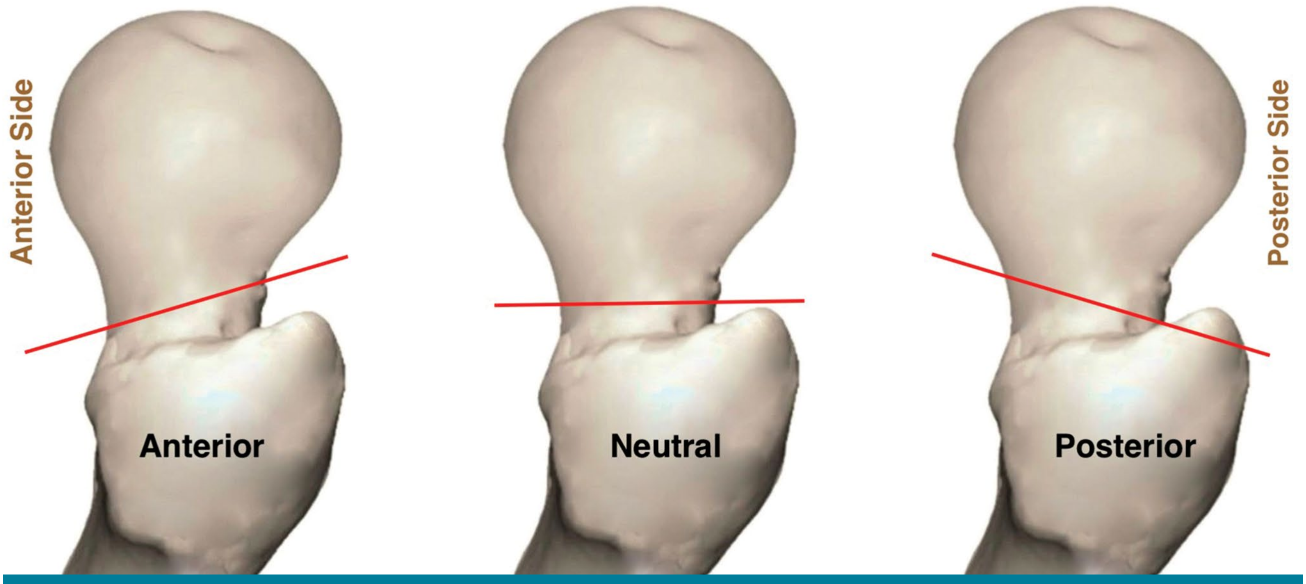

FIGURE 5. Three different fracture morphology in sagittal plane in Pauwels type III femoral neck fracture: posteriorly angled of 20 degrees, neutral and anteriorly angled of 20 degrees.

Loading conditions

The distal end of the femur was restrained (zero displacement) to prevent rigid body movement. The femur models were subjected to three-dimensional forces commonly used in the literature. A load of 2,460 N was applied to the surface of the femoral head with an angle of 23° in the coronal plane and posteriorly at an angle of 68° in the sagittal plane.[11] Similarly, 1,700 N (24° in the frontal plane, 15° in the sagittal plane) and 771 N (41° in the frontal plane, 26° in the sagittal plane) loads were applied to the greater and the lesser trochanter, respectively.[11]

RESULTS

The vertical and rotational displacements of the proximal femur with an anterior fracture angle of 20 degrees in the sagittal plane were 5.12 and 2.32 mm for the 3CS, 4.37 and 1.58 mm for the DHS+CS, 2.45 and 1.18 mm for the PFLP, and 2.12 and 1.05 mm for the 3CS+MBP, respectively. The vertical and rotational displacements of the proximal femur with a neutral fracture angle in the sagittal plane were 4.44 and 2.12 mm for the 3CS, 2.45 and 1.12 mm for the DHS+CS, 2.92 and 1.37 mm for the PFLP, and 1.85 and 0.92 mm for the 3CS+MBP, respectively. The vertical and rotational displacements of the proximal femur with a posterior fracture angle of 20° in the sagittal plane were 4.83 and 2.26 mm for the 3CS, 3.91 and 1.55 mm for the DHS+CS, 2.36 and 1.14 mm for the PFLP, and 1.94 and 1.01 mm for the CS+MBP, respectively (Tables I and II).

The peak VMS values of the fixation devices with an anterior fracture angle of 20° in the sagittal plane were 396.43 MPa for the 3CS, 512.45 MPa for the DHS+CS, 496.56 MPa for the PFLP, and 596.21 MPa for the 3CS+MBP. The peak VMS values of the fixation devices with a neutral fracture angle in the sagittal plane were 361.21 MPa for the 3CS, 453.46 MPa for the DHS+CS, 412.55 MPa for the PFLP, and 567.52 MPa for the 3CS+MBP. The peak VMS values of the fixation devices with a posterior fracture angle of 20° in the sagittal plane were 321.47 MPa for the

TABLE I
Vertical displacements (mm)

	3CS	DHS+CS	PFLP	3CS+MBP
20 anterior	5.12	4.37	2.45	2.12
Neutral	4.44	2.45	2.92	1.85
20 posterior	4.83	3.91	2.36	1.94

DHS: Dynamic hip screw; CS: Cannulated screws; PFLP: Proximal femoral locking plate; 3CS: Three cannulated screws; MBP: Medial buttress plate.

TABLE II
Rotational displacements (mm)

	3CS	DHS+CS	PFLP	3CS+MBP
20 anterior	2.32	1.58	1.18	1.05
Neutral	2.12	1.12	1.37	0.92
20 posterior	2.26	1.55	1.14	1.01

DHS: Dynamic hip screw; CS: Cannulated screws; PFLP: Proximal femoral locking plate; 3CS: Three cannulated screws; MBP: Medial buttress plate.

TABLE III
Von mises stress of implant (MPa)

	3CS	DHS+CS	PFLP	3CS+MBP
20 anterior	396.43	512.45	496.56	596.21
Neutral	361.21	453.46	412.55	567.52
20 posterior	321.47	405.38	425.62	528.74

MPa: Megapascal; DHS: Dynamic hip screw; CS: Cannulated screws; PFLP: Proximal femoral locking plate; 3CS: Three cannulated screws; MBP: Medial buttress plate.

TABLE IV Von mises stress of calcar (MPa)				
	3CS	DHS+CS	PFLP	3CS+MBP
20 anterior	46.38	29.41	19.29	16.36
Neutral	32.25	17.45	22.13	14.11
20 posterior	36.43	27.84	18.34	15.82

MPa: Megapascal; DHS: Dynamic hip screw; CS: Cannulated screws; PFLP: Proximal femoral locking plate; 3CS: Three cannulated screws; MBP: Medial buttress plate.

3CS, 405.38 MPa for the DHS+CS, 425.62 MPa for the PFLP, and 528.74 MPa for the 3CS+MBP (Table III).

The peak VMS values of the calcar region with an anterior fracture angle of 20° in the sagittal plane were 46.38 MPa for the 3CS, 29.41 MPa for the DHS+CS, 19.29 MPa for the PFLP, and 16.36 MPa for the 3CS+MBP. The peak VMS values of the calcar region with a neutral fracture angle in the sagittal plane were 32.25 MPa for the 3CS, 17.45 MPa for the DHS+CS, 22.13 MPa for the PFLP, and 14.11 MPa for the 3CS+MBP. The peak VMS values of the calcar region with a posterior fracture angle of 20° in the sagittal plane were 36.43 MPa for the 3CS, 27.84 MPa for the DHS+CS, 18.34 MPa for the PFLP, and 15.82 MPa for the 3CS+MBP (Table IV).

DISCUSSION

In this study, we evaluated the biomechanical performance of four different fixation devices for the treatment of Pauwels type III femoral neck fractures in different fracture morphologies in the sagittal plane using FEA. For any fracture line in the sagittal plane, the FEA demonstrated that the 3CS+MBP had the minimum displacement in vertical and rotational shear stress, followed by the PFLP and DHS+CS, and the 3CS had the maximum displacement.[12] In addition, the PFLP displayed less vertical and rotational displacement in anterior and posterior fracture lines in the sagittal plane compared to DHS+CS.

The main goal of surgical treatment in femoral neck fractures in younger patients is achieving osteosynthesis through an anatomic reduction and stable fixation.[13] Currently, the 3CS and DHS+CS are the most commonly used fixation devices.[2] Although the 3CS can be minimally invasively placed, it delivers relatively low biomechanical performance, leading to screw back-out and toggling.[14] Compared to 3CS, the DHS+CS provides significantly better biomechanical stability to resist the shear forces.[4] However, increasing bone removal during the lag screw insertion may result in femoral head osteonecrosis.[3] Furthermore, in cases in which the anterior approach is required for anatomical reduction, a second lateral approach may result in high soft tissue damage. This is also supported by a recent meta-analysis in 2021 by Xia et al.[3] comparing the CS and DHS techniques, which concluded that both techniques have pros and cons. They proposed the idea that one should design new implants that can provide more stability while being applied minimally invasively.

In this respect, the PFLP has two theoretical advantages: it has three cannulated screws for the femoral neck and one cortical screw for the shaft.[15] Additionally, cannulated screws can be locked into the plate to provide a fixed angle to avoid neck shortening or varus displacement. Furthermore, it can be performed without the need for a large incision and dissection. We found that the DHS+CS provides less vertical and rotational displacement than 3CS and PFLP in the neutral fracture line in the sagittal plane. In contrast, the PFLP showed less displacement than DHS+CS in the anterior or posterior fracture line in the sagittal plane. The possible explanation was that the PFLP with angle-stable cannulated screws provides three-point fixation in the femoral head to prevent the sagittal bending forces, while the DHS+CS provides two-point fixation. Moreover, the peak VMS in the calcar region was lower in PFLP than DHS+CS, indicating that the PFLP could play a supporting role in the anterior or posterior fracture line in the sagittal plane.

Kunapuli et al.[16] reported that the 3CS+MBP combination effectively resists shearing forces in Pauwels type III femoral neck fractures. Our study also confirmed this conclusion. Regardless of the fracture line in the sagittal plane, the 3CS+MBP exhibited less vertical and rotational displacement than the 3CS, DHS+CS, and PFLP. Furthermore, the peak VMS in the calcar region was lower in the 3CS+MBP group than in the other groups. However, it should be taken into account that the MBP results in a more invasive approach with greater damage to the soft tissues and the femoral head blood supply.

Tan et al.[17] supposed that the calcar region could play a role as a pivot point in the femoral neck fracture, and thus, they suggested that the superior two horizontal screws allowed a more stable configuration than the two vertical screws. However, Stoffel et al.[14] showed the possible failure mechanisms, including sliding, shortening, and varus tilting of the femoral neck, and they recommended the angular stable devices. The effect of the fixation strength on biological healing remains a concern. Berkes et al. [18] reported a case of catastrophic failure after rigid internal fixation in femoral neck fractures, and they emphasized the positive effect of the micromotion with dynamization on the fracture healing. Some studies suggested that the DHS allows the controlled collapse at the fracture site, leading to an increase in healing stimulus. Similarly, Liu et al.[19] reported that the dynamic limited axial compression using cannulated parallel screws combined with MBP or lateral compression plate yields favorable functional outcomes. However, it was reported that a shortening greater than 1.0 cm of the femoral neck changed the hip offset, which lead to poor clinical outcomes.[20] Between the rigidity wrought by internal fixation devices and the failure of the anatomic reduction that emerges in their absence is a narrow corridor for the fate of the femoral neck fractures. There should be a balance between the fixation strength and the micromotion in this corridor. Finally, the success or failure of the fixation remains in the realm of biology, not just the mechanical strength. Future clinical studies are needed to show how these fixation options may affect the healing process.

The main limitation of this study is that it was conducted with a finite analysis model, which may not fully represent the human model. This was a mechanical study that occurred during testing at time zero and where some failure mechanisms cannot be replicated.

In conclusion, regardless of the fracture angle in the sagittal plane, the 3CS+MBP demonstrated better biomechanical behaviors than the 3CS, DHS+CS, and PFLP. In addition, in contrast to the DHS+CS, the PFLP showed less vertical and rotational displacement in the anterior and posterior fracture lines in the sagittal plane.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions: Modeling, analysis, writing: A.Ö.; Idea, concept, analysis, writing: K.Ö.; Review, writing: A.E.O.; Review, writing: M.S.A.; Modeling, analysis, writing: A.Ö.; Idea, concept, analysis, writing: K.Ö.; Review, writing: A.E.O.; Review, writing: M.S.A.

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