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Original Article

Femoral calcar double-supported screw fixation enhances biomechanical stability in Pauwels type III femoral neck fractures: a comparative biomechanical study

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Abstract: Objectives: This study proposed a novel fixation method - femoral calcar double-supported screw fixation (FCDSF) - and evaluated its biomechanical performance. The fixation's mechanical properties were assessed and compared with those of inverted triangular parallel cannulated screws (3CS) and biplane double-supported screw fixation (BDSF) for Pauwels type III femoral neck fractures (FNFs). Methods: Fifty-four synthetic femur models were allocated into three reduction groups simulating positive buttress, anatomical reduction, and negative buttress conditions. Each group was further divided into three subgroups (n = 6), fixed with FCDSF, 3CS, or BDSF. Torsional tests measured torque at the fracture site under 2° and 4° rotation. Load-to-failure tests were then conducted by applying continuous pressure until failure occurred, and the ultimate loads were recorded. Results: Under all reduction conditions, FCDSF demonstrated significantly greater torque at both rotation angles compared with 3CS (P < 0.05), while difference with BDSF was not statistically significant (P > 0.05). FCDSF showed superior load-bearing capacity over both BDSF and 3CS across all conditions (P < 0.05). In both the FCDSF and BDSF groups, positive buttress and anatomical reductions provided significantly better resistance to torsion and shear than negative buttress configurations (both P < 0.05), with no significant difference between the two (P > 0.05). In the 3CS group, only the positive buttress configuration showed a significant improvement over the negative buttress (P < 0.05). Conclusions: FCDSF provides enhanced anti-shear and anti-rotational stability compared with 3CS in managing Pauwels type III FNFs. Negative buttress reduction should be avoided due to its inferior biomechanical performance.

Keywords: Femoral neck fractures, Pauwels type III, biomechanical, cannulated compression screw, osteosynthesis

Introduction

Femoral neck fractures (FNFs) account for approximately 3.6% of all fractures [1]. In young and middle-aged individuals, FNFs typically result from high-energy trauma such as motor vehicle accidents or falls from height. These patients generally maintain good pre-injury function, making hip preservation the preferred treatment option, as hip arthroplasty may not meet their functional demands and carries a risk of revision surgery due to complications [2]. Cannulated compression screws (CCSs) are commonly used for internal fixation due to their minimally invasive nature, simplicity, low surgical trauma, minimal blood loss, and short operative time. Among these, the inverted triangular configuration of three parallel cannulated screws (3CS) is most frequently employed [3].

Pauwels type III FNFs, characterized by steep fracture angles, are considered biomechanically unstable and have long posed challenges in terms of optimal fixation strategy. Their near-vertical fracture orientation subjects the fracture ends to substantial shear forces, increases tensile stress on the proximal femur, decreases the compressive load component along the femoral neck, and impairs interfragmentary contact and stability [2]. These biomechanical disadvantages often lead to proximal fragment displacement and varus deformity. Consequently, internal fixation devices experience high shear stress, resulting in decreased

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fixation reliability. In Pauwels type III FNFs, 3CS fixation is associated with a high incidence of complications such as screw cut-out, fixation failure, femoral neck shortening, and avascular necrosis of the femoral head, primarily due to postoperative mechanical instability [4].

To address these issues, Filipov [5] introduced the biplane double-supported screw fixation (BDSF) technique in 2011. In this configuration, a low-angle distal screw is placed along the compressive trabeculae of the femur, enhancing resistance to axial compression. The greater insertion angle of the screw extends the lateral lever arm, thereby reinforcing the distal and posterior cortical support. Studies have demonstrated that BDSF provides superior resistance to vertical loading, improved functional recovery, and higher union rates than 3CS in Pauwels type III FNFs [6, 7].

Achieving anatomical reduction is widely regarded as critical for fracture healing and complication prevention. However, in clinical practice, obtaining perfect anatomical alignment through closed reduction can be difficult in severely displaced FNFs. Repeated manipulation may further compromise the femoral head's blood supply, significantly elevating the risk of avascular necrosis [8].

To address these clinical challenges, Gotfried et al. [9] proposed the concepts of "positive buttress" and "negative buttress" reduction. In the positive buttress position, the distal fragment is medially displaced beneath the proximal fragment, offering inherent mechanical support. In contrast, the negative buttress position occurs when the proximal fragment is medially displaced over the distal neck fragment, leading to biomechanical disadvantage. Huang et al. [10] retrospectively evaluated the outcomes of Gotfried reduction combined with CCS fixation in young adults with FNFs and found that the positive buttress configuration achieved comparable outcomes to anatomical reduction while lowering complication rates. However, in vertical FNFs with increasing Pauwels angles, the mechanical benefits of positive buttress support may diminish. To date, only limited biomechanical studies have investigated its applicability in Pauwels type III fractures.

Inspired by the distal screw trajectory of BDSF, we developed a new fixation technique: FCDSF, in which two CCSs are inserted parallel to the femoral calcar's compressive trabeculae. This configuration is hypothesized to optimize load transfer, reduce fixation failure risk, and further test the utility of positive buttress reduction in Pauwels type III FNFs. This study employed biomechanical testing to compare the stability of three fixation methods - FCDSF, BDSF, and 3CS-under three reduction types: positive buttress, anatomical, and negative buttress. The findings aim to provide new insights into the optimal fixation strategy for Pauwels type III femoral neck fractures.

Materials and methods

Specimen preparation

Fifty-four synthetic femurs (Sawbones, Pacific Research Laboratories, Inc., Vashon, WA, USA) were used and evenly allocated into three reduction groups: positive buttress, anatomical reduction, and negative buttress. Each group was further subdivided into three fixation subgroups using FCDSF, BDSF, or 3CS, with six specimens per subgroup. All biomechanical tests were performed at the Biomechanics Laboratory, Institute of Orthopaedics, Tianjin Medical University, China.

To simulate Pauwels type III fractures, the femurs were placed on an osteotomy template (**Figure 1A**), and an osteotomy line was marked at a Pauwels angle of 60°. Osteotomy was performed with a hacksaw, leaving a thin cortical bridge intact. After fixation, this remaining cortex was completely transected to replicate an anatomically reduced fracture. For non-anatomical reductions, the proximal and distal fragments were intentionally offset at the inferomedial margin of the femoral neck by one cortical thickness to replicate positive or negative buttress positioning. Each femur was resected more than 20 cm distal to the osteotomy to ensure secure fixation during mechanical testing.

Fixation configurations

All CCSs had a core diameter of 4.8 mm, with thread lengths selected according to insertion method (Dabo Company, China).

3CS configuration: Three guide pins were inserted in an inverted triangular pattern through the lateral cortex at a 130° angle relative

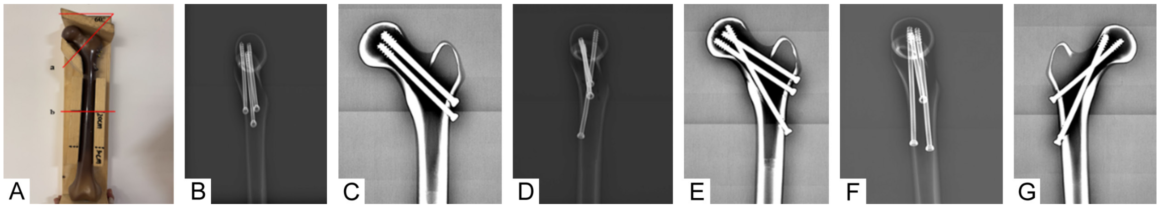

Figure 1. A Creation of the Pauwels type III model. A: 60° fracture osteotomy line; B: distal femoral osteotomy line. B-G Lateral (B- 3CS, D- BDSF, F- FCDSF) and anteroposterior (C- 3CS, E- BDSF, G- FCDSF) fluoroscopy images of implants (3CS: triangular parallel cannulated screws, BDSF: biplane double-supported screw fixation, FCDSF: femoral calcar double-supported screw fixation).

Figure 2. The view of the model in the mold in torsion tests.

to the femoral shaft axis, advancing into the femoral head. Appropriate-length CCSs were then inserted along these pins, followed by guide pin removal (**Figure 1B**, **1C**).

BDSF configuration: Two guide pins were inserted in parallel through the superior and inferior portions of the lateral cortex, angled at 130° to the femoral axis. A third pin was placed below these, angled at 150°, directed toward the femoral calcar. CCSs were inserted along each guide pin, forming an "F"-shaped configuration. All guide pins were then removed (**Figure 1D**, **1E**).

FCDSF configuration: Two guide pins were inserted anteriorly and posteriorly through the lateral cortex, angled at 150° toward the femoral calcar. A third pin was then inserted superiorly at a 130° angle. CCSs of appropriate length were inserted along the guide pins, and all pins were subsequently removed (**Figure 1F**, **1G**).

Biomechanical testing

Each femur was embedded in self-curing denture base resin and mounted on a Bose 3510 Electro-Mechanical Testing System (Bose Corporation, USA). The femoral shaft was aligned at a 7° valgus angle relative to vertical to replicate the coronal plane alignment of bipedal stance. Each subgroup (n = 6) underwent torsion testing followed by axial load-to-failure testing. The nine subgroups included:

Positive buttress: FCDSF, BDSF, 3CS.

Anatomical reduction: FCDSF, BDSF, 3CS.

Negative buttress: FCDSF, BDSF, 3CS.

Torsion testing

The femoral head was fixed using a custom clamp (**Figure 2**). A torsional load was applied clockwise at 15°/min from 0 N·m. Torques corresponding to 2° and 4° of rotation were recorded. Torsional stiffness was calculated to assess rotational stability.

Ultimate load-to-failure testing

After torsion testing, fixtures were adjusted for axial compression (**Figure 3**). A vertical load was applied at 5 mm/min, with continuous recording of load and displacement. Test termination criteria included fracture propagation, fixation failure, a sudden drop in load resis-

Figure 3. The view of the model in the mold in Ultimate load failure tests.

tance on the load-displacement curve, or a plateau indicating no further increase in load. Maximum load and stiffness were documented.

Statistical analysis

All data were analyzed using SPSS version 21.0 (IBM, Armonk, NY, USA). Normality was assessed with the Kolmogorov-Smirnov test. Data conforming to a normal distribution were expressed as mean ± standard deviation (Mean ± SD). One-way ANOVA was used for comparisons across groups, with Bonferroni post hoc tests for multiple comparisons. Statistical significance was set at $P < 0.05$.

Results

Comparison of torsional stability across fixation configurations

The torque data under angular displacements of 2° and 4° during torsional testing are summarized in **Table 1**. Under identical reduction conditions and torsional angles, the FCDSF and BDSF groups demonstrated comparable torque values at the fracture sites, with no statistically significant differences between them ($P > 0.05$). However, both FCDSF and BDSF exhibited significantly greater anti-rotational performance than the 3CS group ($P < 0.05$).

Figure 4 illustrates torque values under different reduction strategies for each fixation method. At a 2° torsion angle, the positive buttress configuration yielded higher torque values than the anatomical reduction and negative buttress configurations in all three fixation groups (FCDSF, BDSF, and 3CS). Although no statistically significant difference was observed between the positive buttress and anatomical reduction conditions ($P > 0.05$), both were significantly superior to the negative buttress configuration ($P < 0.05$).

At a 4° torsion angle, the FCDSF and BDSF groups followed a similar trend: positive buttress and anatomical reduction configurations showed significantly higher torque than negative buttress ($P < 0.05$), with no difference between the former two ($P > 0.05$). In the 3CS group at 4°, the torque under positive buttress (4.23 ± 0.31 N·m) was significantly higher than under negative buttress (3.06 ± 0.43 N·m) ($P < 0.05$). However, no significant difference was observed between anatomical reduction (3.65 ± 0.57 N·m) and negative buttress in this group.

Table 2 presents the torsional stiffness values under anatomical reduction. At both 2° and 4° rotation, FCDSF and BDSF showed significantly higher stiffness than 3CS (both $P < 0.05$), with no significant differences between FCDSF and BDSF (both $P > 0.05$).

Comparison of ultimate load capacity under varying reduction conditions

Table 3 presents the ultimate load-bearing capacities for each fixation method under different reduction types. In all three fixation groups, the positive buttress configuration resulted in significantly higher load capacities than both anatomical reduction and negative buttress ($P < 0.05$). Among the three fixation methods, FCDSF consistently demonstrated the highest ultimate load across all reduction conditions.

Table 1. Results of different configurations in the torsion test under the same reduction conditions (n = 6, means ± SD)

Reduction conditions	Fixation configuration	2° torque(N·m)	4° torque(N·m)
Positive buttress	FCDSF	3.19 ± 0.35	5.29 ± 0.28
	BDSF	3.03 ± 0.28	4.95 ± 0.35
	3CS	2.49 ± 0.38*,#	4.23 ± 0.31*,#
Anatomical reduction	FCDSF	2.96 ± 0.37	5.32 ± 0.42
	BDSF	2.95 ± 0.41	4.97 ± 0.47
	3CS	2.38 ± 0.25*,#	3.65 ± 0.57*,#
Negative buttress	FCDSF	2.35 ± 0.33	4.63 ± 0.40
	BDSF	2.35 ± 0.28	3.93 ± 0.58
	3CS	1.72 ± 0.17*,#	3.06 ± 0.43*,#

FCDSF: femoral calcar double-supported screw fixation, BDSF: biplane double-supported screw fixation, 3CS: inverted triangular parallel cannulated screws. *indicates P < 0.05 for FCDSF vs. 3CS under the same reduction conditions; #indicates P < 0.05 for BDSF vs. 3CS under the same reduction conditions. Statistical significance was assessed by one-way ANOVA followed by Bonferroni post-hoc test.

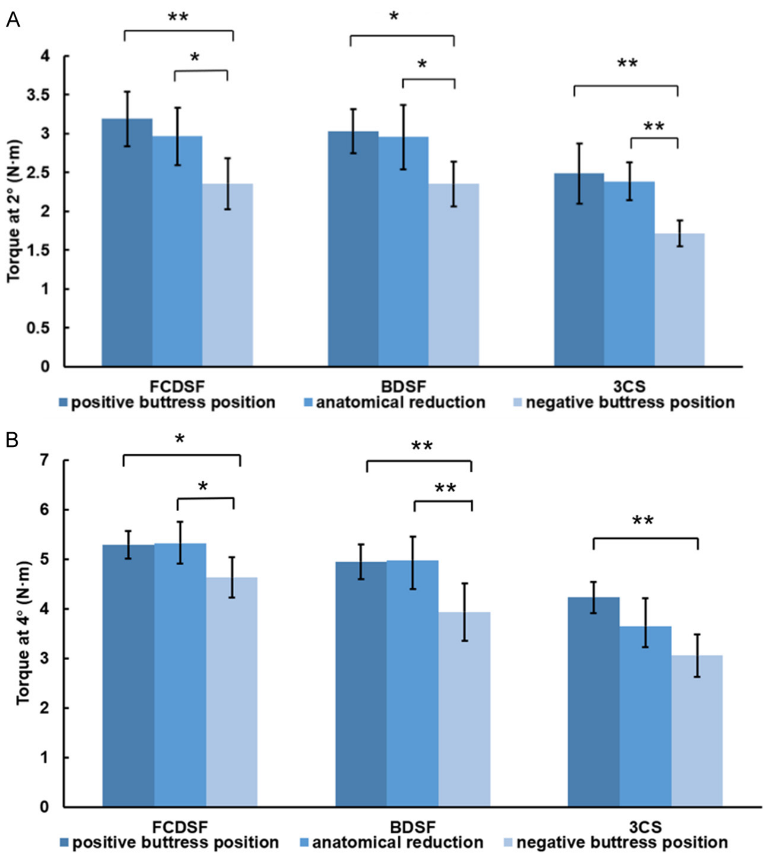

Figure 4. Comparison of the torque values of the same fixation configuration under different reduction conditions. A: The situation at 2°; B: The situation at 4°. *P < 0.05, **P < 0.01, statistical significance was assessed by Bonferroni method. FCDSF: femoral calcar double-supported screw fixation, BDSF: biplane double-supported screw fixation, 3CS: inverted triangular parallel cannulated screws.

As shown in **Figure 5**, pairwise comparisons revealed that the FCDSF configuration had 12.71%, 15.31%, and 16.00% higher ultimate loads than BDSF under positive buttress, anatomical reduction, and negative buttress conditions, respectively (P = 0.030, P = 0.002, P = 0.013). In contrast, 3CS had 37.42%, 37.08%, and 39.17% lower values than FCDSF under the same respective conditions (all P < 0.001). Additionally, BDSF exhibited significantly greater failure loads than 3CS under all reduction types (P = 0.001, P = 0.002, P = 0.010), indicating its biomechanical superiority over 3CS.

Table 4 shows the loading stiffness at displacements of 1.0 mm and 2.0 mm under anatomical reduction. FCDSF demonstrated the highest stiffness, significantly outperforming 3CS (P < 0.05), though the difference between FCDSF and BDSF was not statistically significant (P > 0.05).

Discussion

Given that fracture reduction quality and implant mechanical stability are crucial determinants of fracture healing and key factors in minimizing postoperative complications, this topic has received considerable attention [11]. In this study, we designed an innovative FCDSF method, inspired by the distal screw trajectory of the "F" configuration and the principles of inverted triangular screw placement [5, 12]. The design involves 2CS implanted at high inclination angles along the femoral calcar, aiming to enhance resis-

Table 2. Torsional stiffness of FCDSF, BDSF and 3CS in anatomical reduction (n = 6, means ± SD)

Torsional Angle (°)	Torsional stiffness (N·m/°)		
	FCDSF	BDSF	3CS
2.0	884.50 ± 98.92	768.97 ± 74.70	597.57 ± 66.45*,#
4.0	758.31 ± 83.76	698.61 ± 105.65	556.18 ± 59.91*,#

FCDSF: femoral calcar double-supported screw fixation, BDSF: biplane double-supported screw fixation, 3CS: inverted triangular parallel cannulated screws. At the same torsional angle, *comparison between FCDSF and 3CS, $P < 0.05$; #comparison between BDSF and 3CS, $P < 0.05$ (Bonferroni post-hoc test).

Table 3. Comparison of the ultimate load results under different reduction conditions for the same configuration (n = 6, means ± SD)

Fixation configuration	reduction conditions	Fmax (N)
FCDSF	Positive buttress	2617.88 ± 207.05
	anatomical reduction	2551.30 ± 165.41
	negative buttress	2263.99 ± 144.38*,#
BDSF	Positive buttress	2343.53 ± 125.03
	anatomical reduction	2212.61 ± 117.67
	negative buttress	1951.64 ± 186.66*,#
3CS	Positive buttress	1905.02 ± 138.62
	anatomical reduction	1861.12 ± 130.12
	negative buttress	1626.78 ± 148.77*,#

FCDSF: femoral calcar double-supported screw fixation, BDSF: biplane double-supported screw fixation, 3CS: inverted triangular parallel cannulated screws. In the same configuration, *comparison between positive buttress and negative buttress ($P < 0.05$); #comparison between anatomical reduction and negative buttress ($P < 0.05$). Statistical analysis was conducted using one-way ANOVA with Bonferroni post-hoc test.

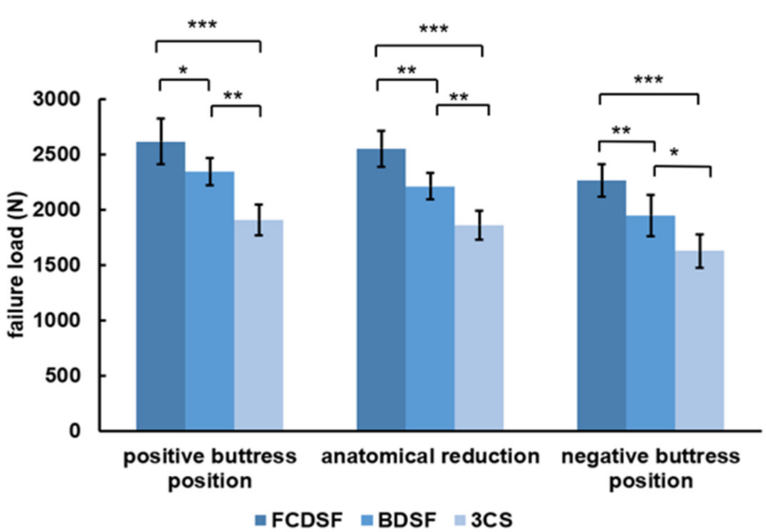

Figure 5. Comparison of the ultimate load among different configurations under the same reduction conditions. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, statistical significance was assessed by Bonferroni method. FCDSF: femoral calcar double-supported screw fixation, BDSF: biplane double-supported screw fixation, 3CS: inverted triangular parallel cannulated screws.

tance to shear forces and improve overall mechanical stability.

To assess its biomechanical performance, torsional and ultimate load failure tests were conducted on Pauwels type III FNF models under three reduction conditions: positive buttress, anatomical reduction, and negative buttress. Results demonstrated that FCDSF achieved similar anti-torsional strength and vertical load-bearing capacity as BDSF but significantly outperformed the conventional 3CS configuration. Notably, the combination of FCDSF with positive buttress reduction provided the most favorable mechanical performance in these unstable fractures.

In the early postoperative period following internal fixation of FNFs, mechanical load relies entirely on the internal fixation construct. Thus, its mechanical behavior directly impacts not only immediate stability but also the vascular environment necessary for subsequent fracture healing. Accordingly, anatomical reduction and mechanically stable internal fixation remain priorities in surgical management. This approach helps counteract vertical shear and varus deformity, promoting stable alignment and successful bone healing. In young patients with optimal bone quality, CCSs are often used to fix both displaced and non-displaced FNFs [13].

Pauwels type III FNFs are biomechanically challenging due to high shear forces across the fracture plane [2, 14]. Meta-analytic data show a nonunion rate of 33% and a

Table 4. Loading stiffness of FCDSF, BDSF and 3CS in anatomical reduction (n = 6, means ± SD)

Displacement (mm)	Loading stiffness (N/mm)		
	FCDSF	BDSF	3CS
1.0	884.50 ± 98.92	768.97 ± 74.70	597.57 ± 66.45$^{*,\#}$
2.0	758.31 ± 83.76	698.61 ± 105.65	556.18 ± 59.91$^{*,\#}$

FCDSF: femoral calcar double-supported screw fixation, BDSF: biplane double-supported screw fixation, 3CS: inverted triangular parallel cannulated screws. At the same displacement, *comparison between FCDSF and 3CS, $P < 0.05$; $^{\#}$comparison between BDSF and 3CS, $P < 0.05$ (Bonferroni post-hoc test).

femoral head necrosis rate of 16% in these fractures. Approximately 36% of patients experience complications such as screw cutout, fragment displacement, delayed union, or nonunion [15]. As a result, numerous studies have sought optimal fixation strategies that can accommodate the biomechanical demands of these vertical fractures and enhance long-term outcomes. However, there is still no consensus on the most effective fixation method, largely due to insufficient high-quality comparative evidence.

While anatomical reduction is widely accepted as critical for favorable outcomes in FNFs [16, 17], repeated manipulation to achieve perfect reduction may jeopardize femoral head vascularity and prolong operative time. To address this concern, Gotfried et al. [9] proposed a non-anatomical reduction approach, introducing the concepts of “positive buttress” and “negative buttress”. In positive buttress reduction, the inner cortex of the proximal fragment lies superior and lateral to that of the distal fragment, and medial displacement of the proximal fragment leads to cortical contact and a step-like configuration. This structure facilitates redistribution of load and disperses shear forces [18, 19].

Huang et al. [10] retrospectively evaluated 67 patients treated with Gotfried reduction and CCS fixation. Harris hip scores in the anatomical and positive buttress groups were comparable and significantly higher than in the negative buttress group. Additionally, the femoral neck shortening rate was 36.36% in the negative buttress group - markedly higher than in the positive buttress and anatomical reduction groups. The primary rationale behind positive buttress reduction lies in improving medial cortical support to redistribute vertical loads. However, with increasing Pauwels angles and associated shear stress, this mechanical advantage may diminish.

Fan et al. [20] conducted a finite element analysis comparing Pauwels type III fractures at 30° and 50° with three reduction strategies. Their findings indicated that the mechanical benefit of positive buttress reduction diminishes as the Pauwels angle increases. Current research on positive buttress reduction primarily focuses on mildly oblique fracture types (Pauwels I-II). Limited data exist on its biomechanical efficacy in Pauwels type III vertical fractures, particularly concerning how medial cortical displacement magnitude affects stability. In this study, cortical offset for positive and negative buttress models was standardized to one cortical thickness, aligning with accepted biomechanical simulation ranges.

Anatomical and biomechanical studies have shown that the position, angle, and spatial configuration of CCSs directly influence the mechanical stability of the fixation [21]. To minimize iatrogenic disruption of the femoral head’s intramedullary blood supply, surgeons typically prefer the 3CS triangular configuration [22, 23], which remains the most widely used CCS-based fixation method [24]. However, the BDSF configuration has been shown to reduce tensile stress and minimize femoral neck shortening compared with 3CS [5]. Filipov et al. [25] reported treating 207 femoral neck fracture cases with the BDSF method, achieving a 96.6% union rate and a 12.4% incidence of femoral head necrosis, with no cases of subtrochanteric fracture. However, it is noteworthy that Pauwels type III fractures were excluded from that study.

In Pauwels type III FNFs, the fracture line is steeply oriented and closely aligned with the femoral shaft axis. Consequently, the component of body weight transmitted along the femoral neck is significantly diminished, and most of the load is transformed into vertical shear forces. This biomechanical configuration reduces interfragmentary compression and frictional resistance, thereby compromising stability and increasing the risk of femoral head displacement along the fracture plane [2].

Given these characteristics, optimal treatment should aim to increase the compressive force component perpendicular to the fracture line. This promotes closer contact and interdigitation between fracture fragments, enhancing resistance to shear and rotational forces, and ultimately improving mechanical stability and healing potential. Holmes et al. [26] reported that parallel screw configurations facilitate controlled femoral head impaction and outperform non-parallel arrangements in biomechanical performance.

In the FCDSF configuration, two cannulated compression screws are inserted in parallel along the direction of the compressive trabeculae at an inclination angle of 150°, functioning as calcar femoral support screws. This orientation increases the lever arm of the screws within the lateral femoral cortex and promotes even stress distribution, thereby enhancing the anti-compression and anti-sliding capacity of the construct. Additionally, a third screw is inserted parallel to the femoral neck axis to provide further axial compression and enhance interfragmentary stability. The wide spacing between screw insertion points effectively disperses stress concentration along the lateral cortex, reducing the risk of postoperative subtrochanteric fractures.

In this study, the mechanical stability of three fixation methods, namely FCDSF, BDSF, and 3CS was assessed by evaluating torque and ultimate load under different rotational angles. Torque, a rotational moment, reflects resistance to femoral head rotation at the fracture interface - higher torque indicates better rotational stability. Ultimate load represents the maximum force the construct can bear before fixation failure, serving as a key index of structural strength [27]. Stiffness, another critical parameter, reflects the construct's ability to resist deformation under load.

Our findings demonstrate that the combination of FCDSF and positive buttress provides the greatest mechanical stability in Pauwels type III FNFs. In torsional tests, FCDSF and BDSF exhibited comparable torque and stiffness, while 3CS showed inferior anti-rotational performance. The prominent anti-shear properties of FCDSF can be attributed to its dual-screw support at the femoral calcar. In load-to-failure tests, FCDSF significantly outperformed both BDSF and 3CS. While FCDSF demonstrated the highest stiffness at both 1 mm and 2 mm displacement, the difference compared to BDSF was not statistically significant. Moreover, the study revealed that at a Pauwels angle of 60°, the positive buttress configuration retains a mechanical advantage, although its superiority over anatomical reduction was not statistically significant.

This study has several limitations. The relatively small number of specimens may limit the generalizability of the findings. The influence of soft tissue structures such as the joint capsule, ligaments, and muscles on mechanical transmission was not considered in the simulation. As a result, the model may not fully reflect the in vivo biomechanical environment after internal fixation. What's more, while synthetic femurs offer uniform material properties, ease of use, and reduced variability, they do not replicate the complex structural and mechanical characteristics of human bone, particularly under physiologic loading. This study employed two classic static tests - torsional testing and ultimate load failure testing. Future research incorporating dynamic mechanical testing may offer more comprehensive insights into the behavior of fixation constructs under cyclic or real-life loading, thereby providing stronger theoretical support for clinical application.

In conclusion, from a biomechanical standpoint, FCDSF demonstrates significantly superior load-bearing capacity compared to BDSF and conventional 3CS constructs. Its anti-rotational performance is comparable to that of BDSF and markedly better than that of 3CS. Furthermore, to minimize the risk of postoperative complications and optimize treatment outcomes, negative buttress positioning should be avoided during closed reduction procedures for FNFs.

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Disclosure of conflict of interest

None.

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