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Biomechanical properties of off-axis screw in Pauwels III femoral neck fracture fixation: Bicortical screw construct is superior to unicortical screw construct

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ABSTRACT

Objectives: The purpose of this study is to determine the biomechanical properties of the bicortical off-axis screw fixation for stabilizing of Pauwels III femoral neck fractures compared with other fixation methods.
Methods: Eighteen synthetic femurs (Sawbones Pacific Research Laboratories, Vashon, WA) were divided into three groups. The osteotomy was made vertically to mimic the Pauwels type III femoral neck fracture. Group A (n = 6) was fixed with traditional inverted triangle cannulated screws. Group B (n = 6) was fixed with a unicortical off-axis screw and two parallel cannulated screws. Group C (n = 6) was fixed with a bicortical off-axis screw and two parallel cannulated screws. Each group was tested with a nondestructive axial compression test at a 7° of valgus followed with 1000 cycles of cyclic loading test from 100 N to 1000 N. Finally, a destructive axial compression test was applied until catastrophic failure.
Results: The average axial stiffness from group A to group C was 856.5, 934, and 1340 N/mm, respectively. The average ultimate failure load from group A to group C was 2612.7, 2508.8, and 3706 N, respectively. Group C exhibited significantly greater axial stiffness and a higher ultimate failure load than the other two groups ($P < 0.05$). Regarding the interfragmental displacement, the values from group A to group C were 0.41, 0.83, 0.36, respectively, and group B exhibited significantly larger fracture gap formation after the cyclic loading test.
Conclusions: The results of this biomechanical study show statistically significant increases in axial stiffness and ultimate failure load for the off-axis screw placed in bicortical fashion. Once the off-axis screw was positioned unicortically, the largest fracture diastasis was observed as compared to the other two methods.

Introduction

The optimal treatment of femoral neck fractures has been developing for several decades. The disease is characterized by a bimodal distribution based on age. In a younger population, the fracture tends to extend in a vertical fashion secondary to a high-energy mechanism. To preserve the femoral head, anatomic reduction with stable internal fixation is the best treatment choice [1,2]. However, it is challenging to withstand the shear force yielded from the vertically oriented fracture, and one clinical study showed that neck shortening and varus collapse of the head would have some negative effect on functional outcome [3]. Pauwels classification, which originally described in 1935, categorizing the femoral neck fractures based on the fracture orientation. Type I fractures are less than 30° from the horizontal, Type II fractures are 30-50° from the horizontal, and the fracture line at an angle of more than 50 degrees from horizontal is defined as a Pauwels type III fracture [4], whose ideal treatment strategy is still controversial. Some biomechanical studies have found biomechanical superiority in the case of fixed angle devices [5–8]. Despite this, these devices are also associated with some inevitable disadvantages in

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comparison with screw construction. Lesser surgical dissection, better rotational stability, and bone preservation make cannulated screw fixation a favorable option for many surgeons [9,10].

To improve the fixation strength of cannulated screws, especially in Pauwels type III fractures, the concept of the off-axis screw was first described by Garden, where an additional screw with a different trajectory is placed perpendicularly to the vertical fracture line in combination with the two original parallel screws [11] [12]. Since then, the effects of the off-axis screw have been heavily studied both biomechanically and clinically, but the results are inconsistent. Although the principle to place the off-axis screw was followed in previous researches, some studies placed it in a bicortical fashion, while others used it unicortically. Such discrepancies in the small details may be crucial and are worth researching more thoroughly. In a biomechanical study, the author positioned a 4.5 mm cortical screw from the greater trochanter to the nonarticular portion of the femoral neck for the bicortical screw purchase, which resulted in better stability compared with the traditional three parallel screw construct [13]. On the other hand, a clinical study applied the off-axis screw in the different way; a 6.5 mm cannulated screw was advanced into the inferior femoral head unicortically [14]. Given that the fixation strength of the internal fixation is closely related to the configuration of the construct, the variabilities in the screw applications discussed in previous studies leads to outcome inconsistencies, resulting in confusion as to the best application of the off-axis screw.

To the best of our knowledge, there are no studies that have directly compared the biomechanical differences in off-axis screws applied in either bicortical or unicortical fashion. Therefore, the goal of this study was focus on the different configurations of the screw constructs in order to determine the ideal model for clinical applications.

Materials and methods

Specimen preparation

Eighteen medium, left side 4th generation synthetic composite femurs (model 3403, Sawbones, Vashon, WA) were utilized in the study. These testing materials were chosen for several particular reasons. Firstly, the biomechanical properties of the selected composited femurs were similar to those of the younger population, who are frequently the victim of Pauwels type III fractures. Secondly, the variations between the synthetic bones are much lower than those found in cadaveric tissue. Each specimen was cut to a 15 cm proximal segment and divided into three groups of 6 each. Then, the anatomic axis of the femurs were aligned in a 6 cm cylinder tube and potted with anchoring cement (PMMA).

Prior to the osteotomy, all of the specimens were predrilled to facilitate the subsequent anatomic reduction. To ensure the consistency of the implant position, a specific prefabricated drilling jig was used to guide the pin placement. The standard surgical procedure was conducted by first advancing the 3.2 mm threaded pin under fluoroscopic guidance, followed with determining the screw length with a direct measuring gauge. Finally, a screw hole was prepared with a 4.9 mm cannulated drill and the 6.5 mm tap was completed.

To mimic the Pauwels type III femoral neck fracture, a vertically oriented osteotomy 80° from the horizontal was made with an oscillating saw. Then, the fractures were reduced anatomically and secured with one of the 3 screw configurations discussed below. All of the fixations were performed by one surgeon under C-arm fluoroscopic guidance to ensure the ideal implant length and position.

Group A: Three partially threaded 6.5-mm titanium cannulated screws (Stryker, Kalamazoo, MI) were inserted in a parallel and inverted triangular configuration (95 mm inferior, 90 mm anterior and posterior).

Group B: Two parallel 6.5-mm cannulated screws were placed into the femoral head vertically (95 mm inferior, 90 mm superior). At a different trajectory, a 6.5-mm cannulated screw was inserted into the femoral head inferiorly and perpendicularly to the fracture site.

Group C: Two parallel 6.5-mm cannulated screws were placed superiorly and inferiorly into the femoral head (95 mm inferior, 90 mm superior), an additional 4.5-mm cortical screw (DePuy Synthes, Solothurn, Switzerland) was inserted from the trochanteric area into the calcar in a bicortical fashion (66 mm) (Fig. 1).

Biomechanical protocol

The mechanical tests were conducted using a materials-testing machine (AG-X; Shimadzu Corp., Tokyo, Japan). The displacement during the static and cyclic loading was detected with a Fastrak 6 degrees of freedom magnetic tracking system (Polhemus, Colchester, VT, USA). Each specimen was fixed in a cement jig distally and secured into a fabricated adjustable metal clamp as described previously. [15] The specimens were loaded vertically using a 5000 N load cell connected to a flat stainless steel plate centered on the femoral head (Fig. 2.). Initially, all of the specimens were loaded with nondestructive axial compression force at a 7° of valgus to simulate a normal two leg stance [16], and an angle level was used to ensure that the valgus degree was accurate. The preload with 200 N was applied to all the specimens at a speed of 2 mm/min. Then, the load was increased to 600 N; the load-displacement curve was recorded, and the slope in the linearly elastic region was used to calculate the axial stiffness. Second, the 1000 cycle loading test was performed with a force between 100–1000 N (valley/peak) at a frequency of 1 Hz [17], the interfragmental displacement between the femoral head and shaft was record after the cyclic loading test. Finally, destructive axial compression was loaded on all the specimens until catastrophic failure occurred. The

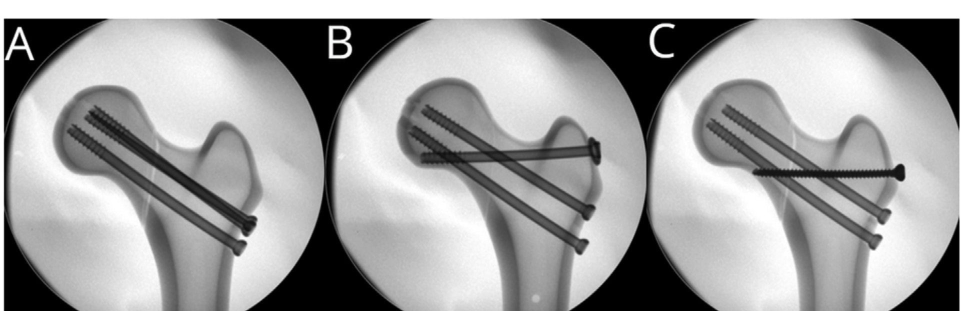

Fig. 1. Pauwels III fractures were simulated via osteotomy 80° to the horizontal plane. The constructs were then repaired anatomically using one of the three constructs.

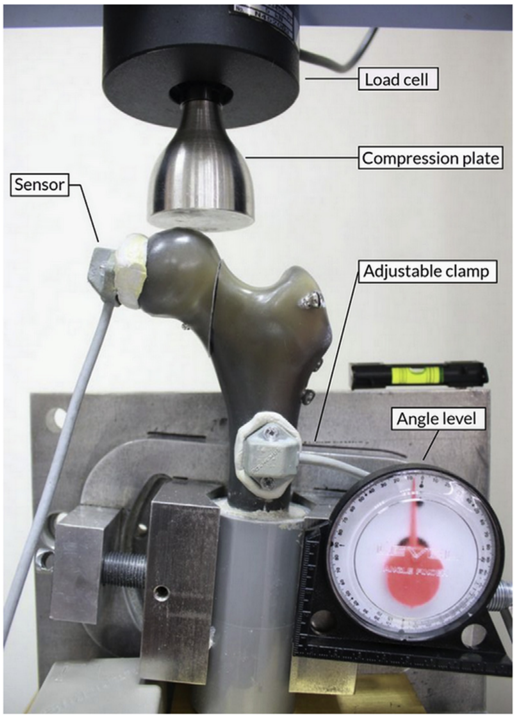

Fig. 2. Biomechanical setup with a composite femur mounted on an adjustable clamp at 7° of valgus, as determined by the angle level. The sensors were secured with anchoring cement and plastic screws.

maximum load during the destructive test was referred to as the failure load. The failure mode of each specimen was recorded for analysis.

Statistical analysis

The statistics were analyzed with the use of SPSS software (SPSS Version 17; SPSS Inc., Chicago, IL, USA. Following confirmation of normality, the data from the three construct groups were analyzed with a one-way analysis of variance (ANOVA) to identify significant differences with respect of axial stiffness, interfragmental displacement, and load to failure. A Bonferroni correction was selected for the post hoc power analysis. A confidence interval of 95% was used for all the tests to determine significance.

Results

The raw biomechanical results of axial stiffness, interfragmental displacement, and ultimate failure load are shown in Table 1.

Axial stiffness

The average axial stiffness from Group A to Group C were 856.5, 936, 1340 N/mm, respectively (Fig. 3). The construct with a bicortical off-axis screw with two vertically parallel cannulated screws exhibited significantly higher axial stiffness as compared to the other two groups ($p < 0.05$).

Table 1
Average axial stiffness, post cyclic load displacement, and ultimate failure load in the different groups.

Groups	Axial stiffness (N/mm)	Displacement (mm)	Failure load (N)
A	856.5(83.1)	0.41(0.14)	2612.7(172.9)
B	934(147.4)	0.83(0.23)[a]	2508.8(210.9)
C	1340(134.6) *	0.36(0.19)	3706(514.5) *

Average values are given along with one standard deviation in parentheses.
[a] Shows a statistically significance increase. (ANOVA with post hoc testing, $p < 0.05$).

Interfragmental displacement

After the cyclic loading test, all the specimens in the three groups survived, for which the mean value of interfragmentary displacement from Group A to Group C was 0.41, 0.83, 0.36, respectively. The fracture diastasis of Group B was significantly larger than that of the other two groups ($P < 0.05$), which indicated that the off-axis screw placed in a unicortical fashion had the lowest resistance to interfragmental displacement. There was no significant difference between the other groups ($p = 0.873$). In the case of the off-axis screws placed in a bicortical fashion, the interfragmental displacements were comparable to the traditional screw triad.

Load to failure

According the load-displacement curve, all the specimens exhibited changes in the degree of stiffness prior to catastrophic failure, which indicated hardware plastic deformation or loss of the fixation before the gross breakage. The average ultimate failure load from Group A to Group C was 2612.7, 2508.8, and 3706 N, respectively (Fig. 3). The construct with a bicortical off-axis screw with two vertically parallel cannulated screws exhibited a significantly higher failure load than the other three groups ($p < 0.05$).

Discussion

In the current study, we compared the biomechanical properties of three different screw configurations for the treatment of a vertically oriented femoral neck fracture. It was found that a combination of one bicortical off-axis screw with two vertically parallel cannulated screws yielded significantly greater values in terms of axial stiffness and failure load. In contrast, the construct with the unicortical off-axis screw exhibited mechanical inferiority in terms of resisting interfragmental displacement.

Regarding the treatment of a Pauwels III femoral neck fracture, the off-axis screw has been proposed in numerous previous studies to simultaneously preserve the advantages of the use of screws and improve the fixation strength [8,12–14,16,18]. Although there seems to be more biomechanical evidence supporting the fixed angle device, some surgeons still prefer cannulated screws considering that the surgery is less invasive and that there is better bone preservation and easier insertion [9,19]. In addition, previous researchers have concluded that a multiple screw construct yields greater rotational stability than a fixed-angle construct [10,20]. Nowotarski et al. conducted a biomechanical study to compare four fixation methods. They demonstrated that the fixed-angle device was stronger than the traditional cannulated screws alone. However, the authors also found that once the traditional screw was replaced by one bicortical off-axis screw, the construct exhibited comparable axial stiffness and rotational rigidity compared with the fixed-angle device [16]. The aforementioned findings were compatible with the results of the current study.

Our biomechanical results indicated that the bicortical off-axis screw construct has significantly greater value than three parallel screws in terms of axial stiffness and destructive load. In contrast, biomechanical enhancement was not observed in the off-axis screws that were placed unicortically. Studies have compared the mechanical effects of the off-axis screw with the traditional three parallel screws construct [8,13,16,21]. However, the results of these studies are inconsistent. According to the findings of the current

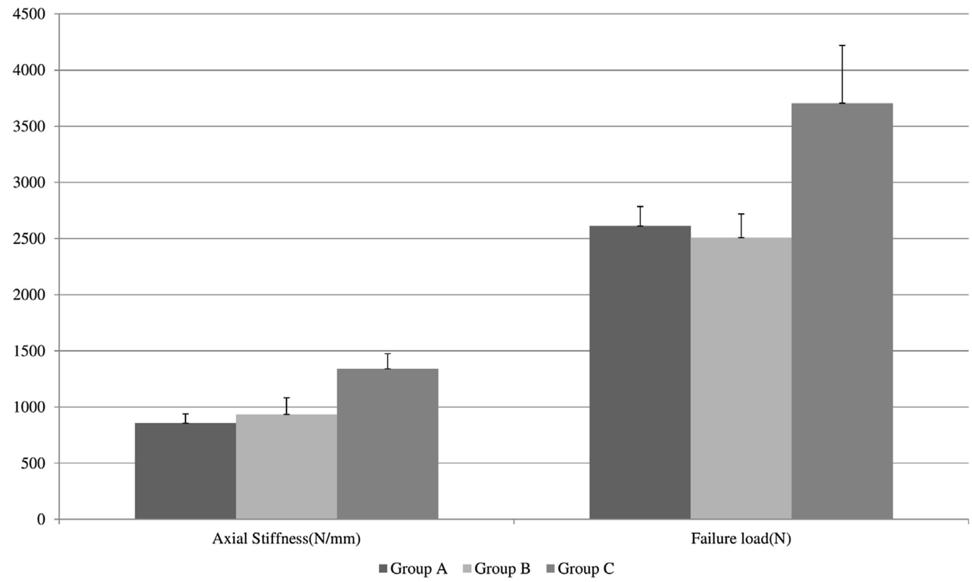

Fig. 3. The axial stiffness and failure load of each group at 7° of valgus.

study, it can be assumed that the inconsistent results found in previous studies might be owing to that the application of off-axis screws was not standardized. Johnson et al. assessed the fixation strength between an off-axis construct and the traditional inverted triad screws in vertically oriented femoral neck fractures and found no significant different between these two groups. However, the off-axis screw was placed in a unicortical fashion [8]. In contrast, studies placing an off-axis screw in bicortical fashion have shown promising results. Hawks et al. found that the bicortical off-axis screw construct exhibited a 70% increase in stiffness as compared to the traditional one [13]. Another biomechanical study conducted by Nowotarski et al. also demonstrated that the bicortical off-axis screw construct had larger axial stiffness in comparison with the traditional three parallel screw construct [16]. Once the off-axis is utilized to strengthen the fixation of a Pauwels III fracture, it should be placed bicortically to achieve optimal grip strength.

A number of studies have compared the different screw configurations with various constructs in clinical settings. However, there is still no consensus as to the clinical impact of the off-axis screw [12,14,18]. In the current study, the interfragmental displacement after the cyclic loading was measured. The migration of the femoral head was 0.83 mm in the unicortical off-axis screw group, which was significantly larger than that found in the other three groups. In the clinical setting, a smaller displacement between fractures is supposed to improve endosteal healing and angiogenesis, which comprise the cornerstone of fracture union. Hoshino et al. conducted a retrospective clinical study to compare the off-axis screw with fixed angle devices and reported failure in 60% of the patients in the screws group versus 21% in the fixed-angle group. However, the authors applied the off-axis screw in various ways, either in unicortical or bicortical fashion. Our results indicated a significant difference in the sturdiness of fracture fixation for these two methods. Furthermore, the overall failure rate of the study was higher than the other studies, and the majority of the patients (>95% of cases) in the study were treated with open reduction, which might account for the increased incidence of fracture nonunion [18]. In contrast, a prospective study treated twenty younger Pauwels III femoral neck fractures with the off axis screw construct, where all surgeries were performed by a single surgeon using a closed reduction method, and the outcomes were satisfactory [14]. To the best of our knowledge, there is only one clinical article directly comparing the use of parallel screws with off-axis screws, and a higher nonunion rate in the off-axis screws group was found [12]. Given that the study included predominantly elderly patients and that the author placed the off-axis unicortically, the inferior results were similar to the findings of our study, where the porous inferior femoral head could not yield adequate holding strength for the unicortical screw. It is suggested that the definite clinical impact of the various off-axis screw configurations should be confirmed in future studies.

The failure pattern of each specimen was analyzed, and we found an obvious distinct mode of failure occurring in the different screw configurations. These findings might account for the biomechanical superiority of the bicortical screw configuration, where the construct exhibited catastrophic failure with cortex disruption (Fig. 4A). In contrast, the cancellous screw cut through (Fig. 4B) was the predominant failure mode in the unicortical configuration. Studies have compared the pull-out strength of cortical screws with cancellous screws in various fractures. However, there have not been any studies focusing on the femoral neck fracture. Jason et al. conducted a cadaveric study to examine the fixation strength of 4.0-mm partially threaded, cancellous screws and 3.5-mm fully threaded, bicortical screws in a medial malleolar fracture, and the unicortical screw group exhibited only 64% of the strength recorded for the bicortical screw group [22]. Likewise, a biomechanical study compared the pull-out strength of screws in cadaveric proximal tibias, where the authors reported the mean pullout strength to be greater in the 4.5 mm bicortical screw than in the 6.5 mm unicortical cancellous screw (544 N versus 428 N) [23]. Even though the results of two previous studies cannot represent the true situation in the femoral neck fracture, the data in the current study indicate that the screw placed in a bicortical fashion is more promising. On the other hand, the specific bone architecture in the femoral head might influence the stability of the unicortical screw. In a cadaveric biomechanical sample, the screw holding power in the four different quadrants of the femoral head were evaluated. The author concluded that given the trabeculae are looser in the inferior portion, the screw here is the weakest [24,25], which supports the finding of the current study. The off-axis screw placed in the inferior femoral head could not exhibit biomechanical superiority.

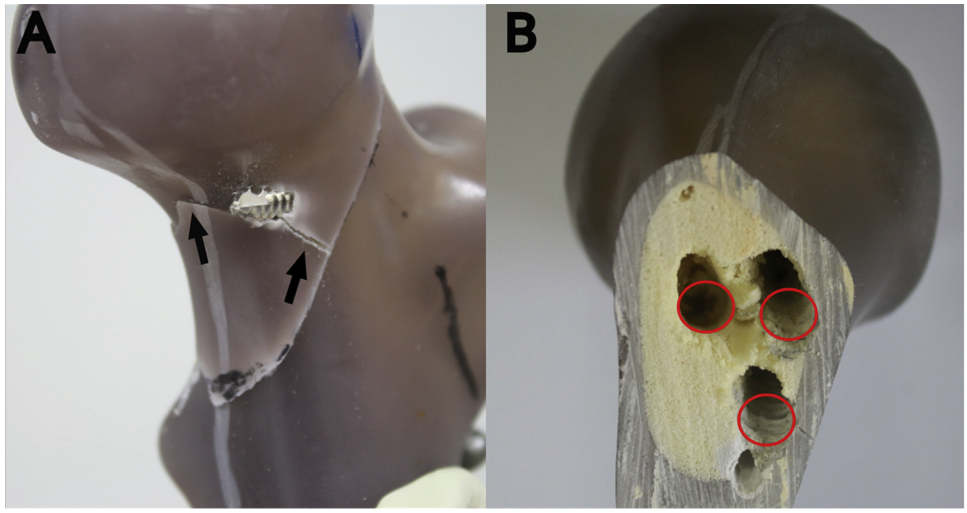

Fig. 4. The different failure patterns after the destructive load (A) Catastrophic failure with cortex disruption (Black arrow) was observed in the bicortical screws constructs (B) Following a load increase, the unicortical screw cut through the cancellous bone superiorly, and the construct failed with significant fracture displacement (Red circles indicate the original screw holes prior to the destructive test). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

There are some limitations of the current study. First, composite bone was chosen as the specimen for the experimental setup rather than cadaveric bone, which seems to be better for simulating an in vivo situation. However, most cadaveric bones are inherently osteoporotic, while our study is mainly aimed at the Pauwels type III fracture in the younger population, so the composite bone could provide denser cancellous bone and reduce the variability between the specimens. Second, not all of the conceivable force components were included in the biomechanical test. For example, the A–P bending and torsion test that accounts for the force vector in the sitting position were not tested. Finally, fixed angle devices such as dynamic hip screws or proximal femoral locking plates were not included in the current study. However, a comparison of fixed angle devices and cannulated screws has been made in previous studies, and both have their proponents. Too many groups in one study would lead to obscure and confusing results. Hence, we focused on different screw configurations in the current study.

Conclusion

Our study demonstrates that an off-axis screw should be placed in bicortical fashion to provide substantial improvements in the mechanical fixation performance for Pauwels type III femoral neck fractures. The results of the current study provide support from a biomechanical perspective for the clinical application of the off-axis screw.

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Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

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