Enhanced Interfragmentary Stability and Improved Clinical Prognosis With Off-axis Screw Technique in the Treatment of Vertical Femoral Neck Fractures of Nongeriatric Patients

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Abstract

Background: The optimal internal fixation strategy for vertical femoral neck fractures (VFNFs) in nongeriatric patients remains uncertain. The purpose of this study was to compare the clinical prognoses and underlying mechanical characteristics of the novel off-axis screw technique with dynamic hip screw (DHS) and traditional three parallel screws.

Methods: This study included a clinical investigation and a patient-specific finite element analysis (FEA). In the clinical investigation, VFNF patients were grouped by fixation type: (1) three parallel screws (G-TRI); (2) augmentation with an off-axis screw (G-ALP); and (3) DHS with an anti-rotational screw (G-DHS). Fixation failures (non-union, femoral neck shortening (FNS), varus deformation, screw cut-out) and avascular necrosis (AVN) of the three types were compared. In the FEA, twenty-four fixation models with the three fixation types were created based on the data of eight healthy volunteers. Models were assessed under walking conditions. Stiffness, interfragmentary motion (IFM), and implant stress were evaluated.

Results: In the clinical investigation, fixation failure rate was significantly (p<0.05) lower in G-ALP (18.5%) than in G-DHS (37.5%) and G-TRI (39.3%). No significant difference of AVN was observed among three fixation groups. In the FEA, stiffness and implant stress in G-DHS models was significantly (p<0.05) higher, and the IFM of G-ALP was significantly (p<0.05) lower among the groups.

Conclusions: Among fixation types for VFNFs, the off-axis screw technique exhibited a better interfragmentary stability (lowest IFM), and lower fixation failure rate (especially, FNS). Analyzing interfragmentary stability in biomechanical experiments is more consistent with clinical prognosis than construct stability for VFNFs, suggesting that internal fixations should aim for this outcome.

Background

The treatment of vertical femoral neck fractures (VFNFs) in patients younger than 60 years of age is problematic[1]. This is primarily because of the high-energy violent nature, inherently unfavourable blood supply to the femoral neck, inherent biomechanical instability, and inappropriate fixation strategy. Typical prognoses for internal fixations are disappointingly poor, with fixation failure rates reaching as high as 41.9% and avascular necrosis rates reaching as high as 21%. [2] These complications severely impair functional outcome and ultimately result in arthroplasties, which lead to lower quality of life for younger patients. Yet, no consensus has been reached concerning the optimal internal fixation strategy for VFNFs. [1]

According to a 2014 questionnaire study of 573 orthopaedic surgeons,[1] dynamic hip screws (DHS) and cannulated screws are two of the most widely used devices for treating VFNFs. These two methods have quite distinct underlying mechanical characteristics. DHS takes advantage of fixed-angle stability, and thus has a much higher stiffness.[3] Cannulated screws, on the other hand, merely provide interfragmentary compression and lack a fixed-angle construction, and thus has meagre stiffness characteristics. [3] Recent studies [4, 5] recommend DHS over cannulated screws, if the femoral neck
fracture is vertically oriented. Biomechanically, DHS can be described as a “load-bearing” device, which means the implant can share a greater load from the deforming force and is more suitable for unstable fractures.[4] By contrast, cannulated screws can be described as a “load-sharing” device, which is better for stable fractures.

The situation is yet not so clear, however, since clinical evidence using large samples of VFNF patients is still lacking. Thus, definitive evidence that the clinical prognosis of VFNFs treated with DHS is better than that treated with cannulated screws is still to be presented.[6–8] Another factor that complicates the picture is that augmentation with an off-axis screw for cannulated screw fixations significantly increases the resistance to shear deformation force.[9] This is because the off-axis screw effectively neutralizes the “sliding effect”, providing better bone purchase as well as cortical support.[9] Overall, this augmentation reduces the complication rate in clinical following-up. [10] Consequently, the question arises: Is it possible that fixation with a load-sharing device can also achieve satisfactory clinical outcome for VFNFs by modifying the standard screw configuration?

The purpose of this study was to compare the clinical prognoses and underlying mechanical characteristics of the novel off-axis screw technique with DHS and traditional three parallel screws.

**Methods**

This study comprised two parts: a retrospective clinical investigation and a patient-specific finite element analysis (FEA).

**Part 1: Retrospective Clinical Investigation**

From December 2013 to December 2017, we conducted a retrospective search for patients being treated for FNFs in one orthopaedic ward. The following patients were eligible: (1) aged between 20 and 60 years old; (2) had Pauwels angle greater than 50° (i.e., vertical-oriented type, VFNF); (3) treated with hip-preserving surgeries; (4) had pre- and postoperative radiography. Pauwels angle was measured using the modified method based on preoperative antero-posterior X-rays[11]. The following patients were excluded: (1) those with severe comorbidities, including osteoarthritis, osteoporosis, cerebrovascular disease, diabetes, among others; (2) those that additionally had femoral shaft, subtrochanteric, intertrochanteric, or contralateral fractures along with a VNF; (3) those with less than 2 years of follow-up. Finally, a total of 204 patients were included in the clinical investigation, and all gave written informed consent to participate. This study was approved by the local institutional ethics review board (No. 2016 – 143), and was carried out in accordance with the World Medical Association Declaration of Helsinki.[12]

Among the 204 VFNFs, 107 patients were treated with three parallel 6.5 mm cannulated screws (Stryker) (denoted as group G-TRI); 65 patients were treated with three parallel screws augmented with an off-axis screw (denoted as group G-ALP); and 32 patients were treated with DHSs (Depuy Synthes) plus one anti-rotational screw (denoted as group G-DHS). In all of the surgeries, closed reduction was attempted first, and then the reduction quality was evaluated based on intraoperative fluoroscopy imaged in the AP and
lateral planes. Acceptable reductions (displacement was < 5 mm, angulation was < 10°) were defined using Haidukewych criteria. For fractures with unacceptable reduction, an open reduction was performed using the modified Smith-Peterson approach. After an acceptable reduction was achieved, an incision was made laterally according to the type of internal fixation device used. Postoperatively, patients were discouraged from engaging in any weight-bearing activities during the first 3 months of recovery. Thereafter, patients were allowed to gradually engage in partial weight-bearing activities only if their radiographs revealed acceptable bone union. Patients were scheduled for postoperative follow-up 6 weeks, 3 months, and one year after fixation surgery. Thereafter, they were evaluated once per year.

Demographic characteristics, including age at surgery, sex, and fracture characteristics, were collected as baseline information. Fracture characteristics included initial displacement, Pauwels angle, reduction method, and reduction quality. During the follow-up, fixation failure and avascular necrosis (AVN) were recorded for subsequent comparisons with clinical prognosis. Fixation failures included non-union (NU), femoral neck shortening (FNS), varus deformation (VD), and cut-out. NU was confirmed when bone healing was not achieved within 6 months. FNS was defined as ≥ 10 mm shortening of femoral neck length, while VD was defined as ≥ 10° decrement of femoral neck-shaft angle. AVN was evaluated radiographically by using the method of Ficat.

Part 2: Subject-Specific FEA

We also conducted a patient-specific FEA based on data from 8 healthy volunteers, ranging in age from 20 to 60 years old (Appendix 1). The patient-specific FEA models were developed in Mimics software (Version 19.0, Materialise, Leuven, Belgium) and further digitally osteotomized with a Pauwels angle of 70° in 3-Matic software (Version 11.0, Materialise, Leuven, Belgium). The three internal fixation strategies we tested in these models were (1) triangle fixation (G-TRI); (2) triangle screws with an off-axis screw (G-ALP); and (3) DHS (G-DHS). These were compared in each patient-specific fracture model (Fig. 1). The digital construction of these devices was created in SolidWorks 2017 (Dassault Systèmes SolidWorks Corporation, Waltham, MA, USA) and assembled in 3-Matic software. In order to control for confounding variables of surgery quality, all fixation devices were digitally implanted based on the same standard criteria (Fig. 1).

All assemblies were meshed into 1mm equal sized facets and converted into 4-node linear tetrahedron (C3D4) solid elements in Hypermesh 13.0 (Altair Engineering, Troy, MI, USA). The solid models were then exported into software Abaqus 6.13 (Simulia Corp, USA) as inp format files. The property of all bone and implant models were assumed as linear elastic material. The density of cortical and cancellous bone was determined by calculating their Hu values based on computed tomography (CT) scans using the formula described previously.

\[
\rho (\text{g/cm}^3) = 0.000968 \times \text{HU} + 0.5
\]

If \( \rho < 1.2 \text{ g/cm}^3 \), \( E = 2014 \times \rho^{2.5} \text{ (MPa)}, v = 0.2. \)
If $\rho > 1.2 \text{ g/cm}^3$, $E = 1763 \times \rho^{3.2} \text{ (MPa)}, \nu = 0.32$.

For cannulated screws, we used values for screws made of titanium (Ti-6L-4V), which has a Young’s modulus (E) of 110,000 MPa and a Poisson’s ratio of 0.3. [18, 19] For the DHS device, we used values for stainless steel, which has a Young’s modulus (E) of 193,000 MPa and Poisson’s ratio of 0.31[20]. As shown in Fig. 2, to simulate mechanical nature of these implants, thread-bone/implant interfaces were tied while others were set to slide contact. The sliding contact of the fracture surface was modeled with frictional coefficient of 0.46, and the frictional coefficient of other self-contacts was set as 0.3 [21]. All fixation models were constrained to within 80 mm distal from the lesser trochanter and subjected to 237.7% of body weight loading,[22] along the femoral mechanical axis. The dynamic compression effect of cannulated screws and lag screws was simulated by using a preloading of 224N for cannulated screws and 591N for DHSs, the same value per mm$^2$ as we described previously[9]. The above finite element simulation process was validated using cadaveric bone in our previous biomechanical test[9], showing a relative coefficient of 0.78–0.94.

Stiffness, IFM, and implant stress (von Mises stress) were analyzed as biomechanical parameters. Note that, in order to overcome the drawback of “center point fallacy” in previous measurement,[23] the IFM of all nodes on both fracture surfaces was calculated, and then the mean IFM value of all nodes was the parameter that was compared among three groups[9]. IFM of each paired node were calculated based on the formula in previous study[9].

**Statistical Analysis**

Both the clinical and biomechanical statistical analyses were performed with SPSS 24 (IBM Corp. Released 2016. IBM SPSS Statistics for Windows, Version 24.0. Armonk, NY: IBM Corp). Differences in baseline information and clinical complications were evaluated using Chi-square tests and one-way ANOVAs. Biomechanical parameters in patient-specific FEA were evaluated using randomised block one-way ANOVAs. Statistical significance was set at $p < 0.05$, and all tests were two-sided. Means and standard deviations (± SD) were calculated, and counts were tabulated.

**Results**

In the clinical investigation, 204 cases with a VFNF were, on average (SD), 45.4 (± 10.4) years old. Overall demographic and fracture characteristics of the G-TRI, G-ALP, and G-DHS internal fixation groups were statistically indistinguishable ($P > 0.05$) (Table 1). Table 2 shows the distribution of clinical prognoses across the three groups. The overall complication rate was highest in patients in G-TRI (50.5%) and lowest in patients in G-ALP (32.3%), a difference that was insignificant ($P > 0.05$) among groups. As shown in Fig. 3, fixation failures were significantly ($P = 0.015$) lower in G-ALP (18.5%) (Fig. 4) compared with G-DHS (37.5%) (Fig. 5) and G-TRI (39.3%) (Fig. 6). The rate of AVN was similar ($P > 0.05$) different among G-TRI (28.0%), G-DHS (31.3%), and G-ALP (21.5%).
Table 1
Baseline characteristics of included patients with vertical femoral neck fractures

<table>
<thead>
<tr>
<th>Variable</th>
<th>G-TRI</th>
<th>G-ALP</th>
<th>G-DHS</th>
<th>P Value†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participants</td>
<td>107</td>
<td>65</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>44.5 ± 10.7</td>
<td>44.6 ± 10.6</td>
<td>48.2 ± 8.2</td>
<td>0.250</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>47</td>
<td>28</td>
<td>9</td>
<td>0.262</td>
</tr>
<tr>
<td>Male</td>
<td>60</td>
<td>37</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Initial displacement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-displaced</td>
<td>22</td>
<td>15</td>
<td>6</td>
<td>0.870</td>
</tr>
<tr>
<td>Displaced</td>
<td>85</td>
<td>50</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>Pauwels angle</td>
<td>56.6°±7.4°</td>
<td>58.0°±7.0°</td>
<td>59.7°±10.7°</td>
<td>0.226</td>
</tr>
<tr>
<td>Reduction method</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open</td>
<td>27</td>
<td>14</td>
<td>10</td>
<td>0.581</td>
</tr>
<tr>
<td>Closed</td>
<td>80</td>
<td>51</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Reduction quality</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excellent-Good</td>
<td>83</td>
<td>53</td>
<td>25</td>
<td>0.820</td>
</tr>
<tr>
<td>Fair-Poor</td>
<td>24</td>
<td>12</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

*G-TRI, treated with three parallel 6.5 mm cannulated screws; G-ALP, treated with three parallel screws augmented with an off-axis screw; G-DHS, treated with dynamic hip screws plus one anti-rotational screw.

†Chi-square test or one-way ANOVA.
Table 2  
Distribution of clinical prognoses of the three fixation groups after at least 2-years of follow-up

<table>
<thead>
<tr>
<th>Outcome, n (%)</th>
<th>G-TRI (n = 107)</th>
<th>G-ALP (n = 65)</th>
<th>G-DHS (n = 32)</th>
<th>P Value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-union</td>
<td>13 (12.1%)</td>
<td>2 (3.1%)</td>
<td>4 (12.5%)</td>
<td>0.111</td>
</tr>
<tr>
<td>Femoral neck shortening</td>
<td>34 (31.8%)</td>
<td>8 (12.3%)</td>
<td>9 (28.1%)</td>
<td>0.015*</td>
</tr>
<tr>
<td>Varus deformation</td>
<td>22 (20.6%)</td>
<td>7 (10.8%)</td>
<td>3 (9.4%)</td>
<td>0.130</td>
</tr>
<tr>
<td>Cut-out†</td>
<td>10 (9.3%)</td>
<td>3 (4.6%)</td>
<td>3 (9.4%)</td>
<td>0.503</td>
</tr>
<tr>
<td>Fixation failure</td>
<td>42 (39.3%)</td>
<td>12 (18.5%)</td>
<td>12 (37.5%)</td>
<td>0.015*</td>
</tr>
<tr>
<td>Avascular necrosis</td>
<td>30 (28.0%)</td>
<td>14 (21.5%)</td>
<td>10 (31.3%)</td>
<td>0.516</td>
</tr>
<tr>
<td>Overall complications</td>
<td>54 (50.5%)</td>
<td>21 (32.3%)</td>
<td>14 (43.8%)</td>
<td>0.066</td>
</tr>
</tbody>
</table>

* Chi-square test.  
† Cut-out is defined as protrusion of screw out of the femoral head.

In the biomechanical analysis (Fig. 7A), the stiffness of G-DHS fixations (993.4 ± 392.3 N/mm) was significantly higher than that of G-ALP (883.6 ± 427.8 N/mm, p = 0.004) and G-TRI (844.6 ± 408.5 N/mm, p < 0.001) fixations. No significant (p = 0.268) difference was observed between G-ALP and G-TRI models in terms of stiffness. IFM was significantly lower in G-ALP (0.071 ± 0.031 mm) compared with G-DHS (0.097 ± 0.037 mm, p = 0.037) and G-TRI (0.113 ± 0.043 mm, p = 0.02) (Fig. 7B). The G-DHS fixation had significantly greater implant stress (343.6 ± 125.9 MPa) than the G-TRI (196.8 ± 64.8 MPa, p = 0.003) and G-ALP (154.0 ± 40.5 MPa, p < 0.001) fixations (Fig. 7C-D).

Discussion

Clinically, the selection of optimal fixation strategies for VFNFs in non-geriatric patients is still a hotly debated topic in orthopaedic medicine. The present study performed a comprehensive clinical and biomechanical evaluation of the most commonly used devices[1], comparing their relative rates of complications after a two-year follow-up. We found that the “load-sharing” type of device, cannulated screw, not only showed a similar non-union, varus deformation, cut-out, AVN, but also exhibited significantly lower FNS rate when it is implanted using the off-axis technique compared to the “load-bearing” device, DHS. In addition to this clinical finding, we found that in a biomechanical analysis using FEA, DHS fixation had the best construct stability, while off-axis screw technique had the best interfragmentary stability. The analysis of the corresponding clinical prognosis showed that interfragmentary stability (IFM) may better reflect fixation failure outcome especially severe FNS.
Generally, cannulated screws are the most commonly used devices to treat femoral neck fractures\cite{24}; it is preferred by orthopaedic surgeons in 90% of non-displaced and 68% of displaced fractures.\cite{25} This preference is related to the advantages of accomplishing fixation with a minimally invasive surgery, good dynamic interfragmentary compression, ease of screw implantation and low expenses. However, cannulated screws lack a fixed-angle construction, thus exhibiting relatively lower stiffness.\cite{3, 4} That is why they are described as a “load-sharing” implant. In VFNFs, the biomechanical environment is not conducive to bone healing due to high shear, compressive, tensile, and torsional strain across the fracture site. In the present study, we found that three parallel screws were unsatisfactory for repairing these fractures, leading to a fixation-failure rate as high as 36.1% and an AVN rate of 25.8% in our series. These two complication rates are comparable with those reported in other clinical investigations.\cite{2, 11} Therefore, as a load-sharing device, it has been hypothesized that cannulated screws may be unsuitable for fixing VFNFs.\cite{2} \cite{4}

DHS is the most commonly used load-bearing implant in treating VFNFs. Its rigid fixed-angle mechanical construction enables DHS to provide more resistance to VD load. The present study also demonstrated that the stiffness of DHSs is significantly greater than that of cannulated screws, with or without an off-axis screw. This, and the finding that patients in the G-DHS group had significantly higher implant stress among the three groups, provided further evidence of the load-bearing character of DHS. Current recommendations for using DHS rather than cannulated screws are based more on mechanical considerations than clinical evidence,\cite{6, 7} indicating that an evidence gap may exist between current biomechanical and clinical studies of VFNFs and how they relate. In our series, use of DHS or TRI fixations were not significantly different in terms of fixation failure, which is in common with the finding of the FAITH study.\cite{8} Besides, the occurrence of AVN was similar among all fixation groups in the present analysis, however, previous FAITH study\cite{8} reported a higher AVN rate in patients who underwent DHS fixation. This is likely due to the dramatic damage to the blood supply \cite{8, 26} and excessive bone volume loss during the invasive DHS procedure. Therefore, the use of load-bearing devices, like DHS, in treating VFNFs is still unsatisfactory. It is necessary to develop novel devices or modify traditional fixation strategies in order to improve clinical prognosis of VFNFs.

What is the benefit of an additional off-axis screw? We found that adding an off-axis screw to parallel screws improved stability while still being minimally invasive and inexpensive. Our study showed that, despite achieving similar stiffness, the off-axis screw technique had significantly lower IFM and fixation-failure rate than did parallel screws alone. As demonstrated in our previous study,\cite{9} the main mechanical advantage of adding the off-axis screw is to temper the “sliding effect”, improving bone purchase and cortical support. The additional screw also provided increased resistance to shearing deformation forces, and ultimately decreased IFM. Until now, no previous direct clinical and biomechanical comparisons had been performed between the off-axis screw and DHS techniques. In spite of a significant lower stiffness, the present clinical observation showed the off-axis screw technique is similar with the load-bearing implant (DHS) in terms of non-union, varus deformation, cut-out, avascular necrosis. Furthermore, this technique can significantly reduce the occurrence of severe FNS, which was reported to be associated with lower functional scores, residual pain, loss of morbidity due to abductor moment reduction as well
as irritation from protruding screws [27, 28]. According to the present biomechanical analysis, a significant lower IFM in off-axis screw fixation can prevent the high strain environment, which is detrimental for bone repair[29] and predispose to fixation failure such as FNS.

Generally, both stiffness and IFM are two important but separate parameters in statics mechanical experiments. Stiffness, the most historical and commonly reported mechanical characteristic[23], is defined by the ratio between the deforming load and displacement along the loading direction,[30] and represents “construct stability”, but cannot isolate the fracture surface. In contrast, IFM, an increasingly common output parameter studied in recent years, is defined as the movement within the fracture gap and reflects interfragmentary stability, and can more directly reflect stability after fixation in real-world situations.[23]

Few contemporary studies have investigated the intrinsic connection and differences between the two types of stability parameters and their relationship to clinical prognosis. Although DHS fixation is stiffer because of its fixed-angle characteristic, it is actually a “two-point” fixation across the fracture site, and thus exhibits relatively poorer interfragmentary stability. In contrast, despite having less stiffness, the off-axis screw technique could be characterized as a “four-point” fixation, and can constitute a crossed configuration; these results in satisfactory interfragmentary stability. According to the results of our clinical investigation, the fixation strategy that had greater interfragmentary stability, rather than construct stability, led to a better clinical prognosis (Fig. 8). Femoral neck fracture is an intra-articular fracture and requires absolute stable internal fixation and primary healing. It is necessary for internal fixations to eliminate any possible interfragmentary movement, a possibility that can be better evaluated by measuring IFM. Consequently, for fractures that require absolute stable fixation and primary healing, measuring IFM in biomechanical studies may be more informative.

We acknowledge that this study has some weaknesses. One limitation is the lack of statistical power due to the relative few occurrences of non-union, varus deformation and cut-out during the following-ups. An increase in sample size may be beneficial to observe a statistical difference in further studies. Additionally, the cases were retrospectively collected in one medical center. Future prospective or RCT studies recruiting multiple centers are still needed to confirm our findings. Besides, both the stiffness and IFM parameters reflect initial stability. Parameters of strength in destructive tests and cyclic number in fatigue tests are also important to measure in order to evaluate fixation stability; these were not variables of interest in our study here.

**Conclusions**

In the treatment of VFNFs, complication rate was lowest for fixations with an off-axis screw, highest for parallel-screw fixation, and the complication rate for DHS fixation was between these former two. DHS had the greatest construct stability, producing significantly greater stiffness. On the other hand, the off-axis screw technique had the best interfragmentary stability, producing the lowest IFM and achieving the lowest fixation-failure rate. Assessment of biomechanical characteristics of different fixation devices
indicate that no inherent consistency exists between construct stability and interfragmentary stability. For VFNFs, analyzing interfragmentary stability in biomechanical experiments is more consistent with clinical prognosis than construct stability.

**Abbreviations**

VFNFs: Vertical Femoral Neck Fractures; DHS: Dynamic Hip Screws; AVN: Avascular Necrosis; NU: Non-union; FEA: Finite Element Analysis; IFM: Interfragmentary Motion;

**Declarations**

**Ethics approval and consent to participate**

This study was approved by the local institutional ethics review board (No. 2016-143), and was carried out in accordance with the World Medical Association Declaration of Helsinki.

**Consent for publication**

Yes.

**Competing interests**

The authors have no conflicts of interest relevant to this article.

**Availability of data and materials**

The data and materials analyzed during the current study are available from the corresponding author on reasonable request.

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**Authors' contributions**

**D.J. Jiang**: Design the study, Computational simulation & Experimental validation, Analysis the results, Draft the manuscript.

**Z. Zhan**: Evaluate the results and technical support

**Qianying Cai**: Evaluate the results
H. HU: Supervised the study Evaluate the results;
WT. Jia: Design the study, Supervised the study, Experimental validation, Revise the manuscript.

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Figures
Figure 1

The three groups of fixation models studied in the clinical and biomechanical investigations, including Group Alpha (G-ALP), Inverted Triangle (G-ITR), Triangle (G-TRI). Three parallel screws were all positioned dispersedly, at 2.5 mm to the cortex and 5 mm distal to the subchondral bone in the femoral head. The off-axis screw in G-ALP was implanted at 5 mm proximal to the most prominent part of the great trochanter and targeted at the inferior femoral head-neck junction. DHS was implanted inferiorly. The anti-rotational screw was of 1.5 cm parallel and superior to the nail.
The schematic diagram of finite element analysis. During the finite element analysis, thread-bone (yellow boxes) and thread-implant (yellow circle) interfaces were tied while others were set to slide contact. All fixation models were constrained to within 80 mm distal from the lesser trochanter and subjected to 237.7% of body weight loading, along the femoral mechanical axis. A preload of 224N for cannulated screws and 591N for DHSs was applied ahead of the weight load.
Fixation failures and avascular necrosis of the three groups. Fixation-failure rate was significantly lower in G-ALP than in G-TRI and G-DHS. Avascular necrosis rate was also the lowest numerically in G-ALP but was not statistically significant. The height of each bar represents the total number of patients in each group, while the rust-colored section in each bar represents the proportion of patients with complications within the group, and the blue-colored section represents the proportion without complications. Red asterisks indicate significant difference.

Figure 3
Figure 4

3-D reconstructed model of hip and AP radiographs of fracture and treatment fixation in a 49-year-old male with a vertical femoral neck. a-b) Preoperative radiograph and reconstructed model showing vertical femoral neck fracture. c) AP radiograph showing initial treatment with three parallel screws augmented with an off-axis screw. d) AP radiograph of same patient taken 36 months postoperatively revealed bone union without any complications.

Figure 5

3-D reconstructed model of hip and AP radiographs of fracture, treatment fixation and revision implant in a 59-year-old woman with a vertical femoral neck fracture. a) Reconstructed model (AP view) from preoperative CT images shows location of fracture. b) AP radiograph showing initial treatment with dynamic hip screw with an anti-rotational screw. c) AP radiograph of same patient taken 5 months after initial surgery, revealing severe screw withdrawal, femoral neck shortening, varus deformation, and delayed union. d) AP radiograph of same patient after revision operation with arthroplasty.
Figure 6

AP radiographs of a parallel screw fixation in a 58-year-old man. a) Preoperative radiograph showing vertical femoral neck fracture. b) Postoperative radiograph showing treatment with three cannulated screws. c) Radiograph taken 6 months postoperatively in the same patient, showing severe screw withdrawal, femoral neck shortening, and delayed union, as seen in the fracture line. Pre-OP = preoperative; Post-OP = postoperative; 6m = 6 months after surgery.
Figure 7

Results of patient-specific finite element analysis (FEA) in the biomechanical part of the study. a-c) Comparison of mean stiffness (N/mm), interfragmentary motion (mm), implant stress (MPa) for the three types of fixations. Error bars are SD. d) Von Mises distribution of the three fixation strategies.
Figure 8

Rank order of construct stability, interfragmentary stability, and clinical prognosis (fixation failure) of the three fixation types. Construct stability, interfragmentary stability, and clinical prognosis was evaluated separately by stiffness, IFM, and fixation failure.

Supplementary Files

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