Finite element analysis of necessity of reduction and selection of internal fixation for valgus-impacted femoral neck fracture

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ABSTRACT

This study compared the biomechanical characteristics of different treatment strategies based on finite element analysis. Posterior tilt and valgus angle were measured on X-ray from ten valgus-impacted femoral neck fractures, and 7 finite element models that were generated to compare the stress and displacement. The results showed that in the intact femur, von Mises stress was concentrated at the medial and inferior sides of the femoral neck. In valgus-impacted femoral neck fractures, von Mises stress was at the same locations but was 5.66 times higher than that in the intact femur. When 3 cannulated screws were used for internal fixation, anatomic reduction diminished the stress at the fracture end from 140.6 to 59.14 MPa, although displacement increased from 0.228 to 0.450 mm. When the fracture was fixed with a sliding hip screw (SHS) + cannulated screw, there was less stress at the fracture end and greater displacement with anatomic reduction than that without reduction (stress: 15.9 vs 37.9 MPa; displacement: 0.329 vs 0.168 mm). Therefore, the SHS + cannulated screw has superior biomechanical stability than 3 cannulated screws, and is recommended following anatomic reduction to treat valgus-compacted femoral neck fractures.

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Introduction

A valgus-impacted femoral neck fracture classified as Garden type I (Garden 1977) has a posteriorly tilted femoral head, is relatively stable, associated with mild symptoms, and easily misdiagnosed. The optimal treatment approach for this type of fracture is controversial. Because of their stability (minimal displacement) they are treated conservatively sometimes. However, there is a high risk of further displacement and the relatively short femoral neck can lead to complications such as hip dysfunction and pain (Zlowodzki et al. 2008; FAITH Trial Investigators, 2013; Noda et al. 2017). Most Garden I and II fractures (79%) have varying degrees of posterior displacement in lateral X-ray radiographs (Leonhardt et al. 2017). The necessity of reduction and method of internal fixation are also debated. Some studies suggest that for Garden I and II fractures—in particular, valgus-impacted femoral neck fractures—intraoperative reduction does not influence the success of the surgery (Palm et al. 2009; Dolatowski et al. 2016). It has also been argued that as valgus-impacted fractures can destabilize after reduction, there is no need for anatomic reduction (Garden 1971). Others recommend anatomic reduction because the fact that malreduction significantly increases the risk of long-term complications (Fuchtmeier et al. 2001). Additionally, valgus impaction can cause femoral neck shortening resulting in lower limbs of unequal length, which could negatively affect hip function and gait (Zlowodzki et al. 2008; FAITH Trial Investigators, 2013). The most commonly used types of internal fixation are as follows: (1) Inverted triangle fixation of three semi-threaded cannulated screws; and (2) Sliding hip screw (SHS) with antirotation cannulated screw (Slobogean et al. 2015; Stockton et al. 2015). In the present study, we compared the biomechanical stability of different types of internal fixation using models generated by finite element (FE)
analysis, and investigated whether reduction can improve surgical outcome.

Materials and methods

Measurement of displacement in valgus-impacted femoral neck fractures

In order to observe the actual displacement and measure the angle of rotation of valgus-impacted femoral neck fracture, we observed fracture morphology, measured displacement, and established the FE analysis model based on data from 10 patients with obvious valgus-impacted femoral neck fractures. The posterior tilt was measured from archived lateral X-ray radiographs as previously described (Lapidus et al. 2013). Briefly, we drew a straight line perpendicular to the femoral neck cortex at the narrowest part of the femoral neck, followed by parallel lines at 5 mm on either side; the midpoints of the three lines were connected as the mid-collum line (MCL). A circle was drawn along the edge of the femoral head; the intersection of this circle with the MCL was taken as the radius collum line (RCL). The angle between the MCL and RCL was taken as the posterior tilt. The valgus angle was measured according to the Garden index, which is defined as the angle between the medial femoral head pressure trabeculae and medial cortex of the femoral shaft (Garden 1971) and normally has a value of 160°. In the event of a fracture, the valgus angle is determined as the increase in Garden index.

Image data acquisition and fracture modeling

An intact femur model was generated from computed tomography (CT) images of a 75-year-old healthy adult female volunteer. Without osteoarthritis of hip joint, the neck-shaft angle was measured in 128°, and 13.5° of anteverision (The neck-shaft angle and the anteverision angle were in the normal range). CT data were collected with a 64-row imaging system (Siemens, Munich, Germany) with a layer thickness of 0.625 mm and pixel size of 512 × 512. A total of 726 DICOM images were imported into Mimics v20.0 software (Materialise, Southport, Australia) to construct a 3-dimensional model of the femur. After conversion to stl format, Geomagic software (3D Systems, Rock Hill, SC, USA) was used to remove noise, optimize parameters, and generate a model of the curved surface of the femur, which was saved in stp format. The file was imported to Unigraphics NX software (Siemens) to obtain a 3-dimensional model of the femur; a cut was made in the subhead area of the femoral neck, with the position adjusted to simulate valgus-impacted femoral neck fractures. The limiting case of acceptable reset (Garden 1971) was simulated: valgus angle of 20° (Garden Index of 180°) and posterior tilt of 20° (lateral Garden Index of 160°). The cancellous bone in the area of overlap between the femoral head and femoral neck was compressed to simulate an actual fracture. Internal fixation assembly and simulation of fracture reduction were performed on the model.

Assembly of the internal fixation

The most commonly used internal fixation methods for femoral neck fractures are cannulated screws and SHS+ cannulated screw. DePuy Synthes (Raynham, MA, USA) product specifications were used for the cannulated screws and SHS. In cannulated screws models, three cannulated screws were modelled in the standard position. The first screw was placed close to the superoanterior cortical bone of the femoral neck, the second screw was placed close to the superoposterior cortical bone, and the other one was placed close to the inferior cortical bone. Three screws were distributed in the shape of an inverted isosceles triangle and paralleled the femoral neck, and the tip-apex distance(TAD) was confirmed less than 10 mm. The starting point for the inferior screw should be at or above the lesser trochanter to avoid generating a stress riser in the subtrochanteric region. In SHS+ cannulated screw models, a SHS with four side plate holes was used, and an antirotation screw was placed in the superoposterior area of SHS. The tip-apex distance(TAD) was confirmed less than 25 mm (Mei et al. 2014; Florschutz et al. 2015).

The following models were compared: Model 1, intact femur; Model 2, valgus-impacted femoral neck fracture (without reduction or fixation); Model 3, valgus-impacted femoral neck fracture (with reduction but without fixation); Model 4, valgus-impacted femoral neck fracture (without reduction but fixed with 3 cannulated screws); Model 5, valgus-impacted femoral neck fracture (with reduction and fixed with 3 cannulated screws); Model 6, valgus-impacted femoral neck fracture
Tetrahedral 10-node 3D meshing of the models was performed using Workbench software (Ansys, Canonsburg, PA, USA). The number of nodes and elements in the fracture model and for the internal fixation (Table 1) were counted. A mesh convergence study was performed to ensure the mesh was sufficient. The models were validated and the mesh quality was >98%.

The properties of bone and the titanium alloy internal fixation materials (Table 2) are reported elsewhere (Mei et al. 2014; Li et al. 2018).

### Boundary and loading conditions

The femur was adducted by 15° (Mei et al. 2014), the lower end of the femur was fixed, and a force of 700 N (Samsami et al. 2015) was applied directly above the femoral head to simulate the situation of an adult standing on 1 leg (Figure 1).

### Results

**Measurement of femoral head displacement in valgus-impacted fractures**

From the measurement based on X-ray of 10 patients with valgus-impacted femoral neck fractures, the femoral head showed valgus and posterior tilting (18 ± 8° and 19 ± 9°, respectively).

**Comparison of von Mises stress distribution between intact femur and valgus-impacted femoral neck fractures**

The von Mises stress distributions and stress peaks of femur were examined to evaluate the stability of the models (Li et al. 2018). In all models, Von Mises stress was concentrated at the medial and inferior sides of the femoral neck. Von Mises stress was 5.66 times higher in the valgus-impacted fracture (Model 2; 67.3 MPa) than that in the intact femur (Model 1; 11.9 MPa) (Figure 2). In the reduction-only model (Model 3), without fixation, the fracture end is very unstable. With a little external force, there is a great displacement. So, no further calculations or processing were performed.

**Valgus-impacted femoral neck fracture fixed with 3 cannulated screws**

Fixation followed by anatomic reduction reduced von Mises stress at the fracture end to 42% of the value for fixation without reduction (59.14 vs. 140.6 MPa; Figure 3). In the reduction with fixation model, cannulated screws bore more stress at the fracture end, yielding a stress value that was 2 times more than that in the non-reduction model.

**Valgus-impacted femoral neck fracture fixed with SHS + cannulated screw**

After reduction, stress distribution at the fracture end was significantly reduced (from 37.9 to 15.921 MPa; Figure 4), but there was little change in the stress on the internal fixation device (Figure 5).

### Comparison of the 2 types of internal fixation

The above comparisons indicate that using SHS + cannulated screw reduced von Mises stress.
distribution at the fracture end compared to 3 cannulated screws, regardless of whether the fracture was reduced.

**Comparison of displacement**

In all models, the femoral head showed the greatest displacement; Model 2 had a maximum displacement closest to that of the intact femur (0.332 and 0.382 mm, respectively). The displacement was significantly reduced in Model 4 (0.228 mm) and the head was the most stable after fixation with the SHS + cannulated screw without reduction (Model 6), with a displacement of just 0.168 mm. In the 2 models with reduction, the maximum displacements were 0.45 mm (Model 5) and 0.329 mm (Model 7) (Figure 6).

**Discussion**

In this study, the main valgus angle was 18° and the average posterior tilt angle was 19°, similar to previous reports (Leonhardt et al. 2017; Hoelsbrekken and Dolatowski 2017; Sjoholm et al. 2019) and close to the limitation of acceptable reduction (Garden 1971). A preoperative posterior tilt ≥20° or anterior tilt
10°C increases the risk of fixation failure; (Dolatowski et al. 2016; Sjoholm et al. 2019) therefore, some doctors consider a neck-shaft angle between 130°C and 150°C and 0–15° of anteversion as acceptable reduction for displaced femoral neck fractures (Weinrobe et al. 1998; Chua et al. 1998). Mild valgus (<15°) is tolerable but varus angulation and posterior tilt are not as they increase the probability of complications (Garden 1971; Weinrobe et al. 1998; Krischak et al. 2003). A more stringent standard for reduction has been proposed as valgus angulation >5° following reduction is thought to significantly affect long-term prognosis, the incidence of severe hip osteoarthritis at the 10-year follow-up was 55.6%, which was 2 times higher than that in cases of valgus angulation <5° (21.2%) (Fuchtmeier et al. 2001). However, it is reported that for Garden I and II femoral neck fractures, good reduction doesn’t reduce the failure rate of surgery, and the reoperation rate is related only to preoperative valgus angulation (Palm et al. 2009). But
another study showed that preoperative posterior tilt measurements on lateral radiographs could not be used to detect healing complications in these fractures (Lapidus et al. 2013).

Cannulated screws and SHS are the most commonly used implants for fixation of femoral neck fractures, and we compared biomechanical characteristics of them for valgus-impacted femoral neck fractures. Our results showed that von Mises stress was concentrated at the medial and inferior sides in the intact femur, the same as the calcar femorale located. The calcar femorale acts an important role in the transmission of forces from femoral neck to the shaft. Zhang et al. stated that the calcar femorale redistributes stress in the proximal femur by decreasing the load in the posterior and medial aspects and increasing the load in the anterior and lateral aspects (Zhang et al. 2009). All 4 surgical methods increased the stress at the medial and inferior sides of the femoral neck in the rank order of Model 7 < Model 6 < Model 5 < Model 4. The stress in Model 7 (15.921 MPa) and displacements in Models 2 and 7 (0.332 and 0.329 mm, respectively) were closest to the values for the intact femur (Model 1: stress, 11.911 MPa; displacement, 0.38 mm). The latter result indicates that the valgus-impacted fracture was stable in Models 2 and 7, and explains why some patients can move the hip joint and feel no pain. Fixing the fracture by cannulated screws after reduction (Model 5) significantly increased the displacement (0.45 mm), making it the most unstable treatment option.

Femoral neck fractures are clinically challenging because of the high risk of complications. Internal fixation and arthroplasty are the most commonly used surgical techniques for treating femoral neck fractures, but there is disagreement over which one is superior. Internal fixation can significantly reduce the occurrence of complications than conservative treatment (Xu et al. 2017). However, femoral head necrosis and fracture nonunion cannot be completely avoided with internal fixation, which has complication rates of 15.9–34.6% (Slobogean et al. 2017; Han et al. 2016), especially in elderly patients. But in another study, internal fixation of stable femoral neck fractures achieved good results in patients >65 years of age (Min et al. 2016). Thus, appropriate internal fixation and surgical technique can reduce the risk of complications and improve outcome.
Our results indicate that fracture reduction is necessary and that the SHS+ cannulated screw yields an outcome that is closest to the intact femur in terms of stress distribution and displacement, and is therefore a better choice for fixation.

**Limitations**

There were some limitations in our study. Only a finite element analysis was studied, and there was no biomechanical analysis to prove it, the result might not fully reflect the actual situation. Only a single load was applied in a quasi-static manner and thus fatigue cannot be evaluated. Only a force of 700 N was applied directly above the femoral head to simulate the situation of an adult standing on one leg, thus we couldn’t get the distribution of stress of femur in motivation.

**Conclusion**

Although valgus-impacted femoral neck fractures are relatively stable, we still recommend surgical treatment to avoid the risk of further displacement and to restore hip function. In the present study, FE analysis revealed that SHS+ antirotation cannulated screw fixation after anatomic reduction showed the highest biomechanical stability, making it the ideal surgical approach. Anatomic reduction is necessary as it can decrease stress on the fracture end, improve postoperative hip joint function, and reestablish the blood supply to the Weitbrecht retinacula; it may also decrease nonunion and osteonecrosis rates, although additional studies are required to confirm this possibility.

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**Authors’ contributions**

Y. Dai performed the literature search, drafted the manuscript, generated the 3D models, and analyzed the data. M. Ni carried out the FE analysis and assisted with manuscript preparation. B. Dou collected data and critically revised the manuscript. Z. Wang analyzed the data and prepared the figures. Y. Zhang and X. Cui assisted with manuscript translation. W. Ma, and T. Qin, collected the X-rays and did the measurement. X. Xu developed the 3D model. J. Mei designed the study and edited, reviewed, and revised the manuscript.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**Availability of data and materials**

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

**Ethics approval and consent to participate**

The study received approval from the Medical Ethical Committee of Shanghai Jiao Tong University Affiliated Sixth People’s Hospital and Tongji Hospital, Tongji University School of Medicine. And we got the patients’ informed consent.

**Consent for publication**

Consent for publication was obtained from all participants.

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