

Impact of tip–apex distance and femoral head lag screw position on treatment outcomes of unstable intertrochanteric fractures using cephalomedullary nails

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Cheng-Hung Lee^{1,2,*}, Kuo-Chih Su^{3,4,*},
Kun-Hui Chen^{1,3}, Chien-Chou Pan¹ and
Yun-Che Wu¹

Abstract

Background: Cephalomedullary nails are frequently used in unstable intertrochanteric fractures. The implant position is an important factor for surgical success. Thus, in the present study, finite element analysis methods were used to investigate the biomechanical behavior of five different cephalomedullary nail positions in unstable intertrochanteric fractures.

Methods: Five different cephalomedullary nail implant positions were investigated. The observed indicators were the maximum displacement of the lag screw, the stress on the intertrochanteric fracture with involvement of the posteromedial cortex, and the tip–apex distance.

Results: The smallest lag screw displacement was achieved when the implant was closer to the inferior femoral head. Lower stress was placed on the posteromedial cortex when the implant was positioned closer to the inferior femoral head. However, the tip–apex distance increased when the lag screw was positioned more inferiorly.

Conclusions: The results of this study suggest that positioning the lag screw closer to the inferior aspect of the femoral head can reduce stress on the posteromedial cortex and

¹Department of Orthopedics, Taichung Veterans General Hospital, Taichung, Taiwan

²Department of Applied Cosmetology, Hungkuang University, Taichung, Taiwan

³Department of Biomedical Engineering, Hungkuang University, Taichung, Taiwan

⁴Department of Medical Research, Taichung Veterans General Hospital, Taichung, Taiwan

*These authors contributed equally to this work.

Corresponding author:

Yun-Che Wu, Department of Orthopedics, Taichung Veterans General Hospital, 1650 Taiwan Boulevard Sect. 4, Taichung 40705, Taiwan.

Email: wcm0806@gmail.com



deformation of the implant in unstable intertrochanteric fractures. These findings provide a biomechanical basis for selection of the cephalomedullary nail implantation site.

Level of evidence: III.

Keywords

Biomechanics, finite element analysis, cephalomedullary nail, tip–apex distance, unstable intertrochanteric fracture, lag screw

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Introduction

Dynamic hip screw systems are currently considered the gold standard for treatment of intertrochanteric fractures.^{1–3} For unstable intertrochanteric fractures, however, the use of a dynamic hip screw with a trochanteric stabilizing plate or cephalomedullary nail is currently the standard option. Intertrochanteric fractures are common among elderly patients with osteoporosis, but the average implant failure rate is 5% to 15%.⁴ Moreover, implants for such fractures are associated with complications and comorbidities (e.g., thromboembolism, immobility-related complications, and infection) in these older patients.² Previous studies of the outcomes of cephalomedullary nail implantation have revealed that the position of the lag screw is an important factor for postoperative implant failure.⁵ The tip–apex distance (TAD) is equal to the TAD measured on an anteroposterior radiograph (TAD_{AP}) + the TAD measured on a lateral radiograph (TAD_{Lat}). This parameter is often used as an evaluation standard for the lag screw to predict surgical success or failure using the femoral head lag screw position. A TAD of >25 mm usually leads to surgical failure (e.g., cut-out).^{6–8} Thus, the implant position is an important factor for surgical success.

Many studies have used clinical observations and mechanical analysis methods to investigate the effect of the implant position

on surgical outcomes. Some researchers have used *in vitro* mechanical experiments to investigate the effect of different TADs and lag screw positions on implant failure caused by external forces.⁹ The results showed that as the TAD decreased, the force needed to cause implant failure increased, and as the distance between the lag screw and inferior femoral head decreased, the force needed to cause implant failure increased.⁹ However, other reports of the TAD as an evaluation standard have raised questions; in particular, external loading was not shown to result in poorer outcomes even with a TAD of >25 mm.^{10,11} A clinical study on evaluation of a proximal femoral nail antirotation system showed that the most successful cases had an average TAD of 20 to 30 mm.¹² Another report focusing on the clinical evaluation of 11 different cephalomedullary nail implant position regions showed that placement of lag screws close to the anterior and posterior aspects of the femur resulted in higher failure rates, whereas placement of implants in a central position resulted in better postoperative outcomes.⁵

Finite element analysis (FEA) is a method commonly used for mechanical evaluation in the field of orthopedics. A previous report described the use of FEA to investigate the mechanical status of four different types of cephalomedullary nails when the lag screw is

positioned closer to either the superior or inferior femoral head.¹³ The results showed that when the lag screw was implanted closer to the inferior femoral head, the strain was lower and the overall structure was more stable.¹³ Researchers have also used FEA to investigate the effects of different lengths and positions of the lag screw on proximal femoral nails and found that changing the length and implant position of the lag screw caused no significant difference.¹⁴ In addition, the results of studies using FEA for assessment of stable intertrochanteric fractures showed that a lag screw position near the inferior posterior femoral head was a relatively ideal option.¹⁵ In contrast, another FEA study of the stress distribution on the fracture line according to different lag screw positions demonstrated that the optimal lag screw position was at the middle portion of the femoral neck in stable intertrochanteric fractures.¹⁶

As shown in the above-mentioned studies, when the lag screw of the cephalomedullary nail is closer to the anterior or posterior aspect of the femoral head, the failure rate is relatively higher. Thus, previous studies have usually recommended an implant position in the center or near the inferior femoral head for better implant

outcomes, but deeper analysis involving finer positions has not been performed. In addition, the effect of the magnitude of the TAD on the implant outcome has been somewhat contradictory. Thus, the present study involved the use of FEA methods to investigate the biomechanical behavior of five different cephalomedullary nail positions (five positions of the lag screw inside the femoral head from superior to inferior) in unstable intertrochanteric fractures (**AO/OTA 31-A2**). The results of this study can serve as a mechanical basis for clinical orthopedic surgeons when selecting a procedure for surgical nail fixation.

Materials and methods

Creation of a simulation geometry model

This study primarily involved the use of three-dimensional FEA computer simulations of five different cephalomedullary nail implant positions. Thus, finite element simulations of the five different positions were first constructed (Figure 1). The models were composed of cortical bone, cancellous bone, a cephalomedullary nail, a lag screw, and cortical screw parts. Femur model construction primarily employed computed tomography

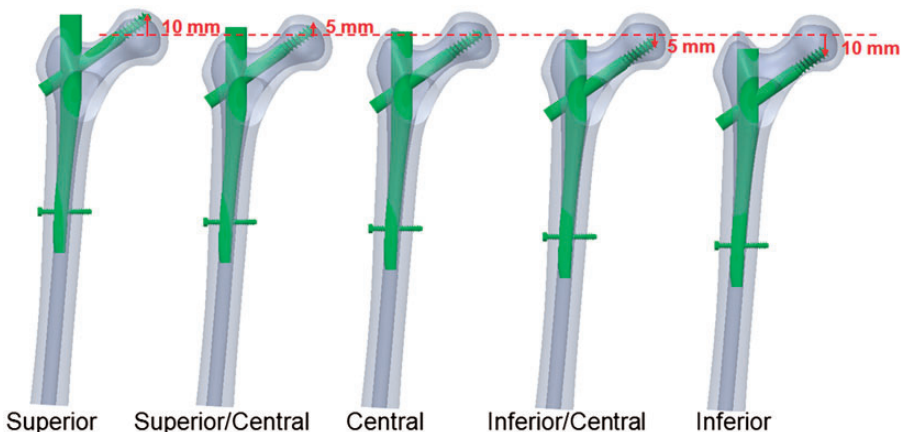


Figure 1. The five groups of computer models used in this study.

images provided by the Visible Human Project of the United States National Institutes of Health. The femur was divided into cortical bone and cancellous bone. The model used in this study was based on the Muller AO classification of unstable intertrochanteric fractures (AO/OTA 31-A2); additionally, an oblique fracture site was constructed at the greater trochanter. For the cephalomedullary nail, lag screw, and cortical screw parts, three-dimensional computer-assisted design software (SolidWorks; Dassault Systèmes SolidWorks Corp., Waltham, MA, USA) was primarily used for drafting. In addition, SolidWorks computer-assisted design software was used to combine the femur, nail, lag screw, and cortical screws. The implantation position of the lag screw of the cephalomedullary nail was divided into five groups. In the standard group, the lag screw of the cephalomedullary nail was positioned in the center of the femoral head and the tip of the lag screw was positioned 10 mm from the apex of the femoral head;^{17,18} in the remaining groups, the tip was moved 5 or 10 mm superiorly or inferiorly along the vertical axis. The five groups were defined as follows. Group 1 (superior): the lag screw was positioned 10 mm superior to the standard position; Group 2 (superior/central): the lag screw was positioned 5 mm superior to the standard position; Group 3 (central): the lag screw was positioned in the standard position; Group 4 (inferior/central): the lag screw was positioned 5 mm inferior to the standard position; and Group 5 (inferior): the lag screw was positioned 10 mm inferior to the standard position. After complete construction of the three-dimensional computer models, the models were imported into FEA software (ANSYS Workbench 15.0; ANSYS Inc., Canonsburg, PA, USA) for FEA simulation.

Convergence test

To use FEA models and obtain accurate results from simulations, convergence tests

must first be performed on the constructed models. Convergence tests primarily use controlled mesh sizes to achieve results, and the sizes of the mesh in the present study were 5, 4, 3, and 2 mm. Mesh elements primarily use the quadratic tetrahedral elements of the ANSYS Workbench software. In the ANSYS Workbench FEA software, the femoral head was given a 100-N downward force (in the direction of the z-axis) as its loading condition. In addition, the distal end of the femur was fixed, serving as its boundary condition (Figure 2). A certain specific point of the femur was observed and its stress value determined. This served as an indicator for the convergence test value, allowing

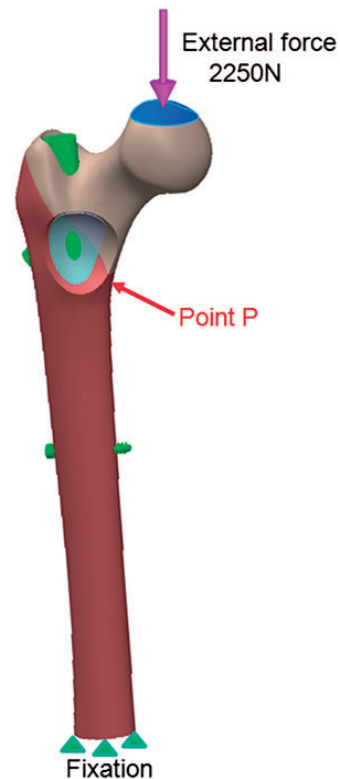


Figure 2. Loading conditions and boundary conditions in unstable intertrochanteric fractures (AO/OTA 31-A2) with cephalomedullary nails.

for determination of whether the convergence criterion was met. After convergence measurement, the three FEA models were divided into a standard grid using quadratic tetrahedral elements with a 3-mm mesh (Figure 3), and mechanical analysis of the simulation was performed using the ANSYS Workbench FEA software. Table 1 shows the numbers of nodes and elements in the meshes of the five groups of models.

Loading conditions and boundary conditions

The simulation of the femur loading was primarily based on the external forces described in previous studies. Therefore,

one load condition and one boundary condition were applied in the present study (Figure 2). The loading condition was a 2250-N downward external force applied to the femoral head.¹² The boundary condition was set as a fixation at the distal end of the femur, setting the displacement along the x-, y-, and z-axes at that site to zero. Additionally, the contact between the cephalomedullary nail and the lag screw and the contact between the implant and the femur were set to no separation type. The goal was to simulate a lack of separation between the lag screw and its point of contact with the cephalomedullary nail; however, a small amount of frictionless sliding is generally acceptable.¹⁹ The contact surface of the oblique fracture site at the greater trochanter

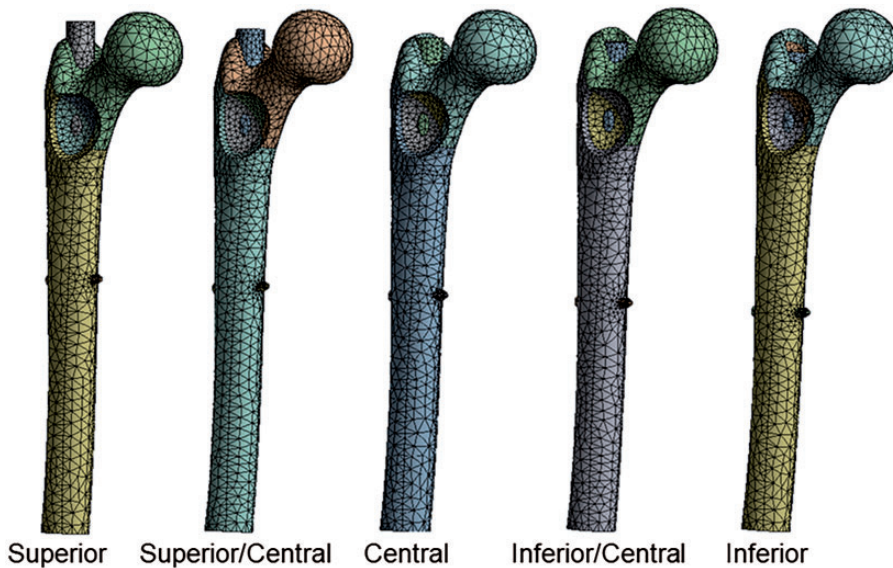


Figure 3. Meshes of the five groups of computer models.

Table 1. Number of nodes and elements in the meshes of the five groups of models

	Superior	Superior/Central	Central	Inferior/Central	Inferior
Numbers of nodes	59,735	60,476	58,577	61,890	59,446
Numbers of elements	31,661	32,402	31,166	33,037	31,264

Table 2. Material properties used in the simulations in this study

Material	Young's modulus (MPa)	Poisson's ratio
Cortical bone	17,000	0.3
Cancellous bone	1000	0.3
Cephalomedullary nail	20,000	0.3
Lag screw	200,000	0.3
Cortical screw	118,000	0.3

was set to frictional type, and the coefficient of friction was set to 0.46.¹⁵ Other parameters in the model were set to bonded type.

Material properties of the model

The models described in this study were composed of five parts: femoral cortical bone, femoral cancellous bone, the cephalomedullary nail, the lag screw, and cortical screws. The material property settings were primarily obtained from previous studies.^{20,21} All materials were assumed to be homogeneous, isotropic, and linear elastic. Thus, Young's modulus and Poisson's ratio were used to represent the properties of the materials. Table 2 shows the material properties used in the simulations in this study.

After FEA, a von Mises stress distribution diagram was used to observe indicators (von Mises stress was calculated as $\sigma_{von} =$

$$\sqrt{\frac{1}{2} \left[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 \right]},$$

where σ_1 , σ_2 , and σ_3 are the principal stresses along the three axes). The primary observed indicators were the maximum displacement of the lag screw, the stress on the intertrochanteric fracture with involvement of the posteromedial cortex (point P in Figure 2), and the different TAD values of the five groups. From the observed data, the differences caused by different cephalomedullary nail implantation positions were investigated.

Ethics and consent

Because of the study design, ethics approval and patient consent were not applicable.

Results

The FEA was performing using different mesh sizes to perform convergence tests. The von Mises stress at a certain specific point on the femur was used as an indicator of the convergence test value. The convergence test values are shown in Table 3. Each simulation model used 3 mm as the model mesh size. Observations of the convergence test values showed that the differences reached 0.41%, 3.74%, 3.54%, 2.34%, and 2.96%, respectively (the levels of convergence were 99.59%, 96.26%, 96.46%, 97.66%, and 97.04%, respectively, based on previous studies¹⁹). These convergence test results were acceptable in the present study because we aimed to have a 5% stop criterion for the convergence test. This result showed that the models converged; thus, the mesh models used for FEA in this study were reasonable.

Figure 4 shows the distribution of lag screw displacement after implantation. The magnitude of the maximum displacement of each group was superior > superior/central > central > inferior/central > inferior. Table 4 shows the maximum displacement values of the lag screw for each group.

Figure 5 shows the stress distribution after implantation into the femur. The stress was relatively high at the bone plate above the cephalomedullary nail. The stress values on the cancellous bone and cortical bone were relatively low. In addition, the stress at an oblique fracture site constructed at the greater trochanter was specifically observed (point p in Figure 2), and the results showed that the distribution of the magnitude of stress at this site was superior > superior/central > central > inferior/central > inferior.

Table 3. Results of convergence test

	von Mises stress on femoral head in superior/central group		von Mises stress on femoral head in inferior/central group		von Mises stress on femoral head in superior/central group		von Mises stress on femoral head in inferior/central group	
	Level of convergence	von Mises stress	Level of convergence	von Mises stress	Level of convergence	von Mises stress	Level of convergence	von Mises stress
5 mm	96.56%	1.6433	89.42%	1.6700	93.87%	1.6831	98.28%	1.3015
4 mm	98.15%	1.7241	93.82%	1.7615	99.02%	1.5916	96.19%	1.4075
3 mm	99.59%	1.7691	96.26%	1.7161	96.46%	1.6161	97.66%	1.3800
2 mm		1.8377		1.7790		1.6547		1.4221

Table 4 shows the stress values at the fracture site (point p in Figure 2) for each group.

Table 4 shows the TAD_{AP} values from the anteroposterior view, the TAD_{Lat} values from the lateral view, and the magnitude of the TAD values for the five groups. Because the tip of the lag screw positioned 10 mm from the apex of the femoral head was used as the standard group, the tip was moved 5 or 10 mm superiorly or inferiorly along the vertical axis in the remaining groups. Thus, all measured TAD_{Lat} values were fixed values. In addition, measurement of the TAD_{AP} values showed that TAD_{AP} was relatively high in the inferior group. Thus, the TAD (TAD = TAD_{Lat} + TAD_{AP}) was relatively high in the inferior group (Figure 6).

Discussion

Cephalomedullary nails are the main tools for treating intertrochanteric fractures, but implant failure can still occur after surgical treatment.¹⁻³ In the present study, we successfully used FEA to investigate the biomechanical effects of implanting cephalomedullary nails in different positions.

The results of this study showed that of all analyzed cephalomedullary nail implantation positions, the smallest lag screw displacement was achieved when the implant was closer to the inferior femoral head. The primary reason for this phenomenon was the fact that when the femoral head sustained an external force, a closer position of the lag screw to the inferior femoral head provided two support points for the lag screw (the first support point was the contact point between the nail and the lag screw, and the second support point was adjacent to the inferior femoral neck, where the cortical bone provided support to the lag screw; thus, the inferior group experienced less displacement) (Figure 7). Therefore, when the lag screw is implanted closer to the inferior femoral head, the

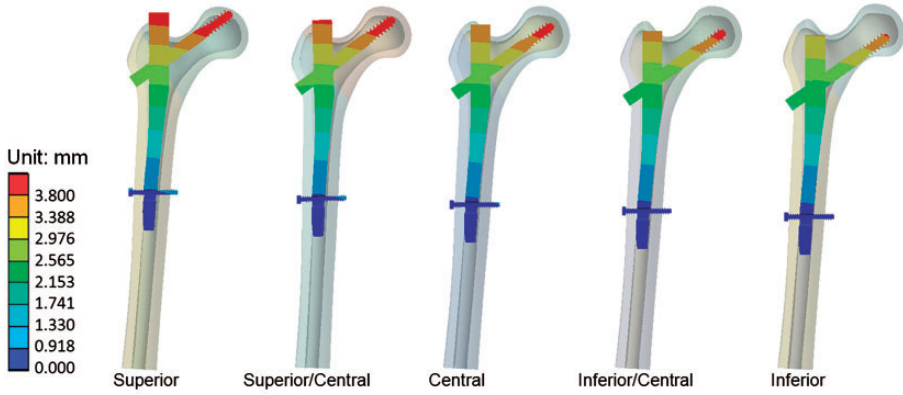


Figure 4. Distribution of displacement on the implant.

Table 4. Distributions of the maximum displacement of the lag screw, the stress on the intertrochanteric fracture with involvement of the posteromedial cortex, and the TAD with different implant positions

	Superior	Superior/Central	Central	Inferior/Central	Inferior
Maximum displacement of the lag screw (mm)	4.596	4.383	4.251	4.0877	3.8603
Stress on intertrochanteric fracture with involvement of posteromedial cortex (MPa)	8.3582	8.1777	7.9174	7.5362	7.279
TAD _{Lat} (mm)	13.1	13.1	13.1	13.1	13.1
TAD _{AP} (mm)	9.5	8.4	10.0	13.5	17.6
TAD (mm)	22.6	21.5	23.1	26.6	30.7

TAD, tip–apex distance; TAD_{Lat}, tip–apex distance measured on a lateral radiograph; TAD_{AP}, tip–apex distance measured on an anteroposterior radiograph.

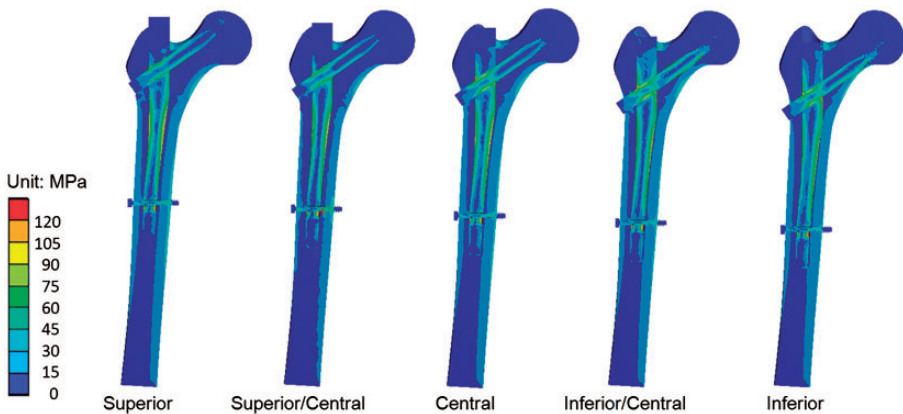


Figure 5. Distribution of stress on the implant after femoral implantation.

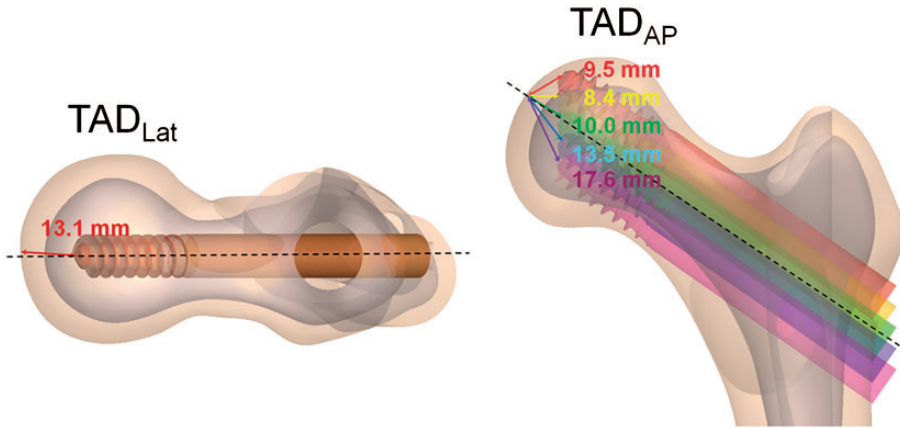


Figure 6. The TAD_{Lat} and TAD_{AP} values of the five groups designed and measured in this study. TAD_{Lat}, tip–apex distance measured on a lateral radiograph; TAD_{AP}, tip–apex distance measured on an anteroposterior radiograph.

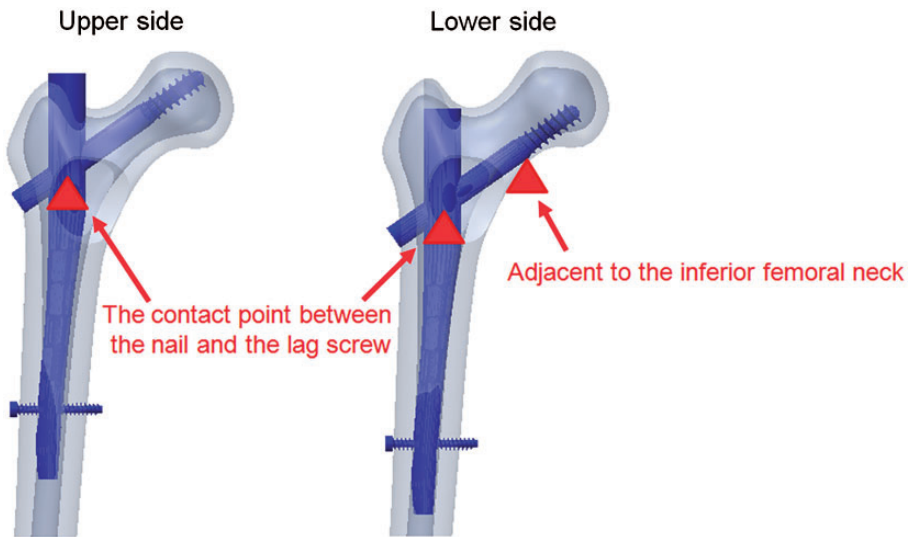


Figure 7. Support points of the lag screw when the cephalomedullary nail is implanted in different positions.

implant is not as prone to deformation because the Young’s modulus of cortical bone is relatively high. Therefore, when the lag screw is implanted closer to the inferior femoral head, loss of reduction can be decreased, preventing instability that can potentially lead to fracture nonunion.^{5,9,11,17}

The stress distribution of each group was also investigated, and the results showed relatively high stress on the implant after cephalomedullary nail implantation and relatively low stress on cancellous bone and cortical bone. The primary reason for this phenomenon was the fact that the Young’s modulus of the implant was

higher than that of the bone, and after implantation, implant deformation occurred as a result of an external force in accordance with Hooke's law (stress = Young's modulus \times strain). The same deformation results in a larger stress value because of a higher Young's modulus. This result is similar to the stress shielding commonly seen in orthopedics, in which the force is conducted primarily through the implant and thus the bone cannot bear the force, causing the bone to become more fragile.^{22,23} In addition, observation of the stress value at the inferior end of the greater trochanter fracture site (assuming a well-aligned state) showed that a lower stress value results if the implant is positioned closer to the inferior femoral head. Thus, positioning the implant closer to the inferior femoral head can reduce the risk of surgical failure, similar to the results of previous studies.^{5,9,11,17}

The present study also focused on the five groups of models constructed and observed their TAD. Generally, the TAD is an important predictor of implant failure. Because the tip of the lag screw positioned 10 mm from the apex of the femoral head was used as the standard group, the tip was moved 5 or 10 mm superiorly or inferiorly along the vertical axis in the remaining groups. Based on the experimental design of the present study, when the lag screw is implanted in the inferior or superior site, the TAD increases (although only the inferior/central and inferior groups showed values exceeding 25 mm) (Figure 6).

A previous study recommended a TAD of <25 mm (this value primarily originates from 198 successful cases in which the average TAD was 25 mm; in the 16 failed cases, the average TAD was 38 mm).⁷ However, most failed cases in previous studies also had implantation in superior sites; implantation in central sites also resulted in failure.^{5,15} Conversely, implantation in inferior sites did not result in failure. Another study showed that implantation in central sites

resulted in lower stress on the fracture line (the TAD was 20 mm).¹⁶ The results of the present study also showed that when the lag screw is implanted in an inferior site, the femur experiences relatively lower stress and the implant experiences less displacement, thus agreeing with the results of previous studies.^{5,14,15} These findings indicate that the TAD is not a primary predictor of implant failure. This concept is similar to the results of the above-mentioned study.¹⁶

The present study using FEA to investigate the biomechanics of different sites of cephalomedullary nail implantation had several limitations. First, all materials were assumed to be homogeneous, isotropic, and linear elastic. This assumption was used to simplify the simulation used in this study, and the material properties were set to values referenced in previous studies by other researchers. Second, only the top half of the femoral model was observed, primarily because the proximal femur was the observational site of the present study and because this simplification reduced the computational time of the simulation. Third, to investigate the effect of the same lag screw on the TAD, lag screws of the same length were selected for the implant. Finally, because previous studies of cephalomedullary nail implantation showed that positioning of the lag screw close to the anterior or posterior aspect of the femoral head resulted in higher failure rates, the present study only investigated implantation of the lag screw in a central position. Although these simplifications generate differences from actual situations, they clarify the results and trends of the present study.

The present study used FEA to investigate the biomechanics of different sites of cephalomedullary nail implantation. The results of the study suggest that positioning the lag screw closer to the inferior femoral head can reduce stress on the posteromedial cortex and deformation of the implant.

Nevertheless, stable reduction and good alignment are still important factors for successful surgery.²⁴ Although the data from this study will differ in some aspects from actual clinical situations, the results can serve as reference values for orthopedists when positioning cephalomedullary nail implants and can reduce implant failure, thereby improving patients' prognosis and providing a biomechanical basis for future implant design and development.

Conclusions

The present study primarily investigated the effect of different sites of cephalomedullary nail implantation for the treatment of unstable intertrochanteric fractures. The results show that although the TAD increases as the lag screw is positioned more inferiorly, the implant experiences less deformation with the screw in this position, reducing postoperative fracture instability. In addition, observation of stress on the posteromedial cortex showed that as the lag screw is positioned more inferiorly, the bone is exposed to less stress, thereby reducing the surgical failure rate. Thus, the results of the present study provide a biomechanical basis for selection of the cephalomedullary nail implantation site by clinical orthopedists during surgery.

Authors' contributions

CHL: project design, data analysis, and project oversight; YCW: manuscript preparation and data collection; KHC: data analysis; CCP: data analysis; KCS: model creation, manuscript preparation, data analysis, simulations, and software supervision.

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Data availability statement

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

Disclaimer

The authors and any research foundations with which they are affiliated have not received any payments or other benefits from any commercial entity related to the subject of this article.

Declaration of conflicting interest

The authors declare that there is no conflict of interest.

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