Application of a Lateral Intertubercular Sulcus Plate in the Treatment of Proximal Humeral Fractures: a Finite Element Analysis and Example in Clinical Practice

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Application of a lateral intertubercular sulcus plate in the treatment of proximal humeral fractures: A finite element analysis and example in clinical practice

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Abstract

Background: Inversion deformities caused by insufficient medial support are especially common when the PHILOS locking plate is used to treat proximal humeral fractures. Using finite element analysis, the present study aimed to compare the biomechanical properties of a PHILOS locking plate (PLP) and a PHILOS plate combined with a lateral intertubercular sulcus plate (PLP-LSP) in the fixation of proximal humeral fractures with loss of the medial column. We also present representative results for a 69-year-old female patient with a comminuted fracture of the proximal right humerus (Neer type four-part fracture) who underwent successful surgical treatment with a PHILOS plate combined

with an auxiliary lateral intertubercular sulcus plate.

Methods: After creating a three-dimensional finite element model of proximal humeral fracture with loss of the medial column, three implant models were established. A full-screw PHILOS plate (PLP) was used in Group A, while a PHILOS plate lacking medial screw support and an auxiliary plate were used in Group B (MPLP-LSP). A full-screw PHILOS plate and auxiliary plate were used in Group C (PLP-LSP). The three fixation models were applied to the proximal humerus fracture model, following which horizontal, compressive, and rotational loads were applied to the humerus model. We evaluated the structural stiffness and stress distribution of the implant and compared displacement and angle changes among the three models.

Results: Displacement and angle changes were smallest in Group C (PLP-LSP). The implant model used in Group C also had the highest structural rigidity, endured less von Mises stress than the other two models, and had the strongest stability. In our clinical case, X-ray and computed tomography images obtained 3 months after the operation indicated that the fracture had healed, with good positioning of internal fixation and good functional recovery.

Conclusion: A lateral intertubercular sulcus plate placed at the internodal groove not only aids in anatomical reduction but also provides effective lateral and medial support, thereby reducing stress on the PHILOS plate and providing better stability in patients with proximal humeral fractures.

Keywords: proximal humerus fracture; finite element analysis; lateral intertubercular sulcus plate; medial support

Background

Proximal humeral fractures are frequently encountered in clinical practice, with an incidence of 4%–5% [1], which continues to increase each year. Treatment for proximal humeral fractures currently involves intramedullary nails, internal fixation using a PHILOS locking plate, shoulder joint replacement, and other methods [2]. While the PHILOS locking plate is commonly used due to its wide scope of application [3], postoperative complications such as poor reduction, varus deformity, screw cutting, nonunion of fractures, infection, and limited function are common. High [4] and Barlow [5] followed up 173 patients over 60 years of age with proximal humeral fractures who were treated with locking plate internal fixation. They reported failure rates of 26%, 39%, and 45% for two-part (16 cases), three-part (23 cases), and four-part fractures (11 cases), respectively. Inversion deformities caused by insufficient medial support are especially common. Therefore, strengthening medial support to reduce postoperative complications associated with use of the PHILOS locking plate remains an urgent clinical need [6].

There are several methods for strengthening medial support in clinical practice, such as allograft fibula implantation [7], titanium mesh implantation [8], bone cement [9], and auxiliary support plates [10–11]. In clinical practice, the authors have used a 1/3 tubular steel plate as an auxiliary plate to develop the shape according to the lateral anatomical structure of the internodal sulcus, placing it on the outside of the internodal sulcus. During the operation, a Kirschner wire is first used for reduction, following which the auxiliary steel plate is inserted so that it can assist in reduction according to the internodal groove. At the same time, the Kirschner wire can be removed to facilitate multi-directional perspective. This surgical method has achieved good therapeutic effects, but whether the auxiliary steel plate can strengthen medial support and enhance stability remains to be verified. Therefore, in the present study, we aimed to evaluate the biomechanical properties and stability of the auxiliary

steel plate using finite element analysis.

Methods

This study was approved by the Ethics Committee of the Affiliated Hospital of Shandong University of Traditional Chinese Medicine, and all patients provided written informed consent before study commencement.

Establishment of fracture model

Standardized computed tomography (CT) data for the humerus were selected to establish a finite element model of the proximal humerus. CT data were obtained from a 27-year-old healthy male individual. The area of the simulated bone defect at the surgical neck of the humerus extended 5 mm laterally and 10 mm medially. We developed a three-dimensional model of the proximal humeral fracture to simulate instability of the medial column (as shown in Figure 1). The distinction between cortical bone and cancellous bone was based on the gray measurement of the CT value, and the ranges of gray values for cortical and cancellous bone were 662–1,841 HU and 148–661 HU, respectively. The types of internals included the PHILOS locking plate and the lateral auxiliary plate of the internodal groove. The PHILOS locking plate had a length of 90 mm, with a thickness of 3 mm and a screw length of 3.5 mm. The auxiliary plate had a length of 50 mm, with a thickness of 2.5 mm and a screw length of 2.5 mm. The arc of the plate was designed according to the anatomical structure of the outer side of the internodal groove.

Implant assembly

The PHILOS locking plate was assembled on the fracture model according to the standard operation method, and the upper end was 5 mm from the apex of the greater nodule. The auxiliary plate was tightly attached to the outside of the intertubercular sulcus, and the upper end was 8 mm from the apex of the greater nodule. In one group, we used a full-screw PHILOS locking plate technique (PLP, Group A). In this group, the PLP was inserted with six locking screws at the proximal end and three locking screws at the distal end. In another group, we used a PHILOS plate lacking medial screw support and an auxiliary plate (MPLP-LSP, Group B). The MPLP-LSP was inserted with four screws at the proximal end, and the auxiliary plate was inserted at the same time. The two medial screw supports were not assembled. Two screws each were inserted at the proximal and distal ends of the auxiliary plate. In the third group, we used a full-screw PHILOS locking plate combined with an auxiliary plate (PLP-LSP, Group C). In this group, the PLP-LSP was inserted with six locking screws at the proximal end and three locking screws at the distal end. An auxiliary plate was placed at the same time, with two screws at the proximal end and two screws at the distal end (as shown in Figure 2). The locking screw thread was omitted to simplify the model. The PHILOS locking steel plate model included 9,566 elements and 16,117 nodes. The auxiliary steel plate model included 1,781 elements and 3,314 nodes.

Setting of parameters

Finite element analysis was carried out using Abaqus 6.14 software (3DS, Waltham, MA). Linear elastic isotropic material properties were assigned to all models and placed materials. The elastic modulus of normal cortical bone was set to 8,844 MPa, that of cancellous bone was set to 660 MPa, and that of the built-in steel plate was set to 114,000 MPa. The interface between the humeral head and glenoid was fixed in all models of proximal humeral fracture. The contact behavior of the

plate/locking-screw and bone/locking-screw interfaces was defined as fully fixed. The contact behavior of the plate/bone and cortical-screw/bone interfaces was defined as surface-to-surface. All contact elements were defined as deformable elements. The analyses were performed assuming frictionless interactions to simplify the contact phenomena. Compression and rotation loads were applied to the humerus model to simulate the functions of the shoulder joint, including abduction, adduction, flexion, extension, axial compression, and internal and external rotation (as shown in Figure 3). Loads of 100 N were applied to the four directions of the humeral shaft to simulate the effects of shoulder muscle abduction, adduction, flexion, and extension, and a load of 200 N was applied to the end of the humerus to simulate axial compression. A torque of 7.5 Nm was applied to the end of the humerus to simulate internal and external rotations [12].

Evaluation indices

Fracture stability

Take the proximal medial (a), lateral (b), distal medial (c), and lateral (d) points of the fractured end. The vertical distance between points (c) and (ab) is defined as e , where e is the displacement of the gap between the fracture ends. The stability of the fractured end was evaluated by measuring the change in the displacement (e) of the gap between the fracture ends (as shown in Figure 4).

Rotational stability

Take the angle of the two straight lines (ab) and (cd) as α . The rotational stability of the humeral head was evaluated by measuring the change in the angle (α) between the proximal and distal fractures of the fractured end [13] (Figure 4).

Stress

We measured equivalent pressure distribution (von Misses stress) and maximum stress on the steel plate to evaluate the degree of stress for each model.

Results

Construct stiffness

The compression and rotation stiffness values of the three models were calculated using finite element analysis (see Table 1). Compression and rotation stiffness values were 39.84 N/mm and 110.20 Nm/Rad in Group A (PLP), 43.67 N/mm and 153.50 Nm/Rad in Group B (MPLP-LSP), and 66.67 N/mm and 204.67 Nm/Rad in Group C (PLP-LSP), respectively.

Table 1. Construct Stiffness		
Group	Compression stiffness (N/mm)	Rotational stiffness (Nm/Rad)
A	39.84	110.20
B	43.67	153.50
C	66.67	204.67

Group A (PLP): Full-screw PHILOS plate; Group B (MPLP-LSP): PHILOS plate without medial screw support plus auxiliary plate; Group C (PLP-LSP): full-screw PHILOS plate plus auxiliary plate.

Implant Stress

The maximum equivalent stress and stress distribution of the three models were calculated using finite

element analysis, as was the maximum von Mises stress for each model under different load conditions (see Table 2). Three sets of model stress distributions and the maximum von Mises stress are shown in Figure 5.

In Group A, stress was concentrated near the support screw area during shoulder joint movement. Stress values under different load conditions were lowest in Group C, suggesting that the auxiliary steel plate greatly disperses the stress, thereby reducing maximum stress.

Table 2. Maximum von Misses Stress (MPa)					
Group	Adduction	Abduction	Flexion	Extension	Axial compression
A	1,025	1,025	212.2	212.2	229.4
B	892.6	892.6	283.8	283.8	198.6
C	858.6	858.6	204.8	204.8	164.1

Group A (PLP): Full-screw PHILOS plate; Group B (MPLP-LSP): PHILOS plate without medial screw support plus auxiliary plate; Group C (PLP-LSP): full-screw PHILOS plate plus auxiliary plate.

Displacement changes

The displacement observed during different simulated activities for each model is displayed in Figure 6.

Angle changes

The angle changes measured during rotation were 3.9° in Group A (PLP), 2.8° in Group B, and 2.1° in Group C (see Table 3).

Table 3. Angle Changes during Rotation			
Group	A	B	C
Angle changes	3.9°	2.8°	2.1°

Illustrative case study

Figure 7 shows preoperative X-ray and computed tomography (CT) findings for a 69-year-old female patient with a comminuted fracture of the proximal right humerus (Neer type four-part fracture). The patient underwent surgical treatment with a PHILOS plate combined with an auxiliary lateral intertubercular sulcus plate. The five-hole, one-third tubular steel plate was shaped according to the external anatomical structure of the internodal sulcus and attached to the outside of the internodal sulcus (see Figure 8). Re-examination after 3 months revealed that the fracture had healed, and that the patient exhibited good recovery of function (see Figure 9).

Surgical technique in clinical practice

After general anesthesia or brachial plexus anesthesia, the patient was placed in the supine position at shoulder height. Routine disinfection and draping of the surgical area were performed, following which an anterior medial incision of approximately 10 cm in length was made. The skin, subcutaneous tissue, and fascia were cut sequentially and separated from the pectoralis major and deltoid muscles. Care was taken to protect the cephalic vein and to expose and remove the fractured end. After soft tissue displacement and blood clotting, Kirschner wire was used to pry the humeral head to restore the neck-stem angle and temporarily reset and fix the broken end to expose the intermuscular groove of the biceps. After pre-bending and shaping, the auxiliary steel plate was attached to the inter-

nodules to guide the reduction on the lateral side of the groove. The angle was adjusted during the operation based on individual differences in patient anatomy. As long as the placement of the PHILOS bone plate is not hindered, the five-hole 1/3 tubular steel plate is sufficient. The top of the plate was placed 5 mm below the top of the greater nodule, The Kirschner wire was removed at this time, and C-arm fluoroscopy from multiple angles indicated good reduction. The PHILOS locking plate was used for internal fixation on the outside, and allogeneic bone was appropriately implanted according to the fracture defect. After confirming correct positioning of the screw plate under fluoroscopy, the rotator cuff was sutured with a tendon suture. The incision was flushed, sutured, and wrapped in a sterile dressing, and a drainage tube was placed at the incision.

Discussion

In the present study, we used finite element analysis to explore the biomechanical properties of a lateral plate at the intertubercular groove in a model of proximal humeral fracture with loss of the medial column. Our findings indicated that higher structural stiffness under axial compression and rotational load was associated with a stronger ability of the internal fixation system to prevent varus displacement of the humeral head. Our comparison between Groups A and B indicated that the auxiliary steel plate can completely replace the support function of the supporting screws while ensuring greater structural rigidity. Results from Group C further suggest that combining the auxiliary plate with the original PHILOS plate leads to even greater structural rigidity and stability than observed in Groups A and B while improving the bone defect area. Regardless of the force applied in the horizontal, vertical, and torsional directions, the changes in displacement and angle in Group C were only one half of those observed in Group A, indicating that the steel plate significantly increases the

stability and medial support of the original PHILOS system. In addition, the maximum von Mises stress on the internal fixation can reflect the load transfer methods of different internal fixation methods, and a higher von Mises stress indicates that the torsion force is greater. Thus, after a long period of repeated twisting, the internal fixation is the most likely part to fail. The maximum von Mises stress values were smallest in Group C under various loads. Therefore, these results indicate that the auxiliary steel plate can provide better internal support, effectively disperse stress, reduce the risk of internal fixation failure, and enhance the stability of internal fixation.

Screw cutting and varus displacement of the humeral head are the most common surgical complications for open reduction and internal fixation of proximal humeral fractures. A lack of medial support has been cited as an important reason for postoperative complications and surgical failure [14], and the two medial support screws of the PHILOS plate are particularly important for ensuring medial support of the proximal humerus [15-16]. A comparative study by Shen et al. [17] reported that placement of the medial support screw greatly reduced the screw cutting, varus deformity, and the probability of secondary surgery. Various methods are used to compensate for the effect of the medial support screw and strengthen medial support in clinical practice, such as autologous or allogeneic fibula implantation, titanium mesh implantation, and the use of an auxiliary steel plate [7-11]. The selection, treatment, and placement of fibula grafts and titanium mesh require high technical experience among orthopedic doctors. At the same time, the cost is high, the supply is limited, the risk of infection is high, and the risk of disease transmission is high [18]. Although an auxiliary plate placed on the inner side of the proximal humerus can directly provide effective medial support, the medial approach is not easy to learn due to the complex anatomy of the neurovascular structure. Improper technique can easily lead to iatrogenic nerve and blood vessel damage, which may be why

the medial plate approach for proximal humeral fractures has not been clinically promoted. In our technique, the auxiliary steel plate is pre-bent (1/3 tubular steel plate) according to the anatomical shape of the outer side of the internodal sulcus. This is because the internodal sulcus can be used as a landmark to assist anatomical reduction [19], and because the lateral side of the internodal sulcus is easily exposed during the operation without additional trauma. The conventional anteromedial approach can reduce the risk of damaging muscle nerve branches[20]. After the auxiliary steel plate is placed for temporary fixation during the operation, the Kirschner wire used to maintain the reduction can be removed, which is convenient for multi-angle fluoroscopy and shortens the operation time.

Since Brekelmans et al. first introduced the finite element method in biomechanics research [21], the application of finite element analysis in orthopedic biomechanics has evolved, and it is widely used to evaluate new implants or materials, strain and stress distribution, and load transfer between objects and bones [22]. However, given the complex structure of the shoulder joint, it is impossible to accurately simulate the real boundary conditions of the interaction of all muscles and ligaments. Our research aims to simplify the study of the shoulder joint by ignoring the interactions of muscles, ligaments, bones, and other surrounding structures [23]. Although finite element analysis can simulate the properties of various bone materials and load forces in various directions, it does not fully reflect the real-world situation due to differences in bone density and fracture types among patients.

Conclusion

In summary, our findings demonstrate that a lateral intertubercular sulcus plate placed at the internodal groove not only aids in anatomical reduction but also provides effective lateral and medial

support, thereby reducing stress on the PHILOS plate and providing better stability in patients with proximal humeral fractures. Moreover, such placement allows for easy exposure, which reduces additional trauma and blood loss. In addition, the plate can be reset according to the internodal sulcus to facilitate fluoroscopy. Given that this technique may also reduce the risk of complications and increase the stability of internal fixation, use of the PLP-LSP method may represent a novel strategy for the treatment of proximal humeral fractures.

List of abbreviations

CT: computed tomography; PLP: full-screw PHILOS locking plate; MPLP-LSP: PHILOS plate lacking medial screw support plus auxiliary plate; PLP-LSP: full-screw PHILOS locking plate plus auxiliary plate

Declarations

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Ethics approval and consent to participate

This study was done at the Affiliated Hospital of Shandong University of Traditional Chinese Medicine, and permission was obtained from the hospital's Ethics Committee. The authors had to obtain patient consent before enrolling participants in this study.

Consent for publication

Not applicable.

Availability of data and materials

Please contact the author for data requests.

274 ***Competing interests***

275 *The authors declare that they have no competing interests.*

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281 ***Authors' contributions***

282 *Bo Yu and WenXue Lv contributed to the conception and design, performance of the experiments,*
283 *data analysis and interpretation; Dong Li and WenMing Chen performed the data analysis and*
284 *manuscript writing; Jing Meng, Song Liu and ZongKang Duan contributed to the performance of the*
285 *experiments and data analysis. Bo Yu contributed to the conception and design, financial support,*
286 *data analysis and interpretation, manuscript writing, and final approval of the manuscript.*
287 *All authors read and approved the final manuscript.*

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Figure Legends

Figure 1. Bone defect area. A bone defect area with a width of 5 mm on the lateral side and 10 mm on the medial side was set at the surgical neck of the humerus to simulate a proximal humeral fracture with an unstable medial column.

358

359 **Figure 2. Three implant models.** A: PHILOS plate (PLP). B: PHILOS plate lacking medial screw support
 360 and lateral intertubercular sulcus plate (MPLP-LSP). C: PHILOS plate and lateral intertubercular sulcus
 361 plate (PLP-LSP).

362

363 **Figure 3. Load application.** Compressive and rotational loads were applied to the humerus model to
 364 simulate the functions of the shoulder joint, including abduction, adduction, flexion, extension, axial
 365 compression, and internal and external rotation.

Figure 4. Stability. The stability of the fracture region under horizontal and compressive loads was assessed based on the distance covered by the medial fracture gap (line e). The angular variation between the proximal and distal fracture gap was determined to assess regional rotational stability (angle α).

Figure 5. The maximum von Mises stress and stress distribution. Group A (PLP): Full-screw PHILOS plate; Group B (MPLP-LSP): PHILOS plate without medial screw support plus auxiliary plate; Group C (PLP-LSP): full-screw PHILOS plate plus auxiliary plate.

Figure 6. Changes in the displacement of the fracture region under different loading conditions.

Group A (PLP): Full-screw PHILOS plate; Group B (MPLP-LSP): PHILOS plate without medial screw support plus auxiliary plate; Group C (PLP-LSP): full-screw PHILOS plate plus auxiliary plate.

Figure 7. Preoperative imaging of a comminuted fracture of the proximal right humerus. (a):

Preoperative X-ray. (b, c): Preoperative computed tomography.

Figure 8. Intraoperative and postoperative images of a comminuted fracture of the proximal

right humerus. (a): Intraoperative use of auxiliary plate reduction fluoroscopy. (b): Intraoperative plate

placement. (c,d): Postoperative X-ray, positive and lateral radiographs.

Figure 9. Three-month follow-up results for a comminuted fracture of the proximal right humerus. (a): X-ray 3 months after the operation showing that the fracture had healed, with good positioning of internal fixation. (b,c): Functional activity 3 months after the operation.

Figures

Figure 1

Bone defect area. A bone defect area with a width of 5 mm on the lateral side and 10 mm on the medial side was set at the surgical neck of the humerus to simulate a proximal humeral fracture with an unstable medial column.

Figure 2

Three implant models. A: PHILOS plate (PLP). B: PHILOS plate lacking medial screw support and lateral intertubercular sulcus plate (MPLP-LSP). C: PHILOS plate and lateral intertubercular sulcus plate (PLP-LSP).

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Intraoperative and postoperative images of a comminuted fracture of the proximal right humerus. (a): Intraoperative use of auxiliary plate reduction fluoroscopy. (b): Intraoperative plate placement. (c, d): Postoperative X-ray, positive and lateral radiographs.

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