Lateral Wall Integrity of the Greater Tuberosity Is Important for the Stability of Osteoporotic Proximal Humeral Fractures After Plate Fixation

Dohyun Kim, MD*, Joon-Ryul Lim, MD, PhD*, Tae-Hwan Yoon, MD, PhD, Seung-Hwan Shin, MD, and Yong-Min Chun, MD, PhD

Investigation performed at the Arthroscopy and Joint Research Institute, Department of Orthopedic Surgery, Severance Hospital, Yonsei University College of Medicine, Seoul, Republic of Korea

Background: Previous studies assessing surgical fixation of osteoporotic proximal humeral fractures have primarily focused on medial calcar support. In this study, we utilized a specific model for 2-part surgical neck fracture of the osteoporotic proximal humerus to investigate how severe comminution of the greater tuberosity (GT) lateral wall affects biomechanical stability after fixation with a plate.

Methods: Ten matched pairs of cadaveric humeri (right and left) were assigned to either a surgical neck fracture alone (the SN group) or a surgical neck fracture with GT lateral wall comminution (the LW group) with use of block randomization. We removed 5 mm of the lateral wall of the GT to simulate severe comminution of the lateral wall. Axial compression stiffness, torsional stiffness, varus bending stiffness, and the single load to failure in varus bending were measured for all plate-bone constructs.

Results: Compared with the SN group, the LW group showed a significant decrease in all measures, including torsional stiffness (internal, $p = 0.007$; external, $p = 0.007$), axial compression stiffness ($p = 0.002$), and varus bending stiffness ($p = 0.007$). In addition, the mean single load to failure in varus bending for the LW group was 62% lower than that for the SN group ($p = 0.005$).

Conclusions: Severe comminution of the GT lateral wall significantly compromised the biomechanical stability of osteoporotic, comminuted humeral surgical neck fractures.

Clinical Relevance: Although the generalizability of this cadaveric model may be limited to the extreme clinical scenario, the model showed that severe comminution of the GT lateral wall significantly compromised the stability of osteoporotic humeral surgical neck fractures fixed with a plate and screws alone.

Proximal humeral fractures account for approximately 4% to 5% of all fractures and frequently occur in older adults with osteoporosis[1]. Although many proximal humeral fractures can be treated nonoperatively, in some cases, open reduction and internal fixation (ORIF) surgery is preferred for achieving fracture stability and early mobilization of the shoulder[2]. In particular, the use of internal fixation with a locking system for a proximal humeral fracture has yielded satisfactory functional outcomes[3-5]. Despite the application of a locking plate, loss of reduction due to varus progression after fixation has been reported[6-8]. Moreover, if osteoporosis is combined with varus angulation or medial calcar comminution, it is difficult to avoid varus progression, even with a locking plate applied on the lateral part of the proximal humerus. Consequently, the medial calcar screw technique was introduced to augment stability following fixation[9-11].

Tuberosity involvement in 2-part fractures with a nondisplaced tuberosity and in 3- or 4-part fractures is common in proximal humeral fractures and is known to be an indicator

*Dohyun Kim, MD, and Joon-Ryul Lim, MD, PhD, contributed equally to this work.

Disclosure: No external funding was received for this work. The **Disclosure of Potential Conflicts of Interest** forms are provided with the online version of the article (http://links.lww.com/JBJS/I161).

of a poor prognosis for patients undergoing ORIF, especially in elderly patients with osteoporosis[12,13]. To promote strong fixation of the proximal fragment resulting from a surgical neck fracture, the locking plate screws should have purchase in the calcar bicortically as well as purchase in the lateral cortex of the greater tuberosity (GT) and the cancellous bone of the humeral head[14]. However, given that many elderly patients have poor cancellous bone quality within the humeral head as a result of osteoporosis and lateral wall comminution, biomechanical stability may be substantially compromised, even with medial calcar support. Consequently, early range-of-motion exercises will be limited, potentially leading to suboptimal functional outcomes.

Previous studies have mainly focused on medial calcar support for osteoporotic proximal humeral fractures, and, to our knowledge, none have assessed the influence of GT lateral wall integrity on biomechanical stability following the fixation of an osteoporotic proximal humeral fracture[9-11]. Therefore, in the present study, we aimed to investigate how the presence of a comminuted versus an intact GT lateral wall affects the biomechanical properties of osteoporotic proximal humeral surgical neck fractures after locking-plate fixation. We hypothesized that the presence of a comminuted GT lateral wall would significantly impair biomechanical stability after fixation, even with medial calcar support.

Materials and Methods

Specimen Preparation

Ten matched pairs of fresh-frozen cadaveric humeri (20 specimens) were utilized for this study. Specimens were obtained from subjects who were 75 to 103 years old (mean age and standard deviation [SD], 84.4 ± 7.9 years), including 7 males and 3 females. As observed macroscopically, all humeri were intact and showed no surgical wounds or old fractures. Cadaveric humeri were kept frozen at –20°C and thawed at room temperature for 24 hours before processing. All soft tissues associated with the humeri were removed.

Trabecular bone mineral density (BMD) of each humeral head was measured with use of quantitative computed tomography (qCT; LightSpeed VCT 64; GE Healthcare). After scanning the entire specimen, BMDs were determined from 3 parallel sections, each separated by 1.5 mm, at the largest transverse diameter of the humeral head (i.e., the axial plane perpendicular to the anatomical axis of the humeral shaft). A square-shaped region of interest was placed on the cross-sectional area of the bone slice, with each edge of the square touching the subcortical bone of the humeral head, so that only cancellous bone would be measured. Final BMD values were obtained from the average of the 3 measurements[15].

After qCT scanning, paired humeri from each cadaveric sample were divided into 2 groups, as follows: (1) a 2-part proximal humeral fracture group with a comminuted surgical neck fracture and no comminution of the GT wall (the SN group) and (2) a 2-part proximal humeral fracture group with both a comminuted surgical neck fracture and comminution of the GT lateral wall (the LW group). Humeri within each pair were assigned to either the SN or LW group with use of block randomization.

For humeral fixation, we utilized the Proximal Humeral Internal Locking System (PHILOS; DePuy Synthes) plate. To simulate comminution of the surgical neck, we resected a 10-mm medially based wedge of bone from the humeral calcar with use of an oscillating saw, as described in previous simulation studies (Fig. 1-A)[4,11]. In brief, we positioned the superior border of the wedge perpendicular to the anatomical axis of the humeral shaft. Suture holes located between rows C and D of the plate (i.e., the calcar screw holes) were then utilized as landmarks when performing the wedge resection, thereby securing the near cortex for calcar screw insertion (Fig. 1-B). For samples with GT lateral wall comminution, we resected the GT along the line connecting 2 dots, each located 5 mm from the plate, on an axial plane toward the center of the humeral head. Because the proximal humerus has been reported to have a cortical thickness of up to 3.5 mm, we removed 5 mm of the GT wall where the plate was to be placed[16].

Fixation using 3.5-mm locking screws was performed from rows A to E, excluding row D. A total of 8 screws were placed, with 3 locking screws utilized for fixation in the shaft region[17]. After plate fixation, a radiograph was made to confirm the appropriate positioning of the plate and screws (Fig. 1-C). We then resected the distal portion of each humerus 16.5 cm from the top of the humeral head, perpendicular to the axis of the humeral shaft. Proximal and distal potting was performed by placing a cadaveric humerus into a customized cuboid jig and securing it with unsaturated polyester resin (EC-304; Aekyung Chemical), which hardens into a rigid state after curing. The proximal portion of the humerus that was attached to the plate was covered with clay before being coated with resin to ensure that the resin did not invade spaces between the resected osseous surface and the plate-screw construct, as described previously[18]. The clay was then removed after the resin hardened. This procedure was necessary to eliminate unnecessary resistance and to deliver pure mechanical force when performing the stability tests. This procedure was performed by an orthopaedic board-certified surgeon (D.K.).

Biomechanical Testing

Biomechanical stability was assessed by performing 4 tests: torsional (internal and external) stiffness, axial compression stiffness, varus bending stiffness, and single load to failure in varus bending. Torsional stiffness was measured with use of a torsional stiffness tester (DPTST; DYPHI). The other stiffness tests, as well as the single-load-to-failure test, were performed with use of an electrohydraulic materials testing system (model 3366; Instron).

We initially performed a nondestructive quasi-static torsional test, and the load levels were selected on the basis of a previous study[19]. Internal and external rotational torques were measured by rotating the humeral head at a rate of 0.2 Nm of torque per second to ±3.5 Nm (Fig. 2-A). A nondestructive axial compression test was then conducted up to a maximum force of 200 N at a rate of 0.1 mm/s (Fig. 2-B). We next performed a varus bending stiffness test under 4-point bending conditions, with a supporting span of 21 cm and a loading span of 13 cm. Bending

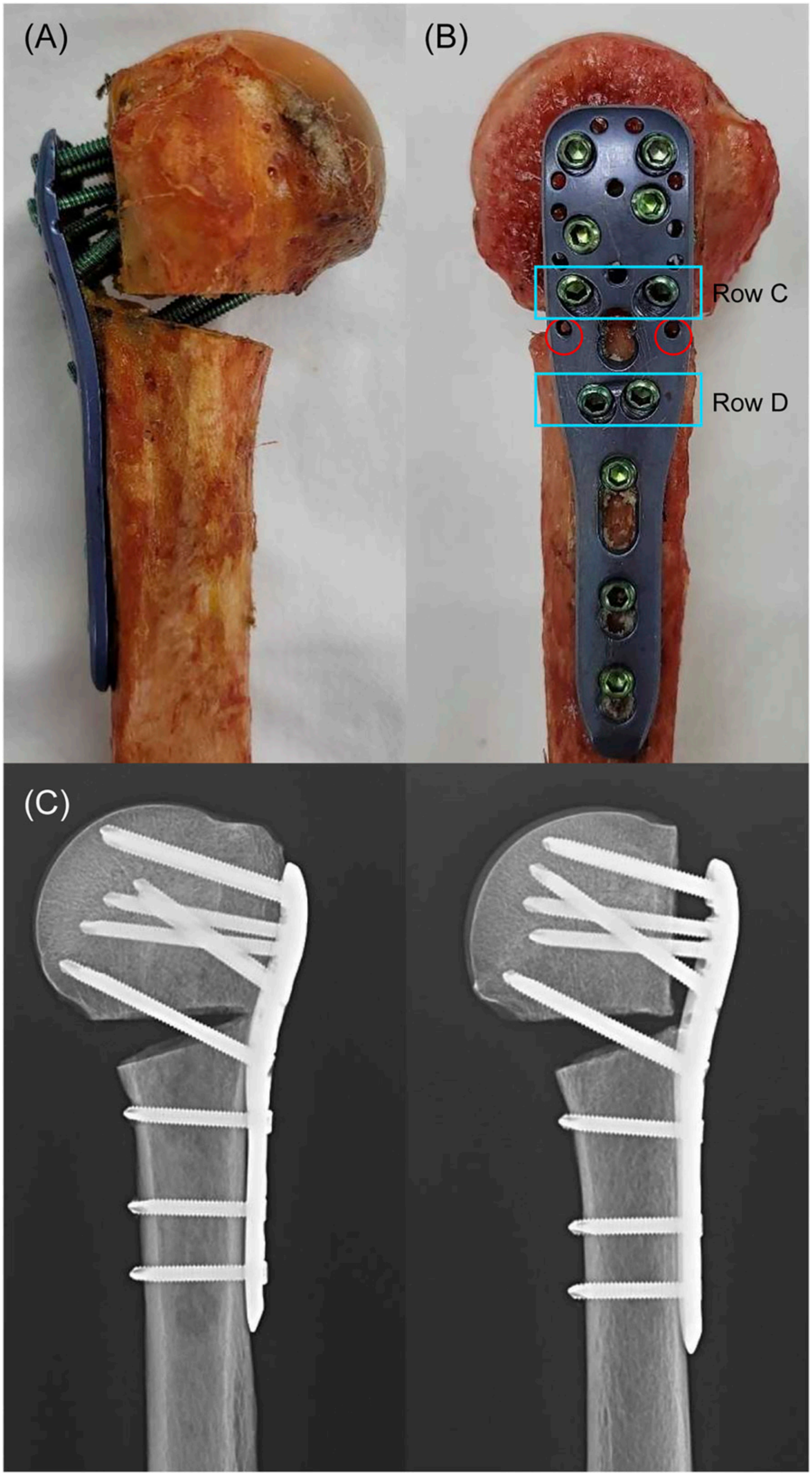
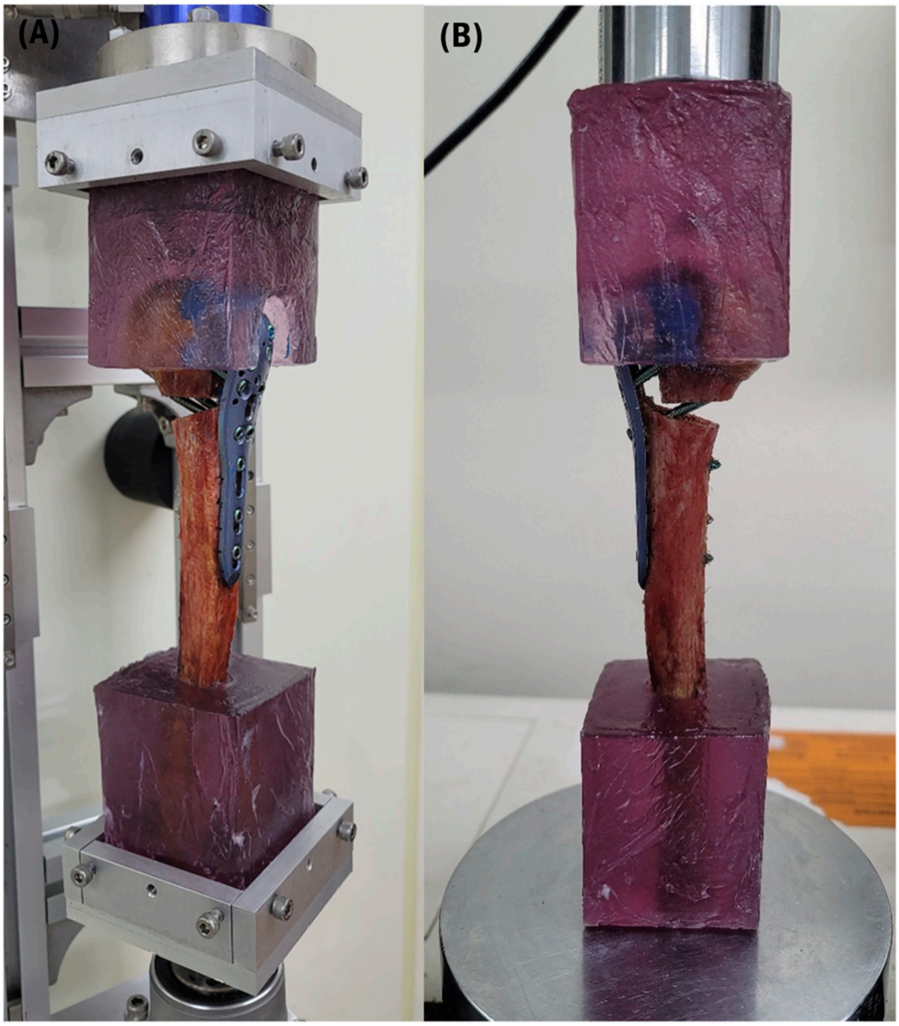


Fig. 1

Fig. 1-A Photograph showing the fracture model for the lateral wall (LW) comminution group. **Fig. 1-B** Wedge resection was performed at the level of the 2 distal suture holes of the plate, as indicated by the 2 red circles between rows C and D. **Fig. 1-C** Radiographs from the SN group (intact GT wall; left panel) and LW group (comminuted GT wall; right panel).



Figs. 2-A and 2-B Setup of the customized cuboid jig, secured with unsaturated polyester resin, that was utilized for torsional testing (**Fig. 2-A**) and axial compression testing (**Fig. 2-B**).

tests were conducted to 3.5 Nm at a rate of 0.1 mm/s. The stiffness values were calculated as the slopes of the linear portions of the fifth force-displacement curves. Lastly, we utilized the varus bending setup to measure the single load to failure, with the point of failure identified as the abrupt change in the force-displacement curve resulting from a loss of fixation. After each test, we confirmed the elasticity of the force-displacement curve and ensured that there had been no loss of fixation before proceeding with the next experiment and the testing of the final load to failure.

Statistical Analysis

Because studies on this subject are lacking, the sample size was calculated from the varus bending stiffness values measured in a pilot study performed with 3 paired humeri (6 specimens). In that study, the mean varus bending stiffness values (and SD) were 418.9 ± 67.6 N/mm for the SN group and 323.1 ± 71.2 N/mm for the LW group. On the basis of these data, we found that 20 specimens (10 per group) were required to provide 90% power at an α level of 0.05. The normal distribution of all variables was tested with use of the Shapiro-Wilk test. The paired t test or the Wilcoxon signed-rank test was utilized to identify significant differences in BMD and mechanical performance values between the 2 groups. Statistical analyses were performed with use of IBM SPSS Statistics for Windows (version 25.0), and the level of significance was set at $p < 0.05$.

Results

Given that the matched pairs of right and left humeri were block-randomized, there were no differences in BMD between the SN (intact GT wall) and LW (comminuted GT wall) groups. Internal torsional stiffness was impaired by 25.2% ($p = 0.007$) and external torsional stiffness was impaired by 19.6% ($p = 0.007$) in the LW group relative to the SN group. Additionally, axial compression stiffness was 43.2% lower ($p = 0.002$), mean varus bending stiffness was 26.1% lower ($p = 0.007$), and the single load to failure was 61.9% lower ($p = 0.005$)

TABLE I BMD and the Stiffness and Single-Load-to-Failure Test Results in the 2 Study Groups*

	SN Group (N = 10)	LW Group (N = 10)	P Value
BMD *(mg/cm³)*	33.32 ± 12.5	34.10 ± 13.9	0.243
Stiffness in internal rotation *(N/deg)*	1.03 ± 0.11	0.77 ± 0.06	0.007
Stiffness in external rotation *(N/deg)*	0.92 ± 0.15	0.74 ± 0.09	0.007
Stiffness in axial compression *(N/mm)*	590.0 ± 69.3	335.1 ± 38.2	0.002
Stiffness in varus bending *(N/mm)*	435.9 ± 27.1	322.1 ± 26.5	0.007
Single load to failure† *(N)*	1,121.7 ± 112.1	427.4 ± 51.8	0.005

*SN group = greater trochanter (GT) lateral wall intact group, LW group = GT lateral wall comminution group. All data are presented as the mean ± standard deviation. †Tested in varus bending.

in the LW group, as compared with the SN group (Table I). Thus, varus bending stiffness, axial compression stiffness, torsional stiffness, and the single load to failure were all significantly reduced in the LW group relative to the SN group.

Discussion

In this study, we aimed to investigate the degree to which the presence of a comminuted versus an intact GT lateral wall compromises the biomechanical properties of osteoporotic proximal humeri with a surgical neck fracture fixed with a locking plate. As we had hypothesized, GT lateral wall comminution significantly compromised the axial compression stiffness, torsional stiffness, varus bending stiffness, and single load to failure of osteoporotic proximal humeri with a 2-part surgical neck fracture fixed with a plate. In particular, the single load to failure was nearly threefold lower in the group with a comminuted GT lateral wall.

Fixation failure and varus collapse are challenging issues in elderly patients with poor cancellous bone quality within the proximal humeral head. Consequently, medial calcar screw support was introduced to stabilize the plate-bone construct, particularly in patients with medial calcar comminution of the surgical neck. Previous studies have compared comminuted surgical neck fractures with and without calcar screws and demonstrated an approximately 34% reduction in axial compression stiffness[9] and a 20% to 36% reduction in the single load to failure in axial compression[11,20] in fractures fixed without calcar screws compared with those fixed with calcar screws. In the present study, GT lateral wall comminution reduced axial stiffness by 43% and the single load to failure in varus bending by 61.9%, even with fracture fixation that included calcar support.

Critically, although GT lateral wall comminution is common in osteoporotic proximal humeral fractures, this issue has received little clinical attention. In the present study, we found that the presence of GT lateral wall comminution significantly compromised biomechanical stability despite the placement of medial column support for medial calcar comminution. Given that rotator cuffs and the deltoid muscle can place a varus bending force on the proximal humerus, decreased stability in patients with a comminuted GT lateral wall is likely to result in varus failure during the postoperative rehabilitation period[21]. Consequently, early range-of-motion exercise is inevitably limited in these individuals.

Many Neer type-II surgical neck fractures that are encountered in clinical and operative settings have a concomitant GT lateral wall fracture (which often involves a longitudinal fracture line just lateral to the bicipital groove), albeit without displacement. Undoubtedly, screws must be introduced in close proximity to the fracture line on the lateral wall, which raises concerns regarding stability, despite the use of a locking screw in the plate system. Fortunately, for patients with only 1 nondisplaced longitudinal fracture in the GT lateral wall, this locking-plate system with medial calcar support appears to work well. However, the situation differs if lateral wall comminution is present. To avoid varus failure with pullout of the locking plate and to facilitate bone union, it appears necessary to either prolong the immobilization period, with the affected arm placed under minimal varus load, or include other augmentation, such as allogenic strut bone or calcium phosphate[22-24].

Gardner et al.[25] were the first to describe the use of endosteal fibular strut bone augmentation to restore the medial column and to add stability in osteoporotic proximal humeral surgical neck fractures with medial wall comminution. Subsequently, multiple clinical studies have reported favorable findings following the use of endosteal fibular strut bone graft in patients with proximal humeral fractures[26,27]. Although a recent randomized controlled trial detected no added clinical benefit of fibular allograft in the treatment of medial comminuted proximal humeral fractures[28], the findings of the present study suggest that, if a proximal humeral fracture has concomitant GT wall comminution, then the benefits of an endosteal fibular strut bone graft would be apparent in clinical trials.

There are several clinically relevant factors that should be considered. First, recent cadaveric models have taken into account the effect of the rotator cuff in biomechanical studies[21,29]. In the present study, resection was performed in the actual model to represent comminution; however, in a real clinical situation, the presence of the rotator cuff would affect the comminuted fragments in the LW group more than those in the SN group. Therefore, our results might appear more severe in a real clinical setting. Nonetheless, the current model alone already shows a significant difference between the groups. Second, given the varying degrees of GT wall comminution, the present study may represent a specific simulation of the worst-case scenario. Lastly, although this study was designed to simulate cases that are surgically fixed with use of a locking plate, other options, including nonoperative treatment, may be considered in clinical settings.

This study has several limitations. First, given the inherent nature of cadaveric studies, there are inevitable differences when compared with an in vivo setting. For instance, the use of braided sutures to secure the multifragmented GT during surgery was not simulated. Second, although the mean BMD values in the present study (33 and 34 mg/cm^3 in the SN and LW groups, respectively) were low relative to those reported in previous, similar studies investigating volumetric BMD in the proximal humerus[30], whether the humeri were indeed osteoporotic could not be confirmed. Third, when modeling a surgical neck wedge osteotomy, we utilized landmarks on the plate for the placement of calcar screws in order to secure the near cortex of the humeral shaft in each model. Thus, the superior margin of the wedge was slightly different in each humerus. In addition, the bending tests were performed with use of the 4-point bending method rather than the cantilever bending test, which has been utilized in previous studies[4,18,31,32]. Although the cantilever bending test represents a more physiologic loading situation, we note that the same overall bending moment between loading spans can be expected with the 4-point bending test[33]. Fifth, we included the axial loading test as a parameter because it has been reported in previous studies; however, this force does not seem to be physiologically relevant. Lastly, to simulate GT lateral wall comminution, we removed 5 mm of the GT lateral wall cortex. Methods for generating bone defects that simulate comminution in the humeral shaft or surgical neck have been established in prior studies[34]. In the present study, we created GT defects in the same manner, as there are no published studies, to our knowledge, that describe a method for lateral wall comminution.

In conclusion, even though the generalizability of this cadaveric model may be limited to the extreme clinical scenario, we found that severe comminution of the GT lateral wall significantly compromised the stability of osteoporotic humeral surgical neck fractures fixed with a plate and screws alone. ■

NOTE: The authors thank J.H. Kim, J.H. Bang, and T.-J. Ha from the Surgical Anatomy Education Center at the Yonsei University College of Medicine, Seoul, Republic of Korea, for their technical support.

Dohyun Kim, MD[1]
Joon-Ryul Lim, MD, PhD[1]
Tae-Hwan Yoon, MD, PhD[1]
Seung-Hwan Shin, MD[1]
Yong-Min Chun, MD, PhD[1]

[1]Arthroscopy and Joint Research Institute, Department of Orthopedic Surgery, Severance Hospital, Yonsei University College of Medicine, Seoul, Republic of Korea

Email for corresponding author: min1201@hanmail.net

References

1. Horak J, Nilsson BE. Epidemiology of fracture of the upper end of the humerus. Clin Orthop Relat Res. 1975 Oct;(112):250-3.

2. Howard L, Berdusco R, Momoli F, Pollock J, Liew A, Papp S, Lalonde KA, Gofton W, Ruggiero S, Lapner P. Open reduction internal fixation vs non-operative management in proximal humerus fractures: a prospective, randomized controlled trial protocol. BMC Musculoskelet Disord. 2018 Aug 18;19(1):299.

3. Koukakis A, Apostolou CD, Taneja T, Korres DS, Amini A. Fixation of proximal humerus fractures using the PHILOS plate: early experience. Clin Orthop Relat Res. 2006 Jan;442(442):115-20.

4. Edwards SL, Wilson NA, Zhang LQ, Flores S, Merk BR. Two-part surgical neck fractures of the proximal part of the humerus. A biomechanical evaluation of two fixation techniques. J Bone Joint Surg Am. 2006 Oct;88(10):2258-64.

5. Faraj D, Kooistra BW, Vd Stappen WA, Werre AJ. Results of 131 consecutive operated patients with a displaced proximal humerus fracture: an analysis with more than two years follow-up. Eur J Orthop Surg Traumatol. 2011 Jan;21(1):7-12.

6. Laux CJ, Grubhofer F, Werner CML, Simmen HP, Osterhoff G. Current concepts in locking plate fixation of proximal humerus fractures. J Orthop Surg Res. 2017 Sep 25;12(1):137.

7. Agudelo J, Schürmann M, Stahel P, Helwig P, Morgan SJ, Zechel W, Bahrs C, Parekh A, Ziran B, Williams A, Smith W. Analysis of efficacy and failure in proximal humerus fractures treated with locking plates. J Orthop Trauma. 2007 Nov-Dec;21(10):676-81.

8. Robinson CM, Wylie JR, Ray AG, Dempster NJ, Olabi B, Seah KT, Akhtar MA. Proximal humeral fractures with a severe varus deformity treated by fixation with a locking plate. J Bone Joint Surg Br. 2010 May;92(5):672-8.

9. Bai L, Fu Z, An S, Zhang P, Zhang D, Jiang B. Effect of Calcar Screw Use in Surgical Neck Fractures of the Proximal Humerus With Unstable Medial Support: A Biomechanical Study. J Orthop Trauma. 2014 Aug;28(8):452-7.

10. Gardner MJ, Weil Y, Barker JU, Kelly BT, Helfet DL, Lorich DG. The importance of medial support in locked plating of proximal humerus fractures. J Orthop Trauma. 2007 Mar;21(3):185-91.

11. Ponce BA, Thompson KJ, Raghava P, Eberhardt AW, Tate JP, Volgas DA, Stannard JP. The role of medial comminution and calcar restoration in varus collapse of proximal humeral fractures treated with locking plates. J Bone Joint Surg Am. 2013 Aug 21;95(16):e113(1-7).

12. Hasan AP, Phadnis J, Jaarsma RL, Bain GI. Fracture line morphology of complex proximal humeral fractures. J Shoulder Elbow Surg. 2017 Oct;26(10):e300-8.

13. Robinson CM, Stirling PHC, Goudie EB, MacDonald DJ, Strelzow JA. Complications and Long-Term Outcomes of Open Reduction and Plate Fixation of Proximal Humeral Fractures. J Bone Joint Surg Am. 2019 Dec 4;101(23):2129-39.

14. Mehta S, Chin M, Sanville J, Namdari S, Hast MW. Calcar screw position in proximal humerus fracture fixation: Don't miss high! Injury. 2018 Mar;49(3):624-9.

15. Röderer G, Gebhard F, Krischak G, Wilke HJ, Claes L. Biomechanical in vitro assessment of fixed angle plating using a new concept of locking for the treatment of osteoporotic proximal humerus fractures. Int Orthop. 2011 Apr;35(4):535-41.

16. Majed A, Thangarajah T, Southgate D, Reilly P, Bull A, Emery R. Cortical thickness analysis of the proximal humerus. Shoulder Elbow. 2019 Apr;11(2):87-93.

17. Fletcher JWA, Windolf M, Richards RG, Gueorguiev B, Varga P. Screw configuration in proximal humerus plating has a significant impact on fixation failure risk predicted by finite element models. J Shoulder Elbow Surg. 2019 Sep;28(9):1816-23.

18. Donohue DM, Santoni BG, Stoops TK, Tanner G, Diaz MA, Mighell M. Biomechanical Comparison of 3 Inferiorly Directed Versus 3 Superiorly Directed Locking Screws on Stability in a 3-Part Proximal Humerus Fracture Model. J Orthop Trauma. 2018 Jun;32(6):306-12.

19. Hast MW, Chin M, Schmidt EC, Sanville J, Van Osten GK, Mehta S. Mechanical Effects of Bone Substitute and Far-Cortical Locking Techniques in 2-Part Proximal Humerus Fracture Reconstruction: A Cadaveric Study. J Orthop Trauma. 2020 Apr;34(4):199-205.

20. Zhang X, Huang J, Zhao L, Luo Y, Mao H, Huang Y, Chen W, Chen Q, Cheng B. Inferomedial cortical bone contact and fixation with calcar screws on the dynamic and static mechanical stability of proximal humerus fractures. J Orthop Surg Res. 2019 Jan 3;14(1):1.

21. Chalmers CE, Wright DJ, Patel N, Hitchens H, McGarry M, Lee TQ, Scolaro JA. Muscular Forces Responsible for Proximal Humeral Deformity After Fracture. J Orthop Trauma. 2022 Jan 1;36(1):e18-23.
22. Egol KA, Sugi MT, Ong CC, Montero N, Davidovitch R, Zuckerman JD. Fracture site augmentation with calcium phosphate cement reduces screw penetration after open reduction-internal fixation of proximal humeral fractures. J Shoulder Elbow Surg. 2012 Jun;21(6):741-8.
23. Kwon BK, Goertzen DJ, O'Brien PJ, Broekhuyse HM, Oxland TR. Biomechanical evaluation of proximal humeral fracture fixation supplemented with calcium phosphate cement. J Bone Joint Surg Am. 2002 Jun;84(6):951-61.
24. Raphael JS, Booker MR, Saing MH, Beaver AB, Marvil SC, Puglisi AS, Samuel SP. Locked Plate Fixation of Proximal Humerus Fractures Using Cannulated Subchondral Support Pegs. Shoulder Elbow. 2013;5(3):178-82.
25. Gardner MJ, Boraiah S, Helfet DL, Lorich DG. Indirect medial reduction and strut support of proximal humerus fractures using an endosteal implant. J Orthop Trauma. 2008 Mar;22(3):195-200.
26. Matassi F, Angeloni R, Carulli C, Civinini R, Di Bella L, Redl B, Innocenti M. Locking plate and fibular allograft augmentation in unstable fractures of proximal humerus. Injury. 2012 Nov;43(11):1939-42.
27. Hinds RM, Garner MR, Tran WH, Lazaro LE, Dines JS, Lorich DG. Geriatric proximal humeral fracture patients show similar clinical outcomes to non-geriatric patients after osteosynthesis with endosteal fibular strut allograft augmentation. J Shoulder Elbow Surg. 2015 Jun;24(6):889-96.
28. Wang Q, Sheng N, Huang JT, Zhu H, Tuerxun M, Ruan Z, Shi T, Zhu Y, Zhang Y, Rui B, Wang L, Chen Y. Effect of Fibular Allograft Augmentation in Medial Column Comminuted Proximal Humeral Fractures: A Randomized Controlled Trial. J Bone Joint Surg Am. 2023 Feb 15;105(4):302-11.
29. Arvesen JE, Gill SW, Sinatra PM, Eng M, Bledsoe G, Kaar SG. Biomechanical Contribution of Tension-Reducing Rotator Cuff Sutures in 3-Part Proximal Humerus Fractures. J Orthop Trauma. 2016 Aug;30(8):e262-6.
30. Röderer G, Scola A, Schmölz W, Gebhard F, Windolf M, Hofmann-Fliri L. Biomechanical in vitro assessment of screw augmentation in locked plating of proximal humerus fractures. Injury. 2013 Oct;44(10):1327-32.
31. Jabran A, Peach C, Zou Z, Ren L. Hybrid blade and locking plate fixation for proximal humerus fractures: a comparative biomechanical analysis. Biomed Eng Online. 2018 Jan 25;17(1):10.
32. Siffri PC, Peindl RD, Coley ER, Norton J, Connor PM, Kellam JF. Biomechanical analysis of blade plate versus locking plate fixation for a proximal humerus fracture: comparison using cadaveric and synthetic humeri. J Orthop Trauma. 2006 Sep;20(8):547-54.
33. Xue H, Khawaja H. Analytical study of sandwich structures using Euler–Bernoulli beam equation. AIP Conf Proc. 2017;1798:020076.
34. Katthagen JC, Schwarze M, Meyer-Kobbe J, Voigt C, Hurschler C, Lill H. Biomechanical effects of calcar screws and bone block augmentation on medial support in locked plating of proximal humeral fractures. Clin Biomech (Bristol, Avon). 2014 Aug;29(7):735-41.