Published in final edited form as:

J Orthop Trauma. 2014 July ; 28(7): 427–432. doi:10.1097/BOT.0000000000000042.

Effect of Off-Axis Screw Insertion, Insertion Torque, and Plate Contouring on Locked Screw Strength

Bethany Gallagher, MD*, Matthew J. Silva, PhD[†], and William M. Ricci, MD[†]

*Department of Orthopaedic Surgery, Vanderbilt University School of Medicine, Nashville, TN

[†]Department of Orthopaedic Surgery, Washington University School of Medicine, St. Louis, MO.

Abstract

Objectives—This study quantifies the effects of insertion torque, off-axis screw angulation, and plate contouring on the strength of locking plate constructs.

Methods—Groups of locking screws ($n = 6$ –11 screws) were inserted at 50%, 100%, 150%, and 200% of the manufacturer-recommended torque (3.2 Nm) into locking compression plates at various angles: orthogonal (control), 5-degree angle off-axis, and 10-degree angle off-axis. Screws were loaded to failure by a transverse force (parallel to the plate) either in the same (“+”) or opposite direction (“–”) of the initial screw angulation. Separately, locking plates were bent to 5 and 10-degree angles, with the bend apex at a screw hole. Locking screws inserted orthogonally into the apex hole at 100% torque were loaded to failure.

Results—Orthogonal insertion resulted in the highest average load to failure, 2577 ± 141 N (range, 2413–2778 N), whereas any off-axis insertion significantly weakened constructs (165–1285 N, at 100% torque) ($P < 0.05$). For “+” loading, torque beyond 100% did not increase strength, but 50% torque reduced screw strength ($P < 0.05$). Loading in the “–” direction consistently resulted in higher strengths than “+” loading ($P < 0.05$). Plate contouring of 5-degree angle did not significantly change screw strength compared with straight plates but contouring of 10-degree angle significantly reduced load to failure ($P < 0.05$).

Conclusions—To maximize the screw plate interface strength, locking screws should be inserted without cross-threading. The mechanical stability of locked screws is significantly compromised by loose insertion, off-axis insertion, or severe distortion of the locking mechanism.

Keywords

locked screw; biomechanics; off-axis; insertion torque

INTRODUCTION

The development of locking plate and screw systems has advanced the treatment of periarticular and osteoporotic fractures. They provide “fixed-angle” constructs and reduce the potential for collapse relative to similar nonlocked constructs.¹ In addition, locking plate constructs rely on different forces for fixation and load transfer. Nonlocked constructs rely on friction between plate and bone generated by screws that compress plate to bone.^{2,3} In the osteoporotic patient, nonlocked screws can strip before generating sufficient compression. Locking plate constructs, in contrast, rely on transfer of axial force directly from bone to plate via the locked screw-plate interface. The screw must seat fully into the locking hole for this force transmission to occur.^{4,5} This can become problematic, in fixed-angle locked plate systems, when screws deviate during insertion to a trajectory off-axis to the locking mechanism of the plate.

The current widely used locking plates have a conically threaded screw head that must be inserted co-axial to a threaded screw hole. This design allows the screw to fully engage the plate, reducing toggle of the screws.⁶ However, the precise angle of insertion is at times difficult to achieve in severely osteoporotic bone and in cancellous metaphyseal bone.¹ In these settings of weakened bone, the screw can deviate from the predrilled path and ultimately rest in an off-axis position and cross-thread into the plate. This off-axis angle weakens the screw-plate-bone construct and potentially results in early construct failure.⁶ As the screw cross threads into the plate, it is tempting to increase the insertional torque to prevent the toggle that may occur when the screw is not fully engaged into the plate. Limited information is available to support this practice of over-tightening the cross-threaded screw to overcome the inherent weakness of the construct.

Although a variety of pre-contoured locking plates are available for periarticular fractures, at times it is necessary to manually contour locking plates for fixation of certain fractures. This contouring deforms the plate and may have a secondary effect on the threads in the locking holes of the plate. Ultimately, to achieve ideal fracture alignment, the surgeon may inadvertently cause a reduction in construct stability due to deformity of the locking mechanism. This study was designed to quantify the biomechanical consequence of off-axis screw trajectory, the effect of insertion torque, and plate contouring on the strength of a locking plate construct.

MATERIALS AND METHODS

Part A: Evaluation of Off-Axis Screw Insertion With Standard Insertion Torque

The first goal of this study was to evaluate the effect of off-axis insertion on the ultimate failure strength of a locking plate-screw interface. Groups of 4.5-mm locking screws ($n = 6-11$) were inserted into 4.5-mm locking compression plates (Peri-Loc; Smith & Nephew, Memphis, TN) at angles 0 (orthogonal to plate), 5, and 10 degrees off-axis. A custom jig was constructed to ensure reliable insertion of the screws at each off-axis angle (Fig. 1). For this test, the screws were tightened using an electronic torque wrench (Snap-On, Versatorq) to a standard insertion torque of 3.2 Nm based on the manufacturer's recommendations.

The plate–screw construct was loaded in an Instron materials testing machine as shown in Figure 2. The plate was secured in a vice midway between the hole being tested and the adjacent hole. A protective sleeve was placed over the screw threads to eliminate variability secondary to the position of the force applicator on the threads. Force was applied to the screw at a perpendicular offset distance of 5.5 mm from the plate. The actuator displaced downward at a rate of 0.016 mm/s after a preload of 20–30 N. Testing was performed with the force applied in 1 of 2 directions relative to the screw angle. Force applied in a direction that would straighten the screw (toward an orthogonal angle) was defined as “+” loading, and force in the opposite direction, to accentuate the off-axis angulation, was defined as “–” loading (Fig. 3). Displacement and force at the actuator were recorded until either catastrophic failure or a displacement of 2 mm (approximately 20 degrees of angulation) was reached. The ultimate force to failure was extracted from the force–displacement plot for each tested screw. Each hole and screw were used a single time only.

Part B: Evaluation of Off-Axis Insertion With Variable Insertional Torque

The effect of insertional torque on the angular stability of cross-threaded locking screws was tested in a protocol similar to that used in Part A. Instead of tightening the screws to the recommended 3.2 Nm, screws ($n = 4–10$) were inserted to 50%, 150%, or 200% of this value. The screws were inserted at 5- and 10-degree angles for each insertional torque. The force to ultimate failure was determined as described previously.

Part C: Evaluation of Plate Contouring With Orthogonal Screw Insertion

This portion of the study used smaller plates and screws, similar to those that may be contoured during fracture fixation. Groups of 3.5-mm locking screws ($n = 6$) were inserted into the apex hole of 3.5-mm locking compression plate (Peri-Loc; Smith & Nephew) that was bent at either 5- or 10-degree angle (Fig. 4). The bend in the plate, centered at the hole used for screw insertion (apex hole), was created uniformly with a custom jig for both 5- and 10-degree angle bends. The bend was centered over a hole to maximize the deformity of the threads. A compensatory bend was placed below the hole to assure that the force applicator would be orthogonal to the axis of the screw. All screws were inserted at the manufacturer’s recommended torque of 3.2 Nm orthogonal to the plate after bending. In addition, a group ($n = 6$) of straight, unbent plates were tested as a control. An identical testing protocol and data extraction were used as in parts A and B.

Statistical Evaluation

Differences between experimental groups were assessed by analysis of variance testing with Fisher protected least significant differences test for post-hoc multiple comparisons (Statview 5.0). Significance was set at $P < 0.05$.

RESULTS

Part A: Evaluation of Off-Axis Screw Insertion With Standard Insertion Torque

Off-axis insertion using the standard insertion torque, at all angles tested, had a significant effect on the ultimate force to failure of the plate–screw construct (Table 1). The control (0-degree angle) screw orientation, that is, orthogonal and non-cross-threaded, resulted in the

highest average load to failure 2577 N (range, 2413–2778 N, SD = 141 N). Off-axis screws all showed significantly reduced average load to failure, as shown in Table 1, when compared with the control group (50%–87% reduced; $P < 0.001$). Loading in the “+” direction (direction to straighten the screw) resulted in significantly weaker constructs than when loading was in the “–” direction (accentuating the off-axis angulation) for both the 5- and 10-degree off-axis insertion angles ($P < 0.001$). The only screws that sustained catastrophic failure with fracture at the screw head–neck junction were those loaded orthogonal to the plate (Fig. 5). Those inserted at an off-axis angle loosened and could be easily pushed out of the plate at the completion of the test. The failure of these screws was at the locking mechanism in the plate in all cases.

Part B: Evaluation of Off-Axis Insertion With Variable Insertional Torque

Increasing insertional torque tended to increase the holding power of off-axis screws on average (Fig. 6). Increasing insertional torque from 100% of the manufacturer’s recommended 3.2 Nm to 150% or 200% of this value yielded modest (9%–40%) but inconsistent improvements on average force to failure for off-axis screws. These improvements for “overtightened” screws were significant or very nearly significant for 3 of 8 possible scenarios (compared with 100% torque) as shown in Figure 6. The force to failure values for these overtightened off-axis screws, however, were still significantly lower than for orthogonal insertion at 100% torque ($P < 0.001$). This illustrates that the decrease in ultimate strength secondary to off-axis insertion cannot be completely overcome by increasing the insertional torque.

Using a lower than recommended insertional torque had a modest nonsignificant weakening effect compared with 100% torque (13%–65%) ($P > 0.05$) (Fig. 6). Compared with overtightened screws (inserted to 150% or 200% torque), undertightened screws (inserted to 50% torque) had reduced average strength for all insertion angles and loading directions ($P < 0.05$) (Fig. 6). Undertightening of 50% did not affect the strength of screws inserted orthogonal to the plate ($P = 0.892$).

Taken together, the results indicate that screw alignment is a more important determinant of the strength of the screw–plate interface than insertion torque (for a range of 50%–200% of the manufacturer’s recommended value). The failure mechanism was also independent of insertional torque and remained similar to that observed for the control insertional torque; loosening of screws inserted off-axis and catastrophic failure at the neck of screws inserted orthogonal to the plate.

Part C: Evaluation of Plate Contouring With Orthogonal Screw Insertion

For plates with a 5-degree angle bend, screws exhibited strength similar to the noncontoured plates as shown in Figure 7 ($P > 0.05$). Screws inserted into the plate with a 10-degree angle bend were significantly weaker compared with both the controls and the plates with a 5-degree angle bend as shown in Figure 7 ($P < 0.05$). Qualitatively, the 10-degree angle deformity clearly affected the ability of the screw to engage fully in the threads of plate, sitting slightly proud in the hole.

DISCUSSION

There are few clear absolute surgical indications for the use of locking plates in orthopaedic fracture care. The locked plating techniques seem to be beneficial for the treatment of fractures in areas of poor bone quality and periarticular fractures.^{1,4,7,8} However, in these locations, cross-threading of locked screws can occur as screws deviate from the predrilled path in the compromised bone, and whenever adjustments to a locked plate contour are required to accommodate complex metaphyseal anatomy, there is potential to affect the integrity of locking mechanism. Each of these situations, based on the data from the current study, reduce the strength of the screw–plate interface.

Many studies have focused on the strength of locked plate constructs both in clinical and in biomechanical studies, often in comparison with traditional plating techniques.^{5,8–11} Fulkerson et al⁵ showed a significant increase in construct strength under axial loads with the use of bicortical locking screws in comminuted diaphyseal fractures as compared with both conventional and unicortical screw constructs. The bicortical nonlocked screws had 25 times the displacement of the bicortical locking screws under axial loading conditions and there were similar results with cantilever loading clearly illustrating increased stability with locked plating constructs.⁵ Although these results showed promise of increased fixation strength, studies have shown that improper locking of the screw can yield failures through screw loosening. Haas et al¹² attributed fixation failure to screw loosening in 7 of 387 of cases using the PC-Fix system. This failure mechanism was also supported by Schutz et al¹³ in a study of distal femur fractures treated with the Less Invasive Stabilization System device (Synthes USA, Paoli, PA). Despite this evidence of locking mechanism failures, there are no data indicating how often such failure occurs in the absence of construct failure. It seems logical that such “subclinical” occurrences of locking mechanism failure would occur with greater frequency than only when construct failure occurs.

Few studies have focused on the mechanism and magnitude of screw–plate weakening secondary to altered screw trajectory and cross-threading in locked plating systems. Kaab et al⁶ addressed this with a study focusing on variable cross-threaded angles of screw insertion into both PC-fix and plates with holes that accommodate both locking and nonlocking screws at different locations within the hole, the so-called Combi hole. The Combi hole design is different than the closed section locking holes tested in the current study. The Combi hole provides 2 overlapping holes, 1 locking and 1 nonlocking, at the expense of having each of these holes being incomplete where they meet. Despite this difference, their findings are consistent with those of the current study: altered insertion angles result in significant weakening of the angular stability of locking screws. The difference in strength between off-axis and orthogonal insertion and the mechanism of failure were similar to those demonstrated in the current study. Kaab et al,⁶ however, did not address the possibility to overcome this loss of strength with increasing screw insertion torque nor did they address the effect of plate contouring.

The results of this study provide clinically applicable information regarding the degree of off-axis insertion, the direction of the applied force, and the effect of overtightening screws as a method to compensate for off-axis insertion. When cross-threading occurs, bending

strength is reduced, compared with orthogonal insertion, by greater than 50% regardless of the degree of off-axis angulation. There was no direct correlation between degree of off-axis angulation and reduction of bending strength. Going from 5- to 10-degree angle yielded reduced strength when the loading was in the direction to increase the off-axis angulation (“-” loading) but going from 5- to 10-degree angle yielded increased strength when the loading was in the direction to straighten the screw (“+” loading). The direction of loading also proved to affect strength at any given off-axis angulation. Loading in a manner that would tend to straighten the screw orientation is associated with much less strength than loading in a direction that would increase the off-axis angulation. Extrapolating this information to the clinical realm indicates that off-axis screw insertion in an end segment away from the articular surface where axial forces will tend to increase screw angulation provides more angular stability than angulation toward the articular surface. Another clinical scenario related to cross-threading is the temptation to compensate for cross-threading by overtightening the effected screw. The data presented in the current study indicates that this practice has limited utility as increasing the insertional torque did not fully compensate for loss of strength related to off-axis insertion. Finally, the practice of plate contouring, even of precontoured periarticular plates, is common to maximize plate conformity to any individual patient’s anatomy. The consequence of plate contouring on the integrity of the locking mechanism in the locking plate was previously unknown. This study indicates that minor adjustments, 5-degree angle of bend, does not significantly affect the integrity of the locking mechanism. But, larger bends distort the locking mechanism to a degree that prevents the screw from fully engaging the plate and decreases strength of screw locking. When possible, placing necessary bends between screw holes might avoid distorting the locking mechanism.

Although this biomechanical study provides the clinician with potentially useful data regarding the subtleties of locked plate screw constructs, there are several limitations that should be considered. In vivo forces are unlikely to be unidirectional as directed in this study and the effect of cyclic loading was not investigated. The results of this study apply only to locked plate systems that are designed to be fixed angle and do not apply to systems that are designed for polyaxial locked screw insertion. Also, the validity of extrapolating results of this study to other locking mechanisms remains unknown.

Although complex forces exist in vivo during bone healing, this simplified laboratory mechanical study clearly showed a relevant decrease in the stability of locking screws that are inserted off-axis or through bent plates. The mechanical stability of the locking plate–screw interface was most significantly compromised with cross-threading of the locking mechanism and loading in a direction that tended to straighten screws. Overtightening of screws did not fully compensate for loss of strength resulting from off-axis insertion. Minor, but not major, degrees of plate contouring seems to minimally effect the screw locking. Based on these data, we recommend that cross-threading of locking screws be avoided when possible.

Acknowledgments

Supported by grant funding from the National Institutes of Health and OREF (to M.J.S.).

M. J. Silva receives research support from Synthes and Merck, and book royalties from Springer. W. M. Ricci receives consulting income from Smith & Nephew, Biomet, and Stryker. He also receives royalties from Smith & Nephew, Wright Medical, Biomet (expected), and Stryker (expected). Research and Institutional support is provided by Smith & Nephew, Synthes, AO North America, and COTA. Book royalties are expected from Lippincott Williams & Wilkins.

REFERENCES

1. Haidukewych GJ, Ricci W. Locked plating in orthopaedic trauma: a clinical update. *J Am Acad Orthop Surg.* 2008; 16:347–355. [PubMed: 18524986]
2. Hayes WC, Perren SM. Plate-bone friction in the compression fixation of fractures. *Clin Orthop Relat Res.* 1972; 89:236–240. [PubMed: 4646262]
3. Beaupre GS, Carter DR, Orr TE, et al. Stresses in plated long-bones: the role of screw tightness and interface slipping. *J Orthop Res.* 1988; 6:39–50. [PubMed: 3334738]
4. Egol KA, Kubiak EN, Fulkerson E, et al. Biomechanics of locked plates and screws. *J Orthop Trauma.* 2004; 18:488–493. [PubMed: 15475843]
5. Fulkerson E, Egol KA, Kubiak EN, et al. Fixation of diaphyseal fractures with a segmental defect: a biomechanical comparison of locked and conventional plating techniques. *J Trauma.* 2006; 60:830–835. [PubMed: 16612304]
6. Kaab MJ, Frenk A, Schmeling A, et al. Locked internal fixator: sensitivity of screw/plate stability to the correct insertion angle of the screw. *J Orthop Trauma.* 2004; 18:483–487. [PubMed: 15475842]
7. Gardner MJ, Helfet DL, Lorich DG. Has locked plating completely replaced conventional plating? *Am J Orthop (Belle Mead NJ).* 2004; 33:439–446. [PubMed: 15509108]
8. Koval KJ, Hoehl JJ, Kummer FJ, et al. Distal femoral fixation: a biomechanical comparison of the standard condylar buttress plate, a locked buttress plate, and the 95-degree blade plate. *J Orthop Trauma.* 1997; 11:521–524. [PubMed: 9334954]
9. Zlowodzki M, Williamson S, Zardiackas LD, et al. Biomechanical evaluation of the less invasive stabilization system and the 95-degree angled blade plate for the internal fixation of distal femur fractures in human cadaveric bones with high bone mineral density. *J Trauma.* 2006; 60:836–840. [PubMed: 16612305]
10. Fulkerson E, Koval K, Preston CF, et al. Fixation of periprosthetic femoral shaft fractures associated with cemented femoral stems: a biomechanical comparison of locked plating and conventional cable plates. *J Orthop Trauma.* 2006; 20:89–93. [PubMed: 16462560]
11. Leung F, Shew-Ping C. A prospective, randomized trial comparing the limited contact dynamic compression plate with the point contact fixator for forearm fractures. *J Bone Joint Surg Am.* 2003; 85:2343–2348. [PubMed: 14668503]
12. Haas N, Hauke C, Schutz M, et al. Treatment of diaphyseal fractures of the forearm using the Point Contact Fixator (PC-Fix): results of 387 fractures of a prospective multicentric study (PC-Fix II). *Injury.* 2001; 32(suppl 2):B51–B62. [PubMed: 11718739]
13. Schutz M, Muller M, Krettek C, et al. Minimally invasive fracture stabilization of distal femoral fractures with the LISS: a prospective multicenter study. Results of a clinical study with special emphasis on difficult cases. *Injury.* 2001; 32(suppl 3):SC48–SC54. [PubMed: 11888194]

FIGURE 1.

Jig used for insertion of screws at 5- or 10-degree angle off-axis.

FIGURE 2.

Testing of a screw inserted at 5-degree angle off-axis insertion with loading in the “+” direction (direction to straighten screw).

FIGURE 3. Loading directions for off-axis screw insertion: “+” loading to straighten screw; “-” loading to increase off-axis trajectory.

FIGURE 4.
Orthogonal screw insertion through straight plates (left) and plates bent 5-degree angle (center) and 10-degree angle (right).

FIGURE 5.
Screw with catastrophic failure at screw head–neck junction.

FIGURE 6.

Graph showing effect of off-axis screw insertion at various insertion torques. Loading conditions are defined by the off-axis insertion angle (5- or 10-degree angle) and the direction of loading ("-" or "+"). Error bars represent standard deviation.

FIGURE 7.
Graph showing effect of plate contouring.

TABLE 1

Effects of Off-Axis Insertion on Ultimate Force to Failure

	Loading Direction	No. Specimens Tested	Mean (Range) Ultimate Force to Failure (N)	SD
Orthogonal	N/A	6	2577 (2413–2778)	141
5-degree angle	–	6	1285* (1095–1387)	106
	+	11	342* (44–1226)	402
10-degree angle	–	6	774* (715–881)	57
	+	9	561* (248–749)	189

* $P < 0.001$ compared with orthogonal position.

N/A, not applicable.