A Biomechanical Comparison of Superior and Anterior Positioning of Precontoured Plates for Midshaft Clavicle Fractures

Paul Toogood, MD, MS, Dezba Coughlin, PhD, David Rodriguez, Jeffery Lotz, PhD, and Brian Feeley, MD

Abstract

With recent studies suggesting improved outcomes in displaced midshaft clavicle fractures treated with open reduction and internal fixation, debate has increased over the preferred plate positioning. Biomechanical studies have yielded conflicting results and have been limited by the almost exclusive use of a simple transverse fracture model.

We conducted a study to biomechanically compare superior and anterior plate positioning for clinically relevant midshaft clavicle fracture patterns. Oblique, bending wedge, and complex comminuted fracture patterns were created sequentially in 12 synthetic clavicles. Half were plated with precontoured superior plates and half with precontoured anterior plates. Constructs were loaded in axial compression, torsion, and cantilever bending to determine construct stiffness for comparison of plate positioning.

Results showed that, for all fracture patterns, more construct stiffness was achieved in axial compression and torsion (except for the oblique fracture pattern in clockwise torsion) with a superior plate, whereas more construct stiffness was achieved in cantilever bending with an anterior plate. Oblique fractures were significantly stiffer than bending wedge and complex comminuted fractures.

Given the unknown relative importance of loading conditions, absolute recommendations for either superior or anterior plates cannot be made.

Based on a historical body of literature suggesting low rates of nonunion,[1,2] midshaft clavicle fractures have traditionally been treated nonoperatively. Over the past 2 decades, however, doubt has been cast on this conservative approach.[2,3] More contemporary prospective series of shortened and displaced fractures have revealed significantly higher nonunion rates (7%-15%), pain scores, and dissatisfaction than previously reported.[3-8] These results fueled renewed interest in open reduction and internal fixation (ORIF).

Both anterior and superior plates have been used for midshaft clavicle fractures. On one hand, the superior surface is readily available with minimal muscular stripping and has a flat surface that is ideal for plating. On the other hand, several authors have advocated plating on the anterior surface because of its less prominent position, potential less need for hardware removal, longer anteroposterior screw purchase, and instrumentation away from at-risk neurovascular structures.[9-11] Little has been done, however, to experimentally compare these plating positions. Direct comparisons have been limited to a small number of biomechanical studies.[12-17] Some authors have concluded that superior plating is biomechanically preferable,[12,14,15] and others have demonstrated more stiffness with the plate placed anteriorly.[16,17]

Although biomechanical studies have examined a number of traditional plate and screw constructs, there has been a major limitation in the almost exclusive examination of a relatively rare and uniquely stable fracture pattern—transverse, or OTA (Orthopaedic Trauma Association) B1.3—despite epidemiologic data suggesting transverse fractures are clinically uncommon (~5%)[2] and the recognition by prior authors of this pattern's unique stability.[12,15]

We conducted a study to biomechanically compare superior and anterior plate positioning for 3 clinically relevant midshaft clavicle fracture patterns (oblique, bending wedge, complex comminuted) loaded in axial compression, torsion, and cantilever bending.

Materials and Methods

Fracture Patterns

Multiple classification systems for clavicle fracture morphology are available.[2,18] The most descriptive was developed by AO/ASIF (Arbeitsgemeinschaft für Osteosynthesefragen/Association for the Study of Internal Fixation)/OTA. This system provides the most detailed description of midshaft fracture morphology, with 3 primary categories (noncomminuted B1, wedge B2, segmental B3), each subdivided according to additional fracture characteristics.

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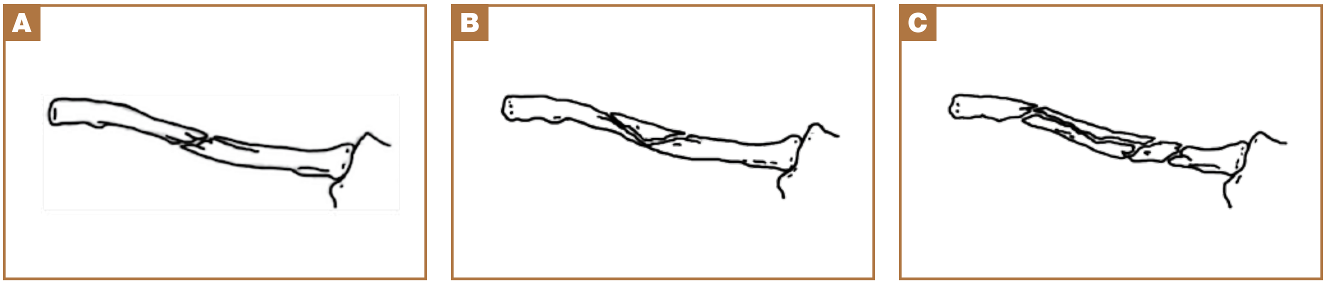

Figure 1. Fracture patterns selected from AO/ASIF classification of midshaft clavicle fractures: (A) oblique (B1.2), (B) bending wedge (B2.2), (C) complex comminuted (B3.3). Adapted with permission from Lippincott Williams and Wilkins/Wolters Kluwer Health: *Journal of Orthopaedic Trauma*, vol. 21, no. 10 supplement; Marsh JL, Slongo TF, Agel J, et al.; Fracture and dislocation classification compendium - 2007: Orthopaedic Trauma Association classification, database and outcomes committee; pages S1-S163; copyright 2007.

The AO/ASIF classification system and prior epidemiologic data were used to select 3 fracture patterns for testing (**Figures 1A-1C**):

- ***Oblique*** (B1.2). From the noncomminuted category (B1), the oblique pattern (B1.2) was selected. As this is the single most common fracture pattern encountered in clinical practice (26.3%),[2] it is highly clinically relevant.
- ***Bending Wedge*** (B2.2). From the wedge category (B2), the bending wedge pattern (B2.2) was selected. Again, the entire B2 category is among the more common fracture patterns encountered clinically (28.9%).[2]
- ***Complex Comminuted*** (B3.3). From the segmental category (B3), the complex comminuted pattern (B3.3) was selected. When segmental fractures occur, they are overwhelmingly comminuted (79.9%).[2] To address this inherently heterogeneous pattern, we decided on a “worst-case scenario” of the comminuted portion providing no mechanical stability. This was modeled using a simple gap.

No literature exists on the specific geometry of the selected fracture patterns. Therefore, to determine the appropriate lengths and angles of the needed osteotomies, we reviewed and measured 25 consecutive radiographs of each fracture type from our institution. The means of these measurements indicated that the oblique fracture (B1.2) consisted of a 32° osteotomy from superolateral to inferomedial; the bending wedge fracture (B2.2) consisted of an inferiorly based triangular wedge comprising 16% of the total clavicular length; and the complex comminuted fracture (B3.3) consisted of a resected portion comprising 21% of the total clavicular length.

Clavicle Model and Plating

Fourth-generation synthetic clavicles (3408-1; Pacific Research Laboratories, Vashon, Washington) were chosen for their consistent biomechanical properties across specimens.[19] These clavicles were left-sided and 175 mm in length and consisted of a cortical composite material with a density of 1.64 g/cm^3.

The superior and anterior plates used (Synthes, Paoli, Pennsylvania) were precontoured, standard, 8-hole, 3.5-mm locking compression plates.

Three locking 3.5-mm bicortical screws were used to secure each plate on each side of the fracture. For the oblique and bending wedge fracture patterns (**Figures 2A, 2B, 3A, 3B**), a single 3.5-mm lag screw was also used to provide compres-

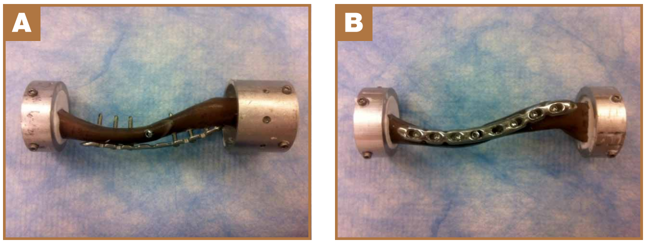

Figure 2. Superior photographs of oblique fracture patterns plated with anterior and superior plates: (A) oblique fracture, anterior plate; (B) oblique fracture, superior plate.

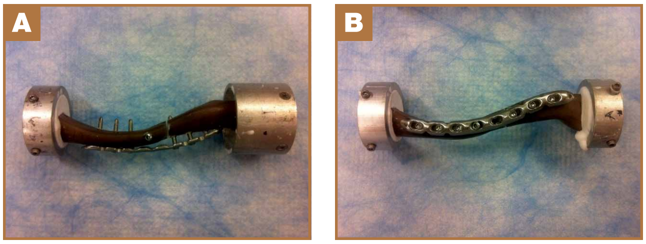

Figure 3. Superior photographs of bending wedge fracture patterns plated with anterior and superior plates: (A) bending wedge fracture, anterior plate; (B) bending wedge fracture, superior plate.

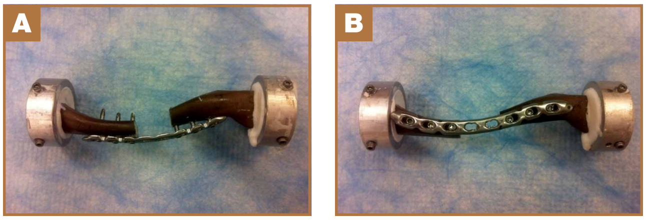

Figure 4. Superior photographs of complex comminuted fracture patterns plated with anterior and superior plates: (A) complex comminuted fracture, anterior plate; (B) complex comminuted fracture, superior plate.

sion across the fracture site before locked plating, consistent with clinical practice. As the complex comminuted fracture pattern removed a large section of each clavicle, no lag screw was present (**Figures 4A, 4B**). Clavicles were tested across the 3 fracture patterns by sequential osteotomies without implant adjustment.

Loading

Loading conditions were modeled after 2 recent, methodologically rigorous publications.[12,15] Testing was performed on a Bionix 858 testing system (MTS Systems; Eden Prairie, Minnesota) after the distal and proximal 1 cm of each specimen was fixed in Smoothcast (Smooth-On, Easton, Pennsylvania) in custom aluminum pots:

- ***Stiffness in Axial Compression.*** Constructs were preconditioned for 5 cycles between 10N and 20N. They were then loaded to 350N at 20 N/s while continuously sampling displacement (mm) and force (N) at 10 Hz. Stiffness was then determined as the slope of the linear portion of the force/displacement curve.
- ***Stiffness in Torsion.*** Specimens were held fixed proximally and rotated about their distal ends. The torsional axis was defined as the line connecting the most lateral point of the clavicle to the center of the medial end of the clavicle when viewed both anteriorly and superiorly. Constructs were preconditioned for 5 cycles between 0.5° and –0.5°. They were then loaded at 0.5°/s between –5° and 5° while continuously sampling displacement (degrees) and torque (Nmm) at 10 Hz. Stiffness was then determined as the slope of the torque/degrees curve both clockwise and counterclockwise.
- ***Stiffness in Cantilever Bending.*** Pilot data demonstrated no need for preconditioning. Constructs were loaded up to 30N at a rate of 0.5 mm/s while continuously sampling displacement (mm) and force (N) at 50 Hz. Stiffness (N/mm) was then determined as the slope of the force/displacement curve. During testing, the specimens were secured medially, and a support was positioned under the clavicle at a point just medial to the most medial screw in the proximal fragment. The load was applied at a standard point 1.5 cm medial to the lateral end of the specimen. The medial support imitated the action of the sternocleidomastoid while the lateral load simulated the downward weight of the arm.[12,13,15]

Testing Sequence

Each of 12 synthetic clavicles was initially osteotomized into an oblique fracture pattern (B1.2). Half of each fracture pattern (12/2 = 6) then underwent ORIF using either the superior or anterior plate. Each construct was then sequentially tested, first in axial compression, second in torsion, and third in cantilever bending. After testing of this fracture pattern was complete, each oblique fracture pattern was changed into a bending wedge pattern (B2.2) with the addition of a second laterally and inferiorly based osteotomy. This osteotomy was made with the implants in place. Constructs were then again tested sequentially under the 3 loading conditions. After testing of the bending wedge pattern (B2.2) was complete, each construct was changed to a complex comminuted pattern (B3.3) by performing a medial osteotomy and removing the intervening fragments. Constructs were then again tested sequentially under the 3 loading conditions.

Statistical Analysis

Means and SDs were calculated, and, for each loading condition, data were analyzed with 2-way analysis of variance ($P < .05$) to test the dependent variables of plate position and fracture pattern. A regular Tukey post hoc correction test ($P < .05$) for multiple comparisons was used.

A pretest power analysis was performed to determine the needed sample size, using cantilever bending as the primary outcome measure. The cantilever bending data from a recent similar study[12] was used to determine the likely effect size (3.08) that could be expected. A more conservative effect size of 2.0 (~10N) was then chosen. With $\alpha = 0.05$, sample size 12, and effect size 2.0, the study power was 0.88.

Results

Means and SDs for each construct under each loading condition are listed in **Tables I through IV**. For axial compression, the superior plate was found to be statistically stiffer than the anterior plate for all fracture patterns ($P = .004$). In addition, the oblique fracture pattern for both plate positions was significantly stiffer than the bending wedge and complex comminuted fracture patterns ($P < .0001$). The Tukey post hoc correction test revealed that the difference in stiffness between the bending wedge and complex comminuted fracture patterns was significant for specimens fixed with a superior plate but not for those fixed with an anterior plate. The interaction term between plate position and fracture patterns was not significant ($P = .7$).

For clockwise and counterclockwise torsion, the superior plate was statistically stiffer than the anterior plate for all fracture patterns ($P = .0144$, $P = .0006$), except for clockwise torsion of the oblique fracture pattern, for which the Tukey post hoc correction test revealed a nonsignificant difference. In addition, the oblique fracture pattern for both plate positions was significantly stiffer than the bending wedge and complex comminuted fracture patterns ($P < .0001$). The Tukey post hoc correction test revealed that the difference in stiffness between the bending wedge and complex comminuted fracture patterns was not significant. The interaction term between plate position and fracture patterns was not significant ($P = .0532$, $P = .65$).

For cantilever bending, the anterior plate was statistically stiffer than the superior plate for all fracture patterns ($P <.0001$). In addition, the oblique fracture pattern for both plate positions was significantly stiffer than the bending wedge and complex comminuted fracture patterns ($P <.0001$). The Tukey post hoc correction test revealed that the difference in stiffness between the bending wedge and complex comminuted fracture patterns was not significant. The interaction term between plate position and fracture patterns was not significant ($P = .41$).

Discussion

We had hypothesized that there would be no significant difference between the biomechanical properties of superior and anterior precontoured plating in 3 clinically relevant clavicle fracture patterns. Our results demonstrated more construct stiffness in axial compression and torsion (except for the oblique fracture pattern in clockwise torsion) with a superior plate and more construct stiffness in cantilever bending with an anterior plate.

Midshaft clavicle fractures have traditionally been treated nonoperatively. This strategy was based on early reports citing nonunion rates of less than 1%.[1] With the advent of improved forms of internal fixation and patient-based outcome studies, nonoperative management of displaced midshaft clavicle fractures has been called into question.[3-8] Such results have fueled renewed interest in ORIF as well as a debate about preferred plate position.

The biomechanically superior plating position remains unclear, partly because of the disparate results of prior investigations. Using a variety of plate and screw constructs to fix transverse osteotomies, various authors have concluded that superior plating is biomechanically preferable.[12-15] Others have demonstrated improved performance with anterior plates.[16,17] Although differences in hardware selection may explain some of the conflicting conclusions that have been suggested, we propose that limitations in loading conditions and fracture modeling of earlier experiments contributed to the contradictions in prior results and reduce the clinical utility of the conclusions based on those results. Of the 6 prior investigations, only 3[12,15,17] used a complete series of loading conditions, as was used in the present study, and 2 of those authors used only a single loading mechanism.[13,16]

Beyond the limitations in loading conditions, the primary limitation in prior studies has been an almost exclusive examination of the transverse fracture pattern (B1.3). Not only is such a pattern rarely encountered clinically,[2] but, as noted by the majority of the prior authors,[12,13,15,17] such a pattern is uniquely stable and possibly biased toward support of superiorly plated constructs. Direct cortical contact exists after fixation of transverse fracture patterns, allowing cantilever and compression loading to produce compression forces on the inferior surface and tension forces on the superior surface of biomechanically tested clavicles.[13] A superiorly applied plate thus acts as a tension band, providing an obvious biomechanical advantage over an anteriorly oriented plate. Conclusions based on the uncommon and biomechanically unique transverse fracture pattern may thus have poor generalizability to more clinically relevant fracture patterns.

The present study demonstrated the importance of the fracture model and of its influence on the biomechanical outcomes of midshaft clavicle fractures. Regardless of plate position, oblique fracture patterns always demonstrated significantly more stiffness compared with bending wedge and complex comminuted patterns. Once compression and direct cortical contact were eliminated—progressing from the oblique to the bending wedge fracture pattern—a significant reduction in stiffness was noted for both plate positions in all loading conditions.

Table I. Mean (SD) Axial Compression Stiffness,[a] N/mm

	Fracture Pattern		
Plate Position	Oblique	Bending Wedge	Complex Comminuted
Superior	3142 (504)	1657 (215)	1257 (226)
Anterior	2873 (393)	1212 (171)	1008 (188)

[a] Plate position ($P = .004$; Tukey critical value, 210); fracture pattern ($P < .0001$; Tukey critical value, 311); interaction ($P = .7$).

Table II. Mean (SD) Clockwise Torsional Stiffness,[a] N/degree

	Fracture Pattern		
Plate Position	Oblique	Bending Wedge	Complex Comminuted
Superior	914 (183)	650 (124)	578 (123)
Anterior	973 (81)	455 (52)	465 (67)

[a] Plate position ($P = .0144$; Tukey critical value, 79); fracture pattern ($P < .0001$; Tukey critical value, 120); interaction ($P = .0532$).

Table III. Mean (SD) Counterclockwise Torsional Stiffness,[a] N/degree

	Fracture Pattern		
Plate Position	Oblique	Bending Wedge	Complex Comminuted
Superior	805 (128)	573 (89)	552 (70)
Anterior	735 (44)	433 (113)	418 (56)

[a] Plate position ($P = .0006$; Tukey critical value, 63); fracture pattern ($P < .0001$; Tukey critical value, 96); interaction ($P = .65$).

Table IV. Mean (SD) Cantilever Bending Stiffness,[a] N/mm

	Fracture Pattern		
Plate Position	Oblique	Bending Wedge	Complex Comminuted
Superior	100 (17)	41 (2.3)	25 (2)
Anterior	116 (26)	69 (14)	75 (22)

[a] Plate position ($P < .0001$; Tukey critical value, 12); fracture pattern ($P < .0001$; Tukey critical value, 17); interaction ($P = .41$).

In this study, the observed differences between the 2 plating positions can be readily rationalized. Although similar, the superior and anterior plates differed in more ways than the mere surfaces to which they were fixed. Although both plates were 8-hole, the superior plates contained more material (18.5 vs 13 g) and were S-shaped. Both the additional mass and the plate curvature—which moves more of the plate's mass away from the centroid, thus increasing its polar moment of inertia—could explain the greater resistance to torsion seen with this plating position. In addition, the superior plate was essentially flat along the line of axial compression, whereas the anterior plate was bowed. Although compressive forces applied to the superior plate would thus be applied through its centroid, the bowing of the anterior plate causes the compressive forces to be eccentrically applied around the centroid of the anterior plate. This inherently reduces the potential resistance of the anterior plate to compression and so again may explain why the superior plate performed better under this loading condition. Finally, although the superior plate lies with its smallest dimension (height) perpendicular to the line of force in cantilever bending, the anterior plate lies with its larger dimension (width) perpendicular to the line of force. This plate orientation increases the areal moment of inertia of the anterior plate and thus potentially explains why the anterior plate performed better under this loading condition.

Comparing the mean stiffnesses found in the present study, which used contemporary locking precontoured plates, with the mean stiffnesses reported in prior studies, which used traditional nonlocking and locking reconstruction or dynamic compression plates, also provides a clinically relevant outcome. Our observed stiffness of oblique fractures in axial compression (2873-3142 N/mm) was 3 to 5 times that observed by Celestre and colleagues[12] and Robertson and colleagues[15] (539-855 N/mm) using synthetic clavicles and a similarly stable transverse osteotomy. Comparisons of torsion (735-973 vs 283-497 N/degree) and cantilever bending (100-116 vs 3.1-24.7 N/mm) yielded similar results. The higher stiffnesses in our study may suggest a biomechanical advantage of contemporary precontoured plates over more traditional plates.

This study had several limitations. Although multiple fracture patterns based on epidemiologic data and clinical radiographs were selected, and multiple loading methods were chosen based on a thorough review of similar literature, little is known regarding the in vivo loading experienced by clavicles. Envisioning the normal range of motion of the shoulder and the clavicle acting as a biological strut and suspensory mechanism for the arm, prior authors have largely tested the clavicle under 3 loading conditions[12-15]: torsion, axial compression, and cantilever bending. Application of the loading force has required similar modeling. Although clinical hardware failure most often occurs after thousands of cycles at physiologic low loads, the inefficiency of performing biomechanical tests in such a manner has led to a reliance on 2 substitute loading methods: load to failure and construct stiffness. While both serve only as a proxy for the outcome of interest, such properties of a construct should correlate with cyclic load to failure. As construct stiffness testing in the linear elastic range yields no implant damage, and therefore allows reuse of implants among specimens, we selected this loading mechanism. Although sequential testing of the various fracture patterns perhaps undesirably biases later tested constructs, the number of loading repetitions experienced by each sample (< 50) was far below that needed for cyclic failure.

Finally, the pretest power analysis suggested that 6 specimens per group created adequate power for the present study, but, because of technical or computation errors by the MTS machine or associated software, some groups consisted of only 4 or 5 specimens. This reduction in power can produce β-type errors and a lack of significant differences between certain testing groups—such as lack of a significant difference between superior and anterior plating in clockwise torsion testing of oblique fractures in this study, for which each group's size was reduced to 4 specimens. It is possible and perhaps likely that, with all 6 specimens in each group, a significant difference would have been found between plate positions for this loading condition as well.

Conclusion

Our results suggest that, for multiple midshaft clavicle fracture patterns, compression and torsion appear better controlled with a precontoured superior plate, whereas cantilever bending is bettered resisted by the improved areal moment of inertia of the precontoured anterior plate. Although prior authors have suggested that cantilever bending is the limiting biomechanical loading condition,[15] which would lead us to conclude in favor of anterior plating, we think that, until the relative importance of these forces is known, it is impossible to make recommendations for either superior or anterior plating.

Dr. Toogood is Resident, Department of Orthopaedics, and Dr. Coughlin is Director, Biomechanics Laboratory, University of California, San Francisco, California. Mr. Rodriguez is Engineering Student, University of California, Berkeley, California. Dr. Lotz is Senior Director, Biomechanics Laboratory, and Dr. Feeley is Attending Orthopaedic Surgeon, University of California, San Francisco, California.

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Address correspondence to: Paul Toogood, MD, MS, Department of Orthopaedics, University of California, 500 Parnassus Ave, MU320W, San Francisco, CA 94143 (tel, 513-319-1916; e-mail, paul.toogood@ucsf.edu).

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