Biomechanical Comparison of Fracture Risk Created by 2 Different Clavicle Tunnel Preparations for Coracoclavicular Ligament Reconstruction

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Background: An anatomic reconstruction of coracoclavicular (CC) ligaments typically requires drilling tunnels in the clavicle. An increase in fracture complications has been associated with graft tunnel position. A method of drilling clavicle tunnels that would better re-create anatomic function of the CC ligaments without increasing fracture risk would be an improvement.

Purpose: To evaluate the feasibility of a novel single anterior-to-posterior tunnel technique and compare the biomechanical properties to the 2-tunnel technique in CC ligament reconstruction. The hypothesis was that the single tunnel will yield similar loads to failure as the 2-tunnel technique and better reproduce the native anatomy of the conoid and trapezoid ligaments.

Study Design: Controlled laboratory study.

Methods: Eight fresh-frozen matched pairs of human clavicles underwent testing. In 1 specimen of the matched pair, 2 bone tunnels were created as previously described. In the other, a single tunnel was placed obliquely from anterior to posterior. The relative position of the tunnels in relation to the conoid tuberosity was recorded. Specimens were tested on a materials testing machine. The ultimate load to failure, linear stiffness, distance of the conoid tuberosity to the conoid tunnel exit point, and mode of failure were recorded.

Results: The ultimate load to failure in the single-tunnel group and the 2-tunnel group was 457.2 ± 139.8 and 488.8 ± 170.6, respectively. There was no significant difference ($P = .5$). The linear stiffness in the single-tunnel group and the 2-tunnel group was 94.6 ± 31.3 and 79.8 ± 33.5, respectively. There was no significant difference ($P = .2$). The 2-tunnel group had a significantly longer average maximum distance from the conoid tuberosity to the conoid tunnel exit point than the single-tunnel group (6.0 ± 2.1 vs 0.8 ± 1.9 mm; $P = .05$). The single-tunnel group was consistently more anatomic with regard to its relationship to the conoid tuberosity than the 2-tunnel group.

Conclusion: The single anterior-to-posterior clavicle tunnel had similar biomechanical properties to the 2-tunnel technique. However, the single-tunnel technique better reproduced the anatomic footprint of the conoid ligament. Utilizing this single-tunnel technique may yield an anatomic advantage that may also reduce the rate of complications caused by posterior wall blowout.

Clinical Relevance: Acromioclavicular joint injuries are common in collision sports. Surgical management is often indicated to reconstruct the joint. This study assesses the feasibility of a novel surgical approach.

Keywords: acromioclavicular joint injuries; biomechanics; coracoclavicular ligaments; anatomic reconstruction

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Acromioclaviclular (AC) joint injuries are common, especially in athletes.[8,12] For injuries involving complete disruption of the coracoclavicular (CC) ligaments and greater than 100% increase in the CC distance, surgical intervention is often indicated. Currently, there are multiple surgical techniques utilized to address these injuries, which includes reconstruction of the CC ligaments with tendon grafts. The important role of the anatomic reconstruction of the CC ligaments in AC joint separations has been increasingly recognized. Anatomic CC ligament reconstruction techniques have been shown to be biomechanically superior to other, nonanatomic, methods in several

studies.[3,9] From a biomechanical perspective, the importance of the CC ligaments in controlling superior and horizontal translations has been well elucidated.[5,7]

An anatomic reconstruction technique popularized by Mazzocca et al[9] requires drilling 2 tunnels from superior to inferior, each at a fixed distance from the distal end of the clavicle, in an attempt to reproduce the native CC ligaments. The tendon graft is looped around the coracoid and passed through the 2 tunnels drilled in the clavicle, and fixation of the graft is maintained with 2 biotenodesis screws. This relatively straightforward technique has demonstrated good results in several biomechanical and clinical studies and has been widely adopted in recent years.[1,3] However, as awareness of the anatomic CC ligament reconstruction method increases and as more surgeons have adopted this technique, it has become evident that there is the potential for complications.[2,14] Many of the complications have in part been attributed to malposition of the clavicle tunnels.

In a study performed by Rios et al,[11] the position of the clavicle tunnels established by Mazzocca et al[9] was refined, based on further evaluation of clavicular anatomy. These authors established ratios of the total clavicular length for each of the CC ligament attachments. They recommended placing the conoid tunnel at 30% of the clavicular length in the posterior half on the superior clavicle and the trapezoid tunnel at 17% of the clavicular length centered in the midportion of the clavicle. Although these ratios are widely utilized by surgeons, there is recent evidence to suggest that using a 30% ratio for the conoid tunnel may not yield an anatomic conoid.[13,16]

Xue et al[16] performed an anatomic study similar to Rios et al[11] that was specific to a Chinese population. Ratios were calculated that represented the distance from the clavicular landmarks to each footprint center divided by clavicular length. They determined the ratios of the distance to the conoid center and to the trapezoid center divided by clavicular length to be 25.5% and 15.6%, respectively.

In a recent study, Cook et al[2] reported early failure of anatomic CC ligament reconstructions in 28% of patients. They determined that conoid tunnel placement at a ratio of 30% was a significant risk factor in the reconstructions that failed. There were no failures in their study when the conoid ratio was less than 25%. The authors further emphasized the importance of the conoid ligament over the trapezoid for maintenance of reduction. This conclusion has been supported by other biomechanical studies that have shown the conoid to be the most important ligament resisting translation.[5]

A method of drilling clavicle bone tunnels that better reproduces the anatomic footprint of the conoid ligament while avoiding the risk of posterior wall blowout would be optimal. The purpose of this study was to evaluate the feasibility of a novel single-tunnel technique and compare the biomechanical properties of matched pairs of human cadaveric clavicles to the accepted standard of a 2-tunnel technique for CC ligament reconstruction. The hypothesis was that the single-tunnel technique will yield similar loads to failure as the 2-tunnel technique and better reproduce the anatomic footprint of the conoid ligament.
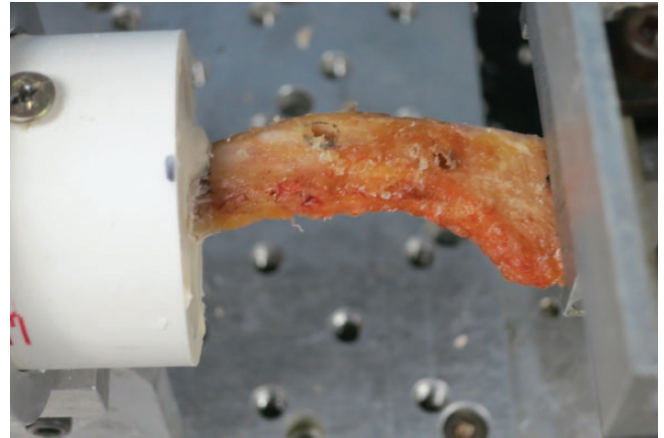

Figure 1. Clavicle with double superior-inferior tunnel potted and affixed to the Instron device.

Figure 2. Clavicle with double superior-inferior drill holes demonstrating the ratio and direction of tunnel placement.

METHODS

Eight fresh-frozen matched pairs of human cadaveric clavicles (4 male, 4 female specimens; mean age, 50.4 years; range, 38-62 years) were obtained. In 1 specimen of each matched pair, 2 bone tunnels were created. Tunnel positions were chosen to simulate the anatomic position of the conoid and trapezoid ligaments, as determined by Rios et al,[11] and a ratio of the total length of the clavicle was utilized to account for variable lengths between pairs. The trapezoid ligament tunnel was placed at 17% per Rios et al,[11] and the conoid tunnel position was modified to 25% based on recent anatomic and clinical studies that suggested better outcomes when the conoid tunnel is placed at a distance of 25% of the clavicular length from the lateral border in the posterior half of the clavicle.[2,13,16] The lateral trapezoid tunnel was placed at 17% of the length of the clavicle from the lateral border in the center of the clavicle (Figures 1 and 2). Tunnels were drilled with a 5 mm–diameter reamer using a cannulated drill and guide pin.

In the other specimen of the pair, a single tunnel was placed in the anterior to posterior direction angled medially following a predrawn line. The line was drawn between 2 positions marked on the superior surface of the clavicle. A position on the posterior cortex, simulating the conoid origin, was marked using a distance 25% of the clavicular
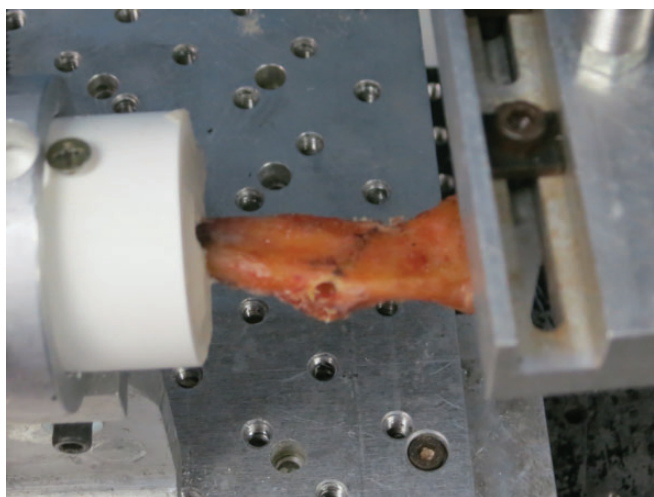
Figure 3. Clavicle with single anterior-to-posterior tunnel potted and affixed to the materials testing device.

Figure 4. Clavicle with single anterior-to-posterior drill hole demonstrating the ratio and direction of tunnel placement.

length from the lateral border. Another position was marked on the anterior cortex, simulating the trapezoid origin, using 17% of the clavicular length from the lateral border. A straight line was then drawn between the 2 marks, and a guide pin was placed aiming from anterior to posterior and from slightly superior to inferior attempting to exit on the posterior inferior surface of the clavicle (Figures 3 and 4). No attempt was made to specifically exit on the conoid tuberosity but rather on the predrawn lines. A tunnel was drilled over the guide pin using a 5-mm reamer.

The relative position of the conoid tunnel in relation to the conoid tuberosity was recorded as being on the tuberosity, medial to it, or lateral to it. The maximum distance from the center of the conoid tunnel to the center of the conoid tuberosity was measured using a digital caliper with 0.01 mm accuracy. In the 2-tunnel technique, the inferior exit of the conoid tunnel was used to measure the distance to the conoid tuberosity. In the single-tunnel technique, the posterior exit of the tunnel was used.

The clavicles were potted at 60% of the clavicular length in 1.5-inch PVC (polyvinyl chloride) pipe and plaster of paris. The potted specimens were fastened to the base of

TABLE 1
Biomechanical Properties of a Clavicle
With 2 Superior-Inferior (SI) Drill Holes
Versus 1 Anterior-Posterior (AP) Drill Hole[a]

	SI Holes	AP Hole	P
Ultimate load, N	488.8 ± 170.6	457.2 ± 139.8	.54
Average maximum distance to conoid tuberosity, mm	6.0 ± 2.1	3.8 ± 1.9	**.05**

[a]Boldface indicates statistical significance.

an Instron materials testing machine (Figure 3). A bending force was applied to the superior distal end equidistant from the lateral hole as the distance from the plaster level to the proximal hole. A bending load was applied to failure at 10 mm/min. The ultimate load to failure, linear stiffness, distance of the conoid tuberosity to the conoid tunnel exit point, and mode of failure were recorded for all clavicles. Statistical analysis was performed with a paired t test to compare load-to-failure characteristics between both tunnel techniques. A statistical significance level was set at $P < .05$ for all comparisons.

RESULTS

As there was not expected to be a difference in ultimate load to failure or linear stiffness between the single anterior-to-posterior tunnel group and the 2-tunnel group, large sample sizes (n = 69-715) would have been needed to detect any significant difference, with power set at 0.85 and alpha at 0.05. The ultimate load to failure in the single-tunnel group and the 2-tunnel group was 457.2 ± 139.8 and 488.8 ± 170.6, respectively (Table 1 and Figure 5). There was no significant difference between the 2 groups ($P = .5$). The linear stiffness in the single-tunnel group was 94.6 ± 31.3 and that in the 2-tunnel group was 79.8 ± 33.5 (Table 1 and Figure 6). There was no significant difference between the 2 groups ($P = .2$).

The failure mode for the 2-tunnel group was 3 failures at the medial hole, 2 at the lateral hole, and 1 at the potting interface. In the single-tunnel group, 5 failed through the single tunnel and 1 failed at the potting interface.

In the single-tunnel group, the exit point of the tunnel in respect to the conoid tuberosity location was as follows: 5 tunnels exited slightly medial to the tuberosity, 2 exited on the conoid tuberosity, and 1 exited slightly lateral. All tunnels exited on the posterior aspect of the clavicle and involved a portion of the tuberosity. In the 2-tunnel group, 6 tunnels were medial to the conoid tuberosity and 2 were in line with the conoid tuberosity; however, none of the tunnels in the 2-tunnel group exited on the tuberosity, all were anterior to it. The average maximum distance of the conoid tuberosity to the conoid tunnel exit point was 3.8 ± 1.9 mm and 6.0 ± 2.1 mm for the single-tunnel group and the 2-tunnel group, respectively (Table 1 and Figure 7). This difference was statistically significant ($P = .05$).
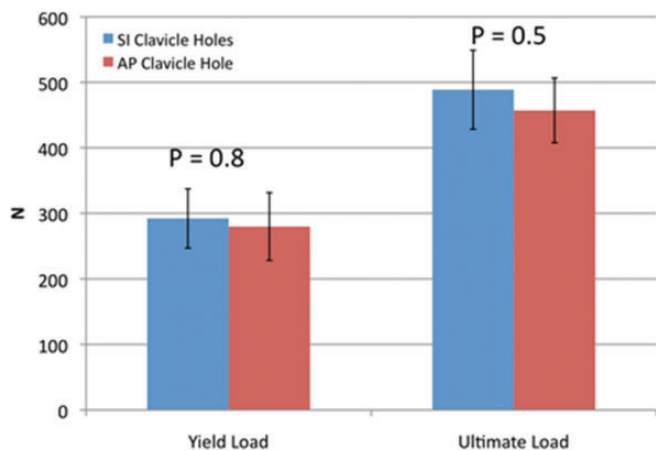
Figure 5. Graphic representation of load-to-failure averages for single anterior-to-posterior (AP) tunnel and 2-tunnel superior-inferior (SI) techniques.
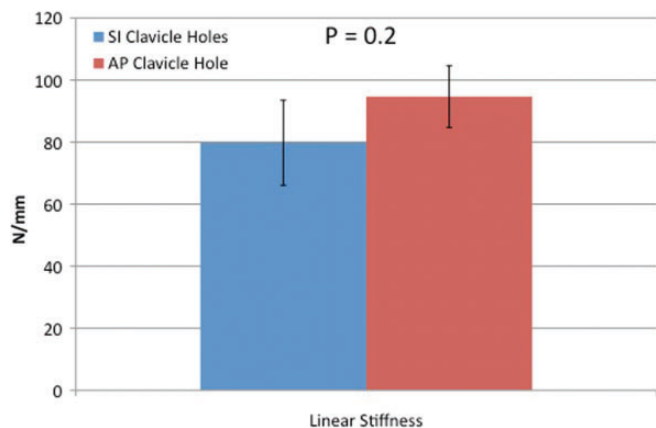

Figure 6. Graphic representation of linear stiffness averages for single anterior-to-posterior (AP) tunnel and 2-tunnel superior-inferior (SI) techniques.

DISCUSSION

There have been multiple biomechanical and clinical studies in the recent literature supporting the use of anatomic CC ligament reconstruction with a tendon graft over other techniques, including the traditional Weaver-Dunn technique.[1,9,10,15] Consequently, as more surgeons adopt this technique, unique complications have arisen. Complications related to anatomic CC ligament reconstruction include loss of AC joint reduction, coracoid fractures, and clavicle fractures. There have been several recent reports in the literature that have warranted caution with this technique. Cook et al[2] reported on the clinical outcomes of 2-tunnel CC ligament reconstructions. They reported early failure in anatomic CC ligament reconstructions in 28% (8/28) of patients. From these results, they concluded that medial tunnel placement was a significant risk factor in the reconstructions that failed. The authors noted that
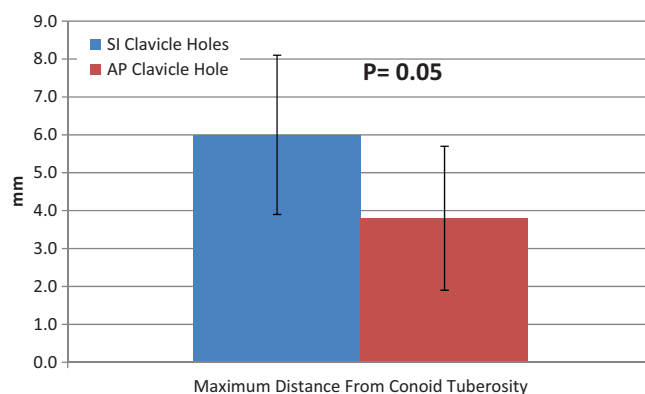

Figure 7. Graphic representation of average maximum distance of the conoid tuberosity to the conoid tunnel exit point for single anterior-to-posterior (AP) tunnel and 2-tunnel superior-inferior (SI) techniques.

reconstructions performed with a conoid ratio of greater or equal to 30% had a failure rate of 100% (5/5), whereas those performed lateral to a ratio of 30% had a rate of failure of 13% (3/23). There were no failures when the conoid tunnel was placed at a ratio of less than 25%. They found no significant difference in distance between tunnels. Lateralization of the conoid tunnel in this fashion was associated with a lower rate of failure. The authors surmised that there may be a biomechanical advantage to tethering the clavicle closer to the applied forces to the AC joint.

In this study, we utilized ratios for clavicle tunnel placement established by Rios et al,[11] in which the authors established ratios based on dry osteology specimens of the total clavicular length for each of the CC ligament attachments. Rios et al[11] recommended placing the conoid tunnel at 30% of the clavicular length in the posterior half on the superior clavicle and the trapezoid tunnel at 17% of the clavicular length centered in the midportion of the clavicle. Even though they found ratios in their fresh clavicles with intact CC ligaments of 24% for the conoid and 17% for the trapezoid, their final recommendation was based on the dry osteology measurements. Their reasoning for conoid tunnel position was that the conoid ligament attachment is broad and was not reliably centered over the conoid tuberosity. However, more recent publications lead us to believe this position is not truly anatomic for the conoid ligament.[2,13,16] A tunnel drilled in the posterior half of the clavicle at a ratio of 30% will likely result in a tunnel anterior and medial to the true anatomic origin.

Placing the conoid tunnel at a ratio of 25% was further supported by Xue et al.[16] They performed an anatomic study that was specific to a Chinese population and determined the ratios of the distance to the conoid center and to the trapezoid center divided by clavicular length to be 25.5% and 15.6%, respectively. This is more aligned with the findings by Rios et al[11] for the clavicle measurements made with fresh-frozen specimens. In another recent anatomic study in 40 cadaveric shoulders, Takase[13] defined the insertions of the CC ligaments on the undersurface of the

clavicle in detail. The author noted the conoid ligament to be centered over the conoid tubercle as it inserts on the posterior inferior edge of the clavicle. The trapezoid was noted to insert more broadly in the anterior aspect.

Collectively from these clinical and anatomic studies, we concluded that conoid tunnel position could be improved by making it more lateral and more posterior. However, since in the 2-tunnel technique the tunnel is drilled in the superior-to-inferior direction, it is limited by its anterior-to-posterior diameter, and placing it further posteriorly results in a greater risk of breaching the posterior cortex. Turman et al[14] described complications from clavicle fractures through the tunnels in 3 of 7 patients undergoing anatomic CC ligament reconstruction. They attributed these fractures, in part, to posterior wall blowout of the conoid tunnel and emphasized decreasing tunnel size and precise tunnel placement to avoid this complication.

In this study, we presented the feasibility of performing a novel single-tunnel technique drilled in the anterior-to-posterior direction. Based on the posterior position of the conoid tuberosity on the clavicle as we have noted, and supported by others,[13,16] the more posterior the tunnel, the closer it will be to the anatomic footprint of the conoid. In this study we demonstrated the single-tunnel technique better simulated the anatomic position of the native conoid ligament footprint compared with the 2-tunnel technique. This technique showed no statistical difference in clavicle resistance to fracture than the established 2-tunnel technique when exposed to a superior bending load, and there is less risk of posterior wall blowout.

In our study, our decision to use a ratio of 25% for the conoid tunnel position for both the 2-tunnel and single-tunnel techniques was based, in part, on recommendations by Cook et al[2] after reporting their poor clinical outcomes associated with tunnels placed at 30%. For the 2-tunnel technique, we placed the conoid tunnel in the posterior one-half of the clavicle, as recommended by Mazzocca et al.[9] We elected to maintain the trapezoid tunnel position at 17% of the length of the clavicle from the lateral border in the center of the clavicle. Our decision to maintain the trapezoid tunnel in this location was further influenced by a recent article by Geaney et al.[6] In this study, the authors compared bone mineral density of the clavicle to tunnel locations along the length of the distal clavicle and failure of a graft fixed with an interference screw. They found that bone mineral density increased from the lateral to the medial clavicle and is optimal between 20 and 50 mm from the lateral end of the clavicle in the anatomic insertion area of the CC ligaments. Using a ratio of 25% for the conoid tunnel and 17% for the trapezoid tunnel, both tunnels were maintained within this optimal region of the clavicle.

Even with using the adjusted ratio of 25% for conoid tunnel placement, the position of the conoid tunnel with the 2-tunnel technique was consistently nonantomic in relation to the center of the conoid tuberosity. In all specimens, it resulted in a tunnel anterior to it, and in 6 of 8 specimens it was medial to it. Using the single-tunnel technique, the tunnel exit point was consistently more anatomic in relation to the conoid tubercle than was the 2-tunnel technique.

To enhance the anatomic reconstruction of the CC ligaments in a real-life application, intraoperative palpation of the conoid tuberosity should be employed in addition to preoperative measurements to place the guide pin as close to the conoid tuberosity as possible in order to make the conoid graft limb more anatomic. The displaced nature of the clavicle in high-grade AC joint separations makes this quite feasible.

Several limitations exist for the current study. This model is a simplified cadaveric model incorporating a singular superiorly applied load to simulate AC joint compression and does not completely simulate the true loads on the clavicle. Furthermore, our choice for tunnel placement in the 2-tunnel group decreases the intertunnel distance, which may theoretically weaken the 2-tunnel construct. However, in their clinical study of anatomic CC ligament reconstructions, Cook et al[2] found no significant difference in the distances between tunnels and failure rates. In our study, the clavicles fractured only through a single tunnel, most often the conoid tunnel. This finding is supported in a recent biomechanical study by Dumont et al[4] that addressed clavicle tunnels in CC ligament reconstruction using a sawbone clavicle model, which demonstrated a 2-fold failure load in clavicles without tunnels versus those with 5-mm tunnels. Interestingly, the Dumont et al[4] study revealed no significant difference in clavicles where 2 tunnels were drilled compared with 1 tunnel or those with the introduction of PEEK (polyether ether ketone) tenodesis screws into the tunnels, suggesting that the clavicles fracture through one of the tunnels regardless of the presence of another tunnel, further minimizing the impact of intertunnel distances.

CONCLUSION

This study demonstrated that a single anterior-to-posterior oblique 5-mm tunnel has similar iatrogenic fracture risk characteristics compared with the established 2-tunnel technique with superior-inferior tunnels placed at the 17% and 25% ratio positions. However, by allowing it to be placed more posterior on the clavicle, the single-tunnel technique better reproduced the anatomic footprint of the conoid ligament, which has been demonstrated to be the more important ligament for AC joint stability. Utilizing this single-tunnel technique yielded a more anatomic graft placement. And although we did not demonstrate a reduction in clavicle fracture risk, in a different in vivo model with the graft in place, the incidence of posterior wall blowout may be reduced. Further study is needed in a cadaveric shoulder model to assess the biomechanical stability of the AC joint when this tunnel technique is utilized with a tendon graft weaved around the coracoid and fixed into the tunnel and to compare this stability to the stability of the current 2-tunnel CC ligament reconstruction technique.

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