Biomechanical Consequences of Coracoclavicular Reconstruction Techniques on Clavicle Strength

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Background: Lateral clavicle fractures have been reported after coracoclavicular (CC) ligament reconstructions with bone tunnels through the clavicle.

Purpose: To biomechanically compare clavicle strength following 2 common CC reconstruction techniques with different bone tunnel diameters.

Study Design: Controlled laboratory study.

Methods: Testing was performed on 2 groups of matched-pair cadaveric clavicles. Clavicles were prepared with either 2.4-mm tunnels and cortical fixation button (CFB) devices or 6.0-mm tunnels with hamstring tendon grafts (TGs) and tenodesis screws; contralateral clavicles were left intact. A 3-point bending load was applied to the distal clavicles at a rate of 15 mm/min until failure. Ultimate failure load and anterior-posterior width of the clavicles 45 mm medial from the lateral border were recorded. Strength reduction was determined as the percentage reduction in ultimate failure load between paired intact and surgically prepared clavicles. Relative tunnel size was determined as the quotient of tunnel diameter and clavicle width, reported as a percentage.

Results: The TG technique significantly reduced clavicle strength relative to intact (P = .011) and caused significantly more strength reduction (mean, −30.7%; range, 8.1% to −62.5%) than the CFB technique (mean, −3.8%; range, 34.2% to −28.1%; P = .031). The CFB technique was not significantly different from intact (P = .314). There was a significant correlation between clavicle width and strength reduction ($\tau = -0.36$, P = .04) and between relative tunnel size and strength reduction (τ = 0.51, P = .005).

Conclusion: The TG reconstruction technique with 6.0-mm tunnels, grafts, and tenodesis screws caused significantly more reduction of clavicle strength compared with the CFB technique with 2.4-mm tunnels and CFB device. Additionally, relative tunnel width correlated highly with the strength reduction.

Clinical Relevance: This information can influence intraoperative decision making based on the individual clavicle width and might influence postoperative treatment protocols. Large bone tunnels may predispose patients to clavicle fractures after anatomic CC reconstructions.

Keywords: coracoclavicular ligament reconstruction; acromioclavicular dislocation; clavicle strength; tunnel size; clavicle width

The treatment of acromioclavicular (AC) joint injuries that entail disruption of the coracoclavicular (CC) ligaments remains a question of debate. Several different anatomic reconstruction techniques of the CC ligaments have been described in the literature.[1,3,4,7,10-13,16,19,21] Recently, the use of tendon grafts (TGs), both autografts and allografts, has gained increased popularity for reconstructing CC ligaments to treat chronic symptomatic AC joint separation.[1-3,7,12] The TG technique is commonly performed with the 2 limbs of a single graft passed through the two 6.0-mm tunnels in the clavicle and fixed with tenodesis screws.[12,13] More recently, the TG technique was reported to be performed with smaller tunnel diameters of 5.0 mm.[3] Alternatively, AC reconstruction has been performed by use of cortical fixation buttons (CFBs),[12,19] for which tunnel sizes were most commonly reduced to 4.0 mm.[9,12] The tunnel diameter can be reduced to as small as 2.4 mm if the inferior coracoid button is introduced arthroscopically through an anterolateral portal. The CFB technique can be combined with a nonanatomic graft reconstruction by looping the graft around the clavicle and does not require additional tunnels.[6,20]

Several studies have reported lateral clavicle fractures after CC ligament reconstruction with bone tunnels

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through the clavicle.[12,14,17] Martetschläger et al[12] recently reported a 4.3% incidence rate of lateral clavicle fractures after CC reconstruction using the TG technique with 6.0-mm tunnels and 5.5-mm tenodesis screws. The fractures in this series all occurred at the medial screw hole. The authors reportedly changed to the CFB technique due to the increased risk of clavicle fractures associated with the TG technique. However, little is known of the biomechanical differences between TG (6.0-mm tunnels) and CFB (2.4-mm tunnels) reconstruction techniques on clavicle strength. Furthermore, no data exist about the potential risk factors for an increased onset of clavicle fractures after CC ligament reconstruction, such as small clavicle diameter.

Therefore, the purpose of this study was to compare the strength of matched-pair cadaveric clavicles after surgical treatment with a TG technique that used 6.0-mm tunnels and a CFB technique that used 2.4-mm tunnels, relative to the intact contralateral side, in response to a 3-point bending force. We hypothesized that the TG technique would significantly weaken the clavicle relative to intact and would cause significantly more reduction in clavicle strength than the CFB technique.

MATERIALS AND METHODS

Specimen Preparation

Testing was performed on 18 matched pairs (N = 36) of fresh-frozen human cadaveric shoulders (9 male, 9 female; mean age, 54 years; range, 44-63 years). Dual-energy x-ray absorptiometry (DEXA) bone mineral density (BMD) analysis was performed on all specimens to assess potential BMD biases (mean BMD, 0.478 g/cm^2; range, 0.345-0.608 g/cm^2). All specimens with a t score of less than 2.5, measured at the forearm (one-third radius), were excluded from this study. Specimens were thawed at room temperature 24 hours before testing, and all soft tissues were dissected. The clavicles were visually inspected, and no preexisting injuries were identified. The medial-most 2 cm of each specimen was fixed in polymethylmethacrylate (PMMA, Fricke Dental International Inc, Streamwood, Illinois, USA) in a custom cylindrical mold with the long axis of the clavicle in line with the cylindrical axis of the mold. Before this, 2 screws were drilled in the superior-inferior and anterior-posterior directions into the medial clavicle to ensure rigid fixation in the PMMA.

Biomechanical Testing

Clavicles were alternately distributed between the TG and CFB groups, starting from highest BMD to lowest BMD, resulting in 9 matched pairs per group. The first pair was assigned by flipping a coin. No significant differences between the groups regarding BMD, clavicle width, age, and sex were detected. One clavicle from each pair was prepared according to 1 of the 2 reconstruction techniques; the contralateral clavicle was left intact. Both techniques placed 2 tunnels anatomically according to the CC ligament reconstruction technique described by Mazzocca et al.[13] The conoid tunnel was placed 45 mm from the lateral edge of the clavicle and 25% of the anteroposterior width from the posterior border. The center of the trapezoid tunnel was placed 15 mm lateral to the center of the conoid tunnel and centered in the anteroposterior direction. The CFB group (5 male, 4 female specimens; mean age, 53 years [range, 44-63 years]; mean BMD, 0.482 g/cm^2 [range, 0.388-0.590 g/cm^2]) was prepared with 2.4-mm tunnels and CFB devices (Dog Bone Button with 2-mm FiberTape, Arthrex, Naples, Florida, USA). Loads were not applied to the grafts or CFB devices. Therefore, it was assumed that an additional graft looped around the clavicle would not affect the results, and so it was not included. The TG group (4 male, 5 female specimens; mean age, 56 years [range, 45-63 years]; mean BMD, 0.474 g/cm^2 [range, 0.345-0.608 g/cm^2]) was prepared with 6.0-mm tunnels with semitendinosus grafts of 4-mm diameter and 10 × 5.5–mm polyether ether ketone interference screws (Tenodesis Screws, Arthrex) (Figure 1). In accordance with the study setup described by Demirhan et al,[5] a superior to inferior–directed 3-point bending load was applied with a 10.0-mm diameter rod to the lateral clavicles, generating a single line of contact 2 cm from the lateral border, at a rate of 15 mm/min until failure using a dynamic tensile testing machine (ElectoPuls E10000, Instron, Norwood, Massachusetts, USA) (Figure 2). The clavicles were oriented parallel to the base of the test frame with a custom fixture and were rigidly fixed to the base. A 6.0-mm diameter rod was placed adjacent to the inferior border of the lateral clavicles at a distance of 55 mm from the lateral end of the clavicles to serve as the fulcrum. We used the same tunnel position in all specimens according to Mazzocca et al,[13] even though the anatomy of the clavicles varied highly. Therefore, the moment arm length and the resultant torque experienced at the tunnels were consistent across all specimens. The accuracy for this system has been calibrated and verified

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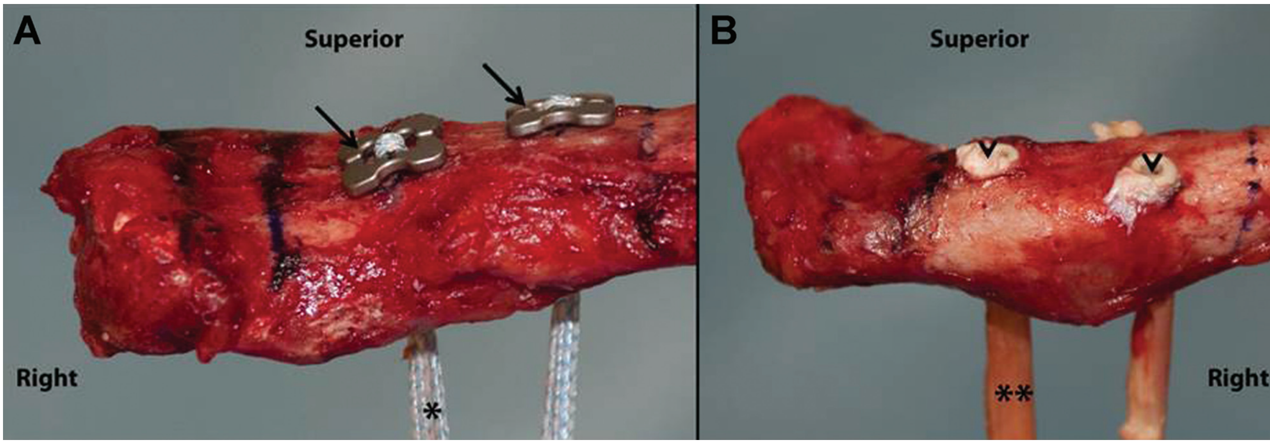

Figure 1. (A) Anterior view on a right lateral clavicle after preparation of a 2.4-mm tunnel and implantation of a cortical fixation button device (arrows, Dog Bone Button; asterisk, FiberTape). (B) Posterior view on a left lateral clavicle after preparation of two 6.0-mm tunnels and semitendinosus graft implantation (asterisks) fixed with tenodesis screw (arrowheads).

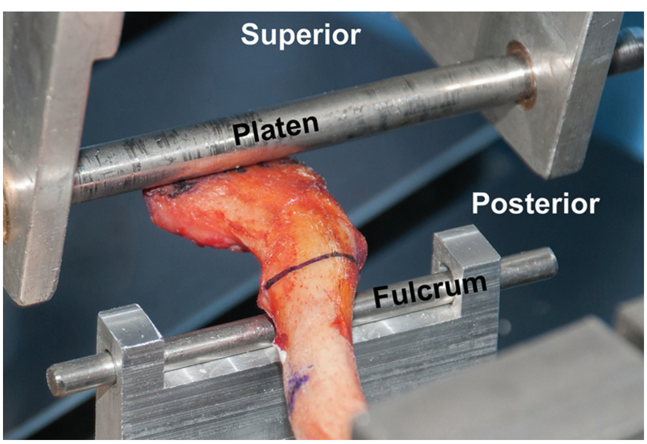

Figure 2. Study setup: Superior view on an intact right lateral clavicle positioned in the jig for 3-point bending. Illustrated is the lateral load-applying anvil positioned 20 mm medial to the lateral border and the fulcrum positioned 55 mm medial to the lateral border.

to be equal to or better than ±0.25% of the indicated force and position. Ultimate failure load was recorded for each specimen, and strength reduction was determined as the percentage reduction in ultimate failure load between paired intact and surgically prepared clavicles. Relative tunnel size was determined as the quotient of tunnel diameter and clavicle width, reported as a percentage. An independent observer performed all clavicle width measurements.

Statistical Analysis

Wilcoxon signed rank tests were used to compare between paired intact and the drilled specimens, while Mann-Whitney U tests were used to compare central tendency between technique groups and Kendall tau (τ) was used to assess correlation. The intraclass correlation coefficient was used to assess measurement reliability. Statistical significance was declared for $P < .05$. All statistical analyses were performed with IBM SPSS Statistics, version 20 (Armonk, New York, USA).

Power Analysis

Power and sample size calculations were performed with data from 4 matched pairs of pilot specimens for each of 3 reconstruction techniques (6.0-mm TG, 4.0-mm CFB, and 2.4-mm CFB). In this small sample size, the percentage weakening was nearly identical in the 6-mm TG and 4.0-mm CFB groups (within 1%). Because of these results, we did not believe that we would find any clinically relevant differences, which we defined at a threshold of 30%. From a clinical perspective, 4-mm tunnels were too small to accommodate a reasonably sized graft given the high loading patterns that are seen clinically. Meanwhile, a total of 18 matched pairs, split into 2 technique groups, was found to be sufficient to detect a 30% difference in the strength of the clavicle with 80% power. Thus, the decision was made to allocate all subsequent specimens equally into the 6-mm TG and 2.4-mm CFB groups.

RESULTS

Strength Reduction

All force-displacement curves are shown in Figure 3. The TG technique significantly decreased clavicle strength relative to intact (mean change, −195.3 N; range, 39.0 to −448.0 N; P = .011, Wilcoxon signed rank test) and caused significantly more strength reduction (mean change, −30.7%; range, 8.1% to −62.5%) than the CFB technique (mean change, −3.8%; range, 34.2% to −28.1%; P = .03, Mann-Whitney U test) (Figure 4). The mean ultimate failure strength of clavicles after the CFB technique was not

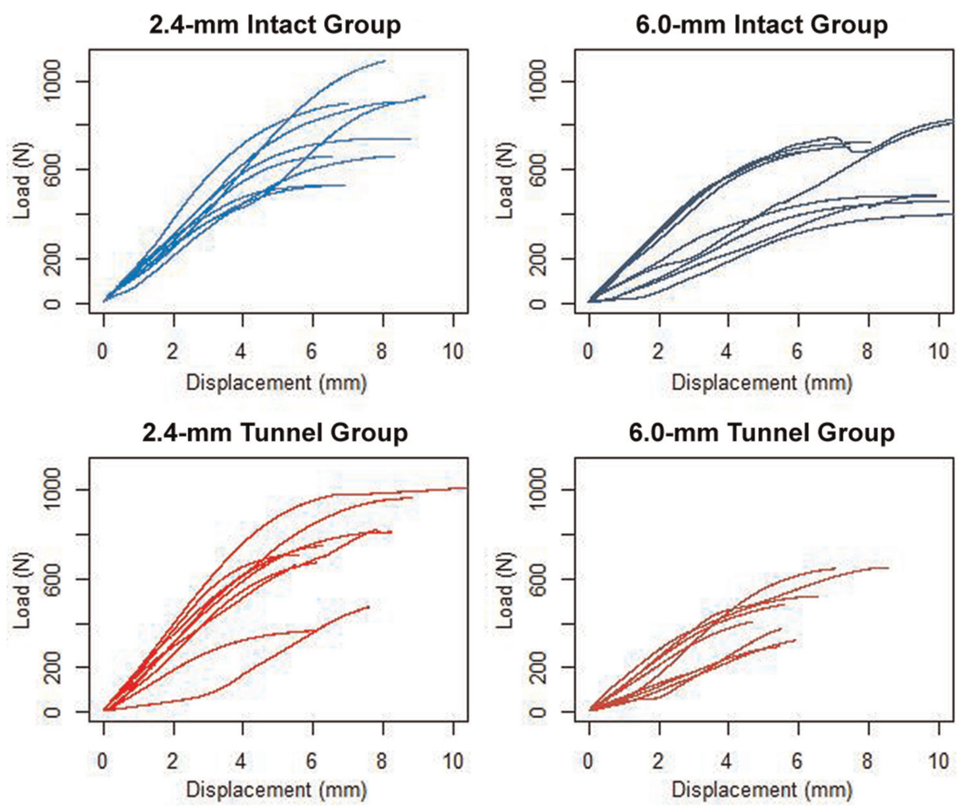

Figure 3. All load-to-failure curves are shown here, 9 in each group, for 2.4-mm tunnel (treatment and control group) and 6.0-mm tunnel (treatment and control).

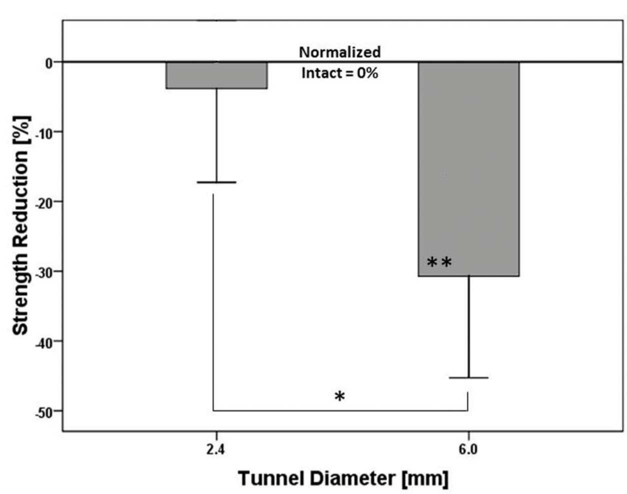

Figure 4. Comparison of mean strength reduction by tunnel diameter. Mean strength reduction after coracoclavicular ligament reconstruction using cortical fixation button devices was −4.5%; reconstruction with a tunnel graft technique caused a mean strength reduction of −30.7% in comparison to the intact contralateral side. Error bars represent the standard error of the mean. *Significant difference between techniques ($P < .05$). **Significant difference from intact ($P < .05$).

significantly different from intact (P = .31, Wilcoxon signed rank test).

Fracture Pattern

All but 2 fractures occurred at the medial tunnel (Figure 5). Both of those fractures occurred after clavicle preparation with the CFB technique at the fulcrum and were comparable with the fracture patterns observed for the intact clavicles. One fracture after TG reconstruction involved both tunnels. Additionally, insertion of the tenodesis screw caused partial iatrogenic fractures at the posterior cortex of the medial tunnel in 3 clavicles of the TG group. All of these iatrogenic fractures outlined as small fissures and were hardly visible. The width of those clavicles ranged from 12.3 to 18.1 mm. In comparison with the other 6 clavicles of the TG group, there were no differences with respect to ultimate failure load, strength reduction, and clavicle width. After we excluded the 3 clavicles with iatrogenic fractures, there was still a significantly reduced ultimate load of failure between both groups (P = .04).

Clavicle Width

Clavicle width at the medial tunnel varied highly, both across all specimens (mean, 18.1 mm; range, 12.3-27.1 mm) and between paired specimens (mean absolute value of difference,

Figure 5. (A) Typical fracture pattern of intact clavicles, as well as after (B) cortical fixation button reconstruction and (C) tendon graft reconstruction. Arrows indicate the fracture site.

1.2 mm [range, 0.2-4.2 mm]; mean absolute value of relative difference, 6.2% [range, 1.0%-17.4%]). There was a significant correlation between clavicle width and strength reduction ($\tau = -0.36$, $P = .04$) and an approximately linear correlation between relative tunnel size and strength reduction ($\tau = 0.49$, $P < .01$). Therefore, the strength reduction caused by a specific tunnel diameter and clavicle width can be roughly estimated with a linear regression (intercept = 15.1, $\beta = -1.31$; $R^2 = 0.453$, $P < .01$). For example, clavicle strength reductions of −30% and −50% relative to the intact state can be expected with relative tunnel sizes of 34.5% (clavicle width of 17.4 mm for 6.0-mm tunnels) and 49.8% (clavicle width of 12.1 mm for 6.0-mm tunnels), respectively (Figure 6). None of the clavicles had a width below the 50% strength reduction threshold of 12.1 mm. However, 50% of the clavicles had a width of less than 17.4 mm, primarily those of female specimens (67%). In contrast, the majority of the clavicles with a width of more than 17.4 mm were of male specimens (67%). No significant correlation was found between BMD and ultimate failure load or strength reduction. The intraobserver reliability of the width measurement was excellent (intraclass correlation coefficient = 0.99; 95% confidence interval, 0.98-0.99).

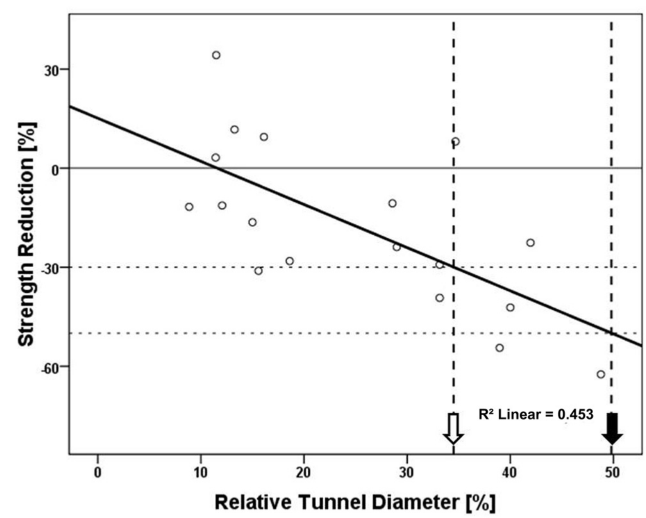

Figure 6. Plot showing linear relationship between relative tunnel diameter and percentage of clavicle strength reduction. Example: A 34.5% relative tunnel diameter (white arrow) is estimated to result in a −30% clavicle strength reduction. This corresponds to a clavicle of diameter 17.4 mm. Likewise, a 12.1-mm diameter clavicle, with a 6-mm tunnel (49.8% relative tunnel diameter, black arrow), is expected to result in a −50% clavicle strength reduction.

DISCUSSION

The most important finding of this study was the high correlation between the reduction in clavicle strength and the size of the tunnel relative to the width of the clavicle. The destabilizing effect of a 6.0-mm tunnel diameter may have no clinical relevance in cases of large clavicles (diameter >17.4 mm at medial tunnel); however, smaller clavicles (≤17.4 mm) showed strength reduction of more than 30% when compared with the intact state, which indicates that patients with small clavicles may be predisposed to clavicle fractures postoperatively. Anatomic variability in the clavicle width at the medial tunnel position was also observed, with a side-to-side difference of up to 21% between paired clavicles. Additionally, half of the clavicles had a width of less than 17.4 mm, the majority of them being female clavicles. As may be assumed, CC reconstruction with 2.4-mm tunnels and CFB devices caused significantly less clavicle strength reduction compared with TG reconstruction through 6.0-mm tunnels fixed with tenodesis screws.

In cases of chronic symptomatic AC joint instability, healing of the CC ligaments after CC reduction cannot be expected. In these cases, biological reconstructions using allogeneic or autologous tendon graft are indicated.[13] Although many techniques for CC ligament reconstruction have been described, we performed the anatomic CC reconstruction technique described by Mazzocca et al[13] and used their anatomic basis for tunnel positions, tunnel diameters, and tenodesis screw fixation. In contrast, the indications for CC reconstruction using CFB devices are predominantly acute unstable AC dislocations with CC ligament disruption to promote healing of the torn CC ligaments.[1,15,18] However, it is possible to combine both strategies in chronic situations, using CFB devices for reduction purposes and adding a biological reconstruction with the limbs of the graft passed anteriorly and posteriorly around the clavicle and tied over the top of the clavicle.[6,20] Even though this technique does not reproduce an anatomic graft position, CC reconstruction with only 1 clavicle bone tunnel is possible.[20] Dumont et al[6] evaluated the effect of 1 versus 2 bone tunnels for CC ligament reconstruction on clavicle fractures using sawbones. The authors reported no significant differences in ultimate failure strength in clavicles prepared with 1 or 2 tunnels. Tunnel positions reported by Dumont et al[6] were consistent with those used in the present study.

Tunnel positions may influence clavicle strength reduction. Particularly, eccentric medial tunnel location as described by Mazzocca et al[13] might increase the risk of posterior cortex lesions and fissures in thin clavicles. Consistent with the findings of Mazzocca et al, 3 fissures of the posterior cortex (33%) were observed here. All occurred in the TG group at the medial tunnel on the posterior cortex after insertion of the tenodesis screws and were barely visible. We believe that there would have been a fair chance of missing these fractures in a clinical setting without dissecting the soft tissue. The clavicle widths at the medial tunnel of those 3 clavicles were all smaller than 19 mm. However, no significant differences regarding the clavicle width were observed compared with the remaining 6 clavicles of the TG group. Additionally, no significant reduction of the ultimate failure load was seen in the 3 clavicles with fissures compared with the other 6, and yet there was still a significant reduction of the ultimate failure load after exclusion of these 3 fissured clavicles. Nonetheless, it might be advisable to position the medial hole more centrally in cases of thin clavicles to minimize the risk of cortex lesion and minimize clavicle strength reduction. The senior surgeon (P.J.M.) has observed iatrogenic intraoperative clavicle fractures occur with placement of the lateral tenodesis screw when tight grafts were used or when there was an ipsilateral distal clavicle resection that conceivably weakened the distal clavicle.

The correlation between relative tunnel size and clavicle strength reduction was approximately linear. Thus, the strength reduction can be roughly predicted as long as the clavicle width at the tunnel position is known and tunnel positions consistent with the present study are chosen. This information can be used by the surgeon to judge the relative risk of fracture based on clavicle morphology, as the clavicle width can be easily measured intraoperatively. From studies on pathologic and impending fractures, prophylactic internal fixation is indicated if cortical destruction affects 50% of the cortical bone.[8] Our results indicate that TG reconstructions with a tunnel diameter of 6.0 mm would cause 50% strength reduction if the clavicle width at the medial tunnel was 12 mm, and considering these data we do not recommend this technique in these settings. If reduced strength of 50% is associated with impending fracture,[8] we assume that a clinically relevant bony strength reduction can be expected at a level of 30% in an active population. In these cases, an anatomic coracoclavicular reconstruction with a TG as described by Mazzocca et al[13] may not be an ideal treatment option in clavicles measuring less than 17.4 mm at the medial tunnel, affecting 50% of the clavicles tested in the present study. Thus, to minimize the fracture risk, the reconstruction technique might have to be modified to match the individual patient's anatomy, with smaller tunnels (and hence smaller graft sizes) or an alternative technique. Given this, in patients with clavicle widths slightly below the threshold of 17.4 mm, the TG technique might still be a good treatment option if the tunnel size is adjusted and 5.0-mm tunnels are used.[3]

This study has limitations. We used a time zero biomechanical model and did not account for the biological restoration processes. No predictions can be made with regard to bony strength regained over time due to the remodeling processes and how long union may take. Next, the techniques investigated in this study are indicated for different clinical situations. The CFB reconstruction relies on tissue healing and is preferred in acute settings, while the TG reconstruction is commonly used in cases where no CC ligament healing is expected. However, as stated above, in chronic cases CFB device techniques can be used as a reliable treatment strategy when combined with tendon graft reconstruction, without the need for additional tunnel preparation. In addition, in this study tunnels of 2.4 mm diameter were compared with 6.0-mm tunnels with semitendinosus grafts and tenodesis screws. However, Dumont et al[6] reported that the addition of tenodesis screws did not significantly affect the strength of the clavicle. Therefore, the comparison of these 2 clinically relevant reconstruction techniques was not confounded by the inclusion of tenodesis screws for the TG technique. This study compared these 2 techniques because they are commonly performed clinically. Additionally, we only investigated 2 reconstruction techniques, which was necessary to achieve adequate power to detect a clinically meaningful difference. A 4.0-mm-diameter tunnel group was not included due to the results of our pilot tests, which indicated that an optimal and realistic study design was to pool all specimen resources into the 2 groups (6.0 mm and 2.4 mm) that intuitively would provide the largest distinction. Comparison of the 4.0-mm CFB, 5.0-mm TG, and 6.0-mm TG techniques remains an interesting topic for future studies. We also believe that a 4-mm tunnel is not clinically relevant for many clavicles because it would necessitate too small of a tendon graft. In such a situation, the tendon graft would be too small to resist the high loading that occurs at the distal clavicle, and a new mechanism for failure—graft failure—would be the primary mechanism. Moreover, no information can be given as to what effect different tunnel positions might have on clavicle strength reduction: for example, with anteroposterior and lateral to medial variations. Additionally, the grafts and CFB devices were not tensioned distally to simulate fixation to the coracoid. Furthermore, all soft tissue was dissected. Thus, this study did not examine all aspects of an anatomic CC reconstruction, particularly the effect of a loaded graft, and did not take into account the stabilizing effect of the surrounding soft tissue, limiting the conclusions that can be drawn. However, dissection of all soft tissue guaranteed a precise and reproducible clavicle tunnel position. Furthermore, the 3-point bending protocol represents a simplified stress model that does not reflect the complex loading conditions acting on the lateral clavicle. However, this model has previously been successfully used for clavicle strength testing[5] and allowed for consistent and reproducible comparison between groups. The results of this study will help surgeons decide how to restore stability to the distal clavicle without weakening it precipitously.

The strengths of the study are its matched-pair study design, the inclusion of grafts and fixation devices representing a clinically relevant test setup, the inclusion of a young population with a mean age of 53 years, the even distribution of BMD between groups, and the exclusion of osteoporotic specimens. Further studies are necessary to investigate whether these biomechanical time zero results can reduce the incidence of clavicle fracture after CC reconstruction in a clinical setting. Additionally, it would be interesting to investigate the effect of tunnel position variation on the clavicle strength.

CONCLUSION

Coracoclavicular ligamentous reconstruction with 6.0-mm tunnels, grafts, and tenodesis screws caused significantly greater strength reduction of the clavicle compared with 2.4-mm tunnels with CFB devices. Additionally, strength reductions correlated highly with the ratio of tunnel width relative to overall clavicle width. This information can help optimize techniques for reconstructing high-grade acromioclavicular joint dislocations and can influence the intraoperative decision-making process based on the individual clavicle width. Understanding the effects of bone tunnels might also guide the choice of surgical technique and might affect the postoperative rehabilitation protocols.

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