Original Research

Biomechanical Analysis of Coracoid Stability After Coracoplasty

How Low Can You Go?

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Background: Arthroscopic coracoplasty is a procedure for patients affected by subcoracoid impingement. To date, there is no consensus on how much of the coracoid can be resected with an arthroscopic burr without compromising its stability.

Purpose: To determine the maximum amount of the coracoid that can be resected during arthroscopic coracoplasty without leading to coracoid fracture or avulsion of the conjoint tendon during simulated activities of daily living (ADLs).

Study Design: Controlled laboratory study.

Methods: A biomechanical cadaveric study was performed with 24 shoulders (15 male, 9 female; mean age, 81 ± 7.9 years). Specimens were randomized into 3 treatment groups: group A (native coracoid), group B (3-mm coracoplasty), and group C (5-mm coracoplasty). Coracoid anatomic measurements were documented before and after coracoplasty. The scapula was potted, and a traction force was applied through the conjoint tendon. The stiffness and load to failure (LTF) were determined for each specimen.

Results: The mean coracoid thicknesses in groups A through C were 7.2, 7.7, and 7.8 mm, respectively, and the mean LTFs were 428 ± 127, 284 ± 77, and 159 ± 87 N, respectively. Compared with specimens in group A, a significantly lower LTF was seen in specimens in group B ($P = .022$) and group C ($P < .001$). Postoperatively, coracoids with a thickness ≥4 mm were able to withstand ADLs.

Conclusion: While even a 3-mm coracoplasty caused significant weakening of the coracoid, the individual failure loads were higher than those of the predicted ADLs. A critical value of 4 mm of coracoid thickness should be preserved to ensure the stability of the coracoid process.

Clinical Relevance: In correspondence with the findings of this study, careful preoperative planning should be used to measure the maximum reasonable amount of coracoplasty to be performed. A postoperative coracoid thickness of 4 mm should remain.

Keywords: coracoplasty; subcoracoid impingement; coracohumeral interval; coracoid fracture; arthroscopy

Arthroscopic coracoplasty (AC) is a procedure in orthopaedic surgery for patients affected by subcoracoid impingement (SCI). The underlying pathology is an entrapment of the subscapularis tendon and/or the biceps tendon pulley between the coracoid and the lesser tubercle.[13,14] This entrapment leads to anterior shoulder pain and might affect the subscapularis tendon, leading to secondary degenerative rupture. When nonoperative therapy is not effective, surgical treatment often consists of AC, during which the posterolateral coracoid tip is resected with a shaver to widen the subcoracoid space (SCS).[7,19,25,26,36]

The reasons for SCI can be manifold. Cunningham and Lädermann[9] proposed a subgrouping of underlying pathologies into 2 categories: (1) narrowing and (2) filling of the SCS. A narrowing of the SCS can occur because of anatomic variations of the coracoid and the lesser tubercle or because of rotator cuff insufficiency and subsequent anterior translation of the humeral head.[39] Variations can occur from patient to patient not only in coracoid shape and dimension but also in the SCS.[35] Filling of the SCS can be caused by tendon calcification, cysts, ganglions, or osteophytes.[1,2,22,28,39,41] Additionally, with age, the SCS becomes narrower and coracoid thickness increases, both of which make the occurrence of SCI more likely.[11] Even though SCI is less common than subacromial impingement, it often presents with anterior shoulder pain as well as tenderness worsened by forward flexion, adduction, and internal rotation.[33]

To date, there is no consensus on how much of the coracoid can or should be resected during AC without risking a theoretical secondary fracture of the coracoid or avulsion of

The Orthopaedic Journal of Sports Medicine, 10(2), 23259671221077947
DOI: 10.1177/23259671221077947

the conjoint tendon (CJT). Several clinical studies showed that subcoracoid decompression can be a sufficient form of treatment of SCI and anterior shoulder pain. While this was previously achieved by open trimming of the coracoid, AC is nowadays the treatment of choice.[18-20,25-27,31] In biomechanical studies to date, the coracoid has not been the center of attention regarding SCI. The influence of AC on coracoid stability remains unclear. In the context of coracoclavicular ligament reconstruction and the Latarjet procedure, however, coracoid failure loads have been described to range between 148 N and 724 N.[8,12,30,38]

The goal of this biomechanical study was to determine the maximum amount of the posterolateral coracoid that can be resected during AC without leading to coracoid fracture or avulsion of the CJT during simulated activities of daily living (ADLs). Our primary hypothesis was that a 3-mm coracoplasty of the posterolateral coracoid, in contrast to a 5-mm AC, would not significantly weaken the coracoid.

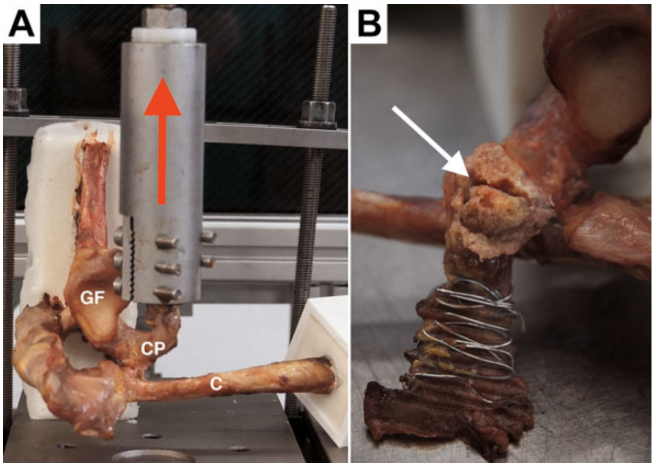

Figure 1. (A) Test setup with the frame mounted at 180° and the soft tissue clamp gripping the distal 35 mm of the conjoint tendons. The red arrow indicates the direction of loading. (B) Specimen with reinforced metal wiring and visible fracture of the coracoid (white arrow). C, clavicle; CP, coracoid process; GF, glenoid fossa.

METHODS

Study Design

A total of 24 fresh-frozen human shoulder specimens (15 female, 9 male; mean age, 81 ± 7.9 years) were randomized into 3 treatment groups: group A (native, intact coracoid), group B (3-mm coracoplasty), and group C (5-mm coracoplasty).

Specimen Preparation

Each specimen was thawed over a 24-hour duration at room temperature. A preoperative computed tomography (CT) scan was performed to ensure that no prior injuries such as fractures were present and to determine the bone mineral density (BMD) of each specimen. BMD values from the CT scans were calculated according to the method described by Krappinger et al[23] at the coracoid level. The deltoid muscle was removed to reveal scapula and coracoid. Coracoclavicular ligaments were kept in place, as well as the tendinous attachments that form the CJT: the coracobrachialis and the short head of the biceps. The CJT was dissected 50 mm distal from the coracoid tip.

Biomechanical Testing

To investigate the biomechanical stability of the coracoid, the CJT served as load transmitter. The biomechanical test setup was slightly modified from the setup described by Martetschläger et al[30] and Montgomery et al.[34]

To facilitate a stable fixation, the scapula was embedded with Rencast (Huntsmann) in a custom-made rectangular frame. To ensure a reproducible alignment, the distance between the frame and the glenoid cavity was kept at 70 mm consistently. The frame was then attached to a baseplate of a servohydraulic testing machine (Instron 8874, Instron, MA, USA). The frame was mounted upside down (180°) so that the CJT could be pulled upward. The CJT was constrained 35 mm from the coracoid tip by a mechanical soft tissue clamp serving as a load transmitter (Figure 1A). The clamp anchored the distal 35 mm of the 50-mm-long CJT. To create more friction between the CJT and the soft tissue clamp, the CJT was reinforced with FiberWire baseball stitches (Arthrex), and an additional 0.7 mm of metal wire was wrapped around the tendons and the musculotendinous junction.

For the biomechanical testing, the CJT was preloaded with 50 N, followed by 250 cycles of dynamic loading with a minimal load of 50 N and a maximal load of 100 N at 2 Hz. This setup was modified from the one described by Montgomery et al.[34] This preconditioning was followed by a path-controlled load-to-failure (LTF) test. For the LTF, the soft tissue clamp covered a distance of 25 mm/min, similar

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Final revision submitted September 28, 2021; accepted October 22, 2021.

One or more of the authors has declared the following potential conflict of interest or source of funding: L.F.H. was supported by a research scholarship from the Deutsche Vereinigung für Schulter und Ellenbogenchirurgie (German Society for Shoulder and Elbow Surgery). AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approval for this study was obtained from the Ethics Commission of the University Hospital Muenster in Muenster, Germany.

to the method described by Campbell et al.[8] Failure was defined as a fracture of the coracoid or an avulsion of the CJT (Figure 1B).

It was our goal to relate the calculated LTF values to ADLs. To achieve this, we adhered to simulation data published by Montgomery et al.[34] They estimated the force on the coracoid from the CJT to range between 148 and 242 N with no weight in the hand that increased to 200 to 340 N when a 2-kg weight was placed in the hand, which simulated carrying a plate of food with an elbow joint at 90° of flexion. Based on these data, 200 N was used as a lower limit and was set as threshold in the present study to simulate ADLs in a postoperative phase.

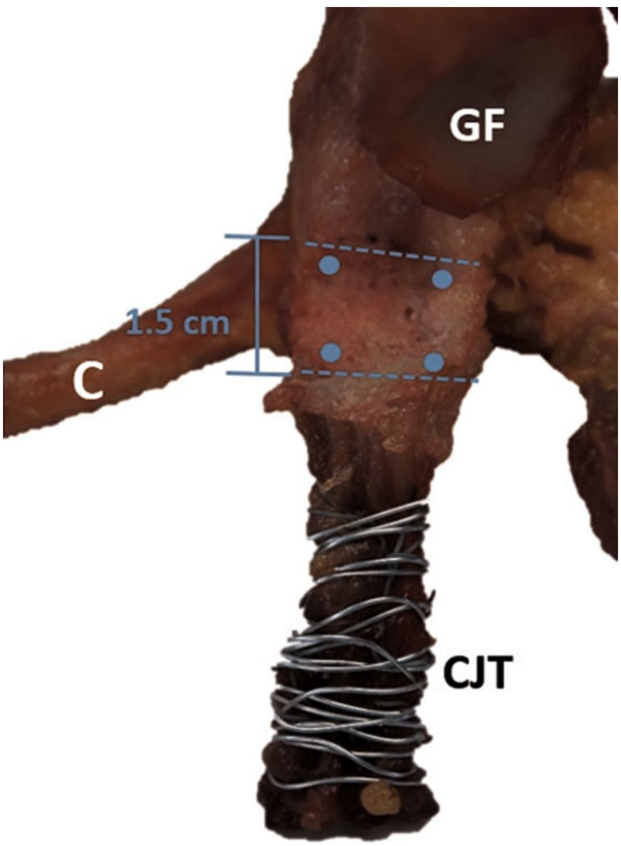

Figure 2. Shoulder specimen after anatomic preparation. The blue dots represent the 4 landmarks on the lower surface used for the coordinate measuring system. Another 4 landmarks were recorded on the upper surface in the same way. C, clavicle; CJT, conjoint tendon; GF, glenoid fossa.

Measurements

After anatomic preparation, the coracoid thickness was measured with a portable coordinate measuring system (Absolute Arm, Modell 8320-70; Hexagon). For this, 4 points on the upper surface and their opposing landmarks on the lower surface of the coracoid were measured (Figure 2). The distance between the landmarks on the upper and lower surface was calculated by creating a plane between the data points on the upper surface.

Afterward, the distances between the plane and the 4 points on the lower surface were analyzed. To assess the amount of coracoid resected during coracoplasty, the distances were again determined after the coracoplasty for the specimens in groups B and C. From the 4 calculated distances, an arithmetic mean value was calculated to obtain the coracoid thickness before and after the coracoplasty. A linear regression was performed with GraphPad Prism (version 8.3.1) to determine the minimum coracoid thickness required to preserve coracoid stability.

Surgery

Specimens in group A were not subject to any surgery and were therefore ready for testing after their measurements were taken (Figure 3A). AC was performed on the specimens of group B and group C at the posterolateral tip of the coracoid with a length of 15 mm, consisting of 3 and 5 mm in thickness (width), respectively, in a similar fashion to that done during AC in surgery (Figure 4).[25] The choice of using 3- and 5-mm resection levels was made as they represent commonly used widths of arthroscopic burrs. The resected amount of the coracoid was scaled to the width of

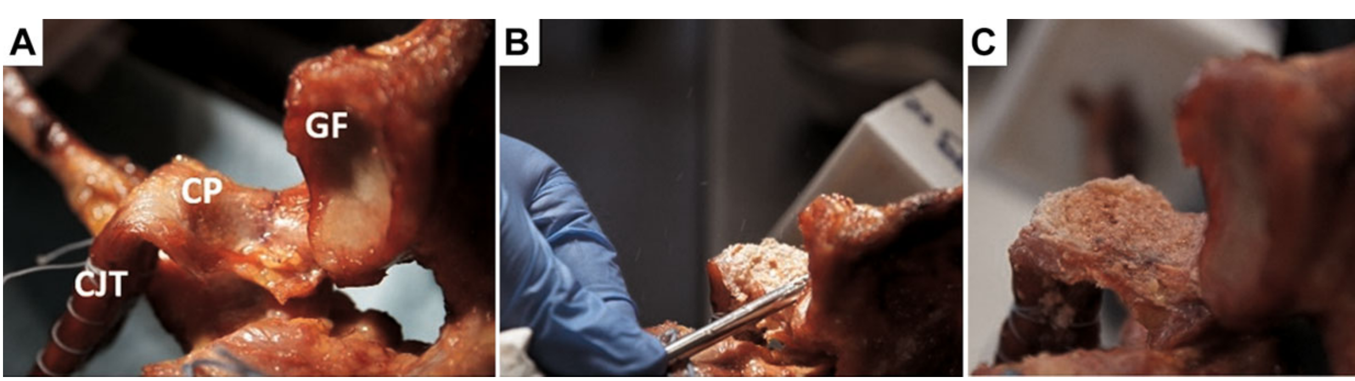

Figure 3. Test setup for the biomechanical testing. (A) On an intact coracoid (group A), no surgery was performed. (B) Coracoplasty with a burr. (C) Example of a specimen from group B or C after the coracoplasty. CJT, conjoint tendon; CP, coracoid process; GF, glenoid fossa.

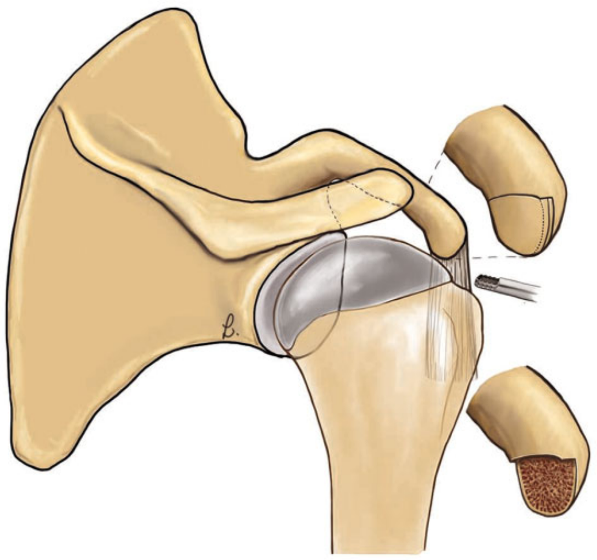

Figure 4. Schematic drawing of the posterolateral view of the coracoid process (CP) and its anatomic surroundings as well as the arthroscopic shaver. Upper-right magnification: CP with a 3-mm resection line (dotted) and a 5-mm resection line (straight line); lower-right magnification: CP after 5-mm coracoplasty.

the burr that was used during coracoplasty, which was either a 3- or 5-mm-wide burr (Arthrex) (Figure 3B). After surgery, specimens of groups B and C were ready for biomechanical testing (Figure 3C).

Data Analysis

A customized Matlab script (2019b; MathWorks) was used to determine the maximum LTF as well as the stiffness. The stiffness was defined by the slope of the linear section of the LTF graph. The statistical analysis for the stiffness and LTF values was performed with GraphPad Prism (version 8.3.1). The results were compared with a 1-way ANOVA, and the level of significance was set to $P < .05$. The data collected by the coordinate measuring system were analyzed with PC-DMIS (Pro 2019 R1; Hexagon). All results are given as mean ± SD unless stated otherwise.

RESULTS

Anatomic Measurements

The age and BMD distributions were equal for all 3 groups ($P = .67$), with a mean age of 81 years and a mean BMD of 85.27 mg/cm^3 (group A: mean age, 78 years; mean BMD, 93.07 mg/cm^3; group B: mean age, 80 years; mean BMD, 76.68 mg/cm^3; and group C: mean age, 79 years; mean BMD, 86.07 mg/cm^3).

The mean native coracoid thickness was 7.2 ± 1.7 mm (95% CI, 5.8-8.6 mm) for group A, 7.7 ± 1.4 mm (95% CI, 6.5-8.8 mm) for group B, and 7.8 ± 0.9 mm (95% CI, 7.1-8.6 mm) for group C. The difference in coracoid thicknesses among the groups was not statistically significant ($P = .64$). After the coracoplasty, the mean coracoid thickness was 4.7 ± 1.8 mm for group B and 2.8 ± 1.3 mm for group C. In relative terms, the postoperative thickness ratio compared with preoperative coracoid thickness was 61.3% for group B and 35.7% for group C.

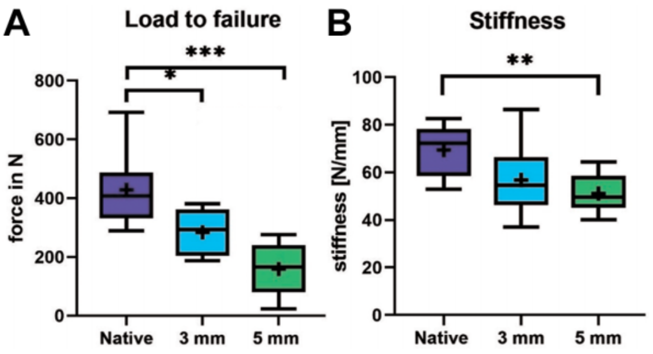

Figure 5. Box plots for (A) load to failure and (B) stiffness. The plus symbol indicates the mean, the center line indicates the median, the shaded box indicates upper and lower quartiles, and the error bars indicate minimum and maximum values. *$P < .05$; **$P < .01$; ***$P < .001$.

The specimens in group A reached the highest LTF (428 ± 127 N; 95% CI, 322.1-534.4 N). When compared with the native group, the LTF values were significantly lower in group B (284 ± 77 N; 95% CI, 219.8-348.0 N; $P = .022$) and group C (159 ± 87 N; 95% CI, 86.24-231.9; $P < .001$) (Figure 5A and Table 1). Two specimens in group C sustained a fracture of the coracoid immediately after the coracoplasty. Those 2 coracoids showed thicknesses of 6.5 mm and 7.0 mm preoperatively, which was thinner than the other coracoids in their group. Their failure loads were 23 N and 61 N. All but 1 specimen failed by fracture during LTF. One coracoid failed by avulsion of the CJT and was part of group A. Overall, there was no difference between male and female specimens regarding LTF ($P = .32$).

There was no significant difference between the specimens in group A (69.5 ± 10.6 N/mm; 95% CI, 60.6-78.4 N/mm) and those in group B (56.8 ± 15.5 N/mm; 95% CI, 43.9-69.8 N/mm; $P = .07$) regarding stiffness. However, the stiffness of the specimens in group C (51.1 ± 8.5 N/mm; 95% CI, 42.2-60.1 N/mm) was significantly lower compared with those in group A ($P = .03$) (Figure 5B and Table 1).

By setting 200 N as the threshold to perform ADLs, the respective coracoid thickness can be calculated (Figure 6). The minimal thickness was calculated with a linear regression ($y = 55.797x$, with $y = 200$), resulting in a value of $x = 4$ mm. Therefore, based on the threshold of 200 N, a postoperative coracoid thickness <4 mm weakens the coracoid in a potentially clinically relevant manner.[34]

DISCUSSION

The most important finding of our study was that a critical value of 4 mm of coracoid thickness should be preserved

TABLE 1
Comparison of Load to Failure and Stiffness Between the Study Groups[a]

	Load to Failure, N				Stiffness, N/mm			
	Mean ± SD	Min-Max	95% CI	*P*	Mean ± SD	Min-Max	95% CI	*P*
Group A (native)	428.2 ± 127	288.3-692.4	322.1-534.4	—	69.5 ± 10.6	53.0-82.7	60.6-78.4	—
Group B (3-mm coracoplasty)	283.9 ± 77	187.3-380.9	219.8-348.0	**.02**	56.8 ± 15.5	37.0-86.3	43.9-69.8	.07
Group C (5-mm coracoplasty	159.1 ± 87	23.0-275.1	86.24-231.9	**<.001**	51.1 ± 8.5	40.0-64.4	42.2-60.1	**.03**

[a]Bold indicates a statistically significant difference compared with group A ($P < .05$). Max, maximum; Min, minimum.

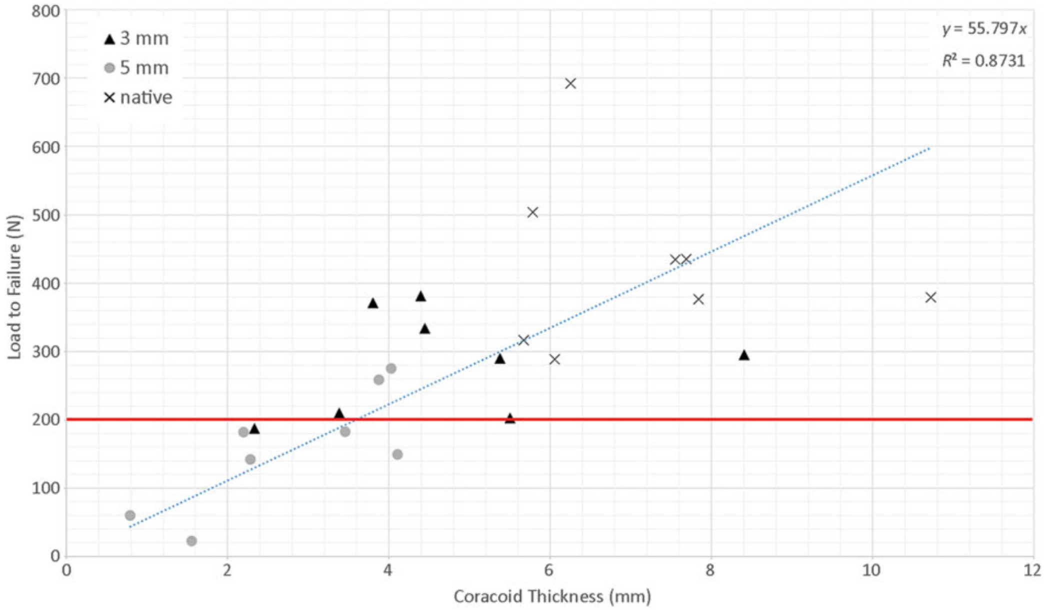

Figure 6. Linear regression: by setting 200 N as the threshold for activities of daily living (*y*), the respective coracoid thickness can be calculated (*x*). The coracoid thickness of the native specimens (×) and postoperative coracoid thicknesses of group B (triangles) and group C (circles) are displayed. Values below the red line did not withstand a force of 200 N with their postoperative thickness.

postoperatively in order to minimize the risk of a fracture or an avulsion of the conjoint tendon. In correspondence with the findings of this study, surgeons should remove only the minimum amount of bone necessary to decompress the shoulder joint.

A clinically relevant weakening of the coracoid could lead to a coracoid fracture or avulsion of the CJT. Coracoid fractures are generally rare and make up only 5% of all fractures of the shoulder. Most cases either are caused by direct trauma, especially in sports, or consist of avulsion fractures.[21] The occurrence of coracoid fractures after coracoclavicular ligament reconstruction surgery has previously been described, where the coracoid was weakened by coracoid drilling tunnels, leading to a fracture.[29] To the best of our knowledge, there are no published data on coracoid fractures after AC.

This study shows that a coracoid thickness <4 mm after AC can weaken the coracoid significantly. Unfortunately, the structural makeup of the coracoid and subcoracoid areas differs from person to person, which several anatomic studies were able to show.[4,14,17,35,38] Boutsiadis et al[5] reported coracoid thicknesses between 5.5 and 13 mm. Our study supports these measurements with coracoid thicknesses ranging from 5.3 to 10.7 mm. At the same time, the mean coracoid thicknesses between the different groups in this study were similar, which demonstrates a balance regarding age, sex, and BMD among treatment groups. This study suggests that the coracoid should not be weakened significantly and should consequently withstand ADLs in a postoperative setting if a postoperative coracoid thickness of at least 4 mm remains. In some cases, the coracoid thickness might be low to begin with, so that its thickness would be below the threshold of 4 mm preoperatively. In that case, it could be beneficial to perform a tuberoplasty of the lesser tubercle instead of a coracoplasty to widen the SCS, as has been described for the arthroscopic management of proximal humerus malunions.[24]

Until now, the influence of AC on coracoid failure loads remained unclear. There are a few studies that looked at coracoid failure loads associated with different tunnel diameters of the coracoid for coracoclavicular ligament reconstruction surgery and for the Latarjet procedure. Such studies recorded failure loads between 148 and 724 N, depending on the respective treatment group.[8,12,30,38] To bridge the biomechanical findings in this study to a relevant clinical issue, we correlated the results with a simulation of the postoperative loads described by the aforementioned study by Montgomery et al.[34] And while the threshold of 200 N in this study represents quite a low level of activity (lifting a 2-kg plate of food), the risk of coracoid fracture may be higher in athletes and laborers. All LTF values in group A were above the threshold of 200 N. In group B, 7 of 8 specimens showed values above this threshold. In group C, only 2 specimens were able to reach an LTF above this threshold (258 and 275 N); all other LTF values in group C fell below 200 N. With the 200-N threshold for ADLs, a postoperative thickness of 4 mm should remain to minimize the risk of fracture.

The indications for AC can be manifold. Most patients that underwent AC described in the literature had concomitant subscapularis (SSC) pathologies or showed clinical signs of SCI and did not respond to nonoperative treatment.[18,20,27] There is no consensus on how much of the coracoid can and/or should be resected during AC. Dines et al[10] recommended resecting 10 to 15 mm of the lateral coracoid during open osteotomy of the coracoid, before arthroscopic treatment was introduced. To date, the amount of the coracoid to be resected during AC is often determined by the newly created clearance between the coracoid and the SSC tendon. Lo and Burkhart[25] recommended a minimum clearance of 7 mm between SSC tendon and the coracoid process to adequately treat SCI by AC. Consequently, to create a 7-mm clearance, the amount of coracoid resected can differ significantly from patient to patient. Another approach was reported by Suenaga et al,[39] who used the width of a finger as a measurement to be consistent with the amount of coracoid to be resected. As the width of a finger is not an accurate measurement and can vary substantially from surgeon to surgeon, the critical amount of coracoid thickness is yet to be defined and might be instrumental when considering postoperative stability after AC.

Another key topic has been the coracohumeral distance (CHD) when discussing SCI. Several studies show that the CHD decreases significantly in 90° of flexion of the arm, in 90° of flexion with concurrent horizontal adduction, and during internal rotation and can consequently facilitate SCI.[6,15,16,31] Lo and Burkhart[25] postulated that a CHD <8 mm in women and <10 mm in men, with associated clinical findings, may warrant operative treatment, such as AC.[32] And while for several years it was believed that the decreased CHD was the bottleneck leading to anterior shoulder pain associated with SSC pathologies, indications for AC have been discussed to be controversial in recent years. While AC does not seem necessary for all patients with SSC tears, patients with SCI and narrow CHD seem to benefit from AC.[37,40] A recent study claims that the CHD is only significantly narrower in patients with degenerative SSC tears and not in patients with traumatic tears.[3] This study suggests that AC may only be beneficial in patients with degenerative SSC tears and not in those with traumatic SSC tears. As there are limited studies available, though, the underlying pathology of SCI is not yet fully understood.

This study shows that preoperative planning is crucial. Surgeons should measure the coracoid width as well as CHD preoperatively with appropriate imaging at hand, such as magnetic resonance imaging (MRI)/CT, to try to determine how much coracoid removal is required while retaining a minimum of 4 mm of width of the coracoid. Failure to do so risks instability with consecutive fracture of the coracoid or avulsion of the CJT. Additionally, knowing the anatomic dimensions at hand potentially allows for a greater resection than initially planned if the anatomic landmarks determined on CT/MRI can accommodate it.

As mentioned earlier, Lo and Burkhart[25] recommend using the subcoracoid clearance that can be observed via the arthroscope as a guide. Our claim is that combining this strategy with preoperative planning and measuring of the anatomic landmarks gives the surgeon a better idea of how much coracoid can be resected during AC.

Limitations

A limiting factor of this study is the male-to-female ratio. The current distribution within groups is unequal (5 female vs 3 male specimens), and a distribution of 50% of each sex would be favorable in any study.

Another limitation is the age of specimen in this study (mean, 81 ± 7.9 years). This is attributed to the fact that this study was performed with cadaveric shoulders and most donations are of the elderly. This poses an issue when interpreting these results, given that SCI can affect young as well as old patients. Bones of younger patients will most likely be stronger than those of an 81-year-old, so the amount of bone that is safe to resect might not be identical to that of an 81-year-old. Furthermore, coracoid width has been shown to increase with age, so coracoid thicknesses in this study may be thicker than those of younger patients. It can be argued that the degree of tension in the CJT of a younger patient might be higher as well. We therefore think that the results of this study mimic the "worst-case" scenario. An issue that accompanies the age of the specimens is the BMD, which is rather low. Furthermore, the coracohumeral interval (CHD) was not assessed. Being a time-zero bench test, all findings of this study only apply to the time of initial fixation and do not reflect conditions under physical loading and in vivo healing.

CONCLUSION

Depending on the amount of bone resected, AC can weaken the coracoid in a potentially clinically relevant manner. While even a 3-mm coracoplasty caused significant weakening of the coracoid, the individual failure loads were higher than those of the predicted ADLs. A critical value of 4 mm of coracoid thickness should be preserved to ensure the stability of the coracoid process.

In correspondence with the findings of this study, surgeons should remove only the minimum amount of bone necessary to decompress the shoulder joint to minimize the risk of fracture. A postoperative coracoid thickness of 4 mm should remain.

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