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SHOULDER

Acromioclavicular and coracoclavicular PDS augmentation for complete AC joint dislocation showed insufficient properties in a cadaver model

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Abstract

Purpose Optimal surgical treatment of high-grade acromioclavicular joint dislocations is still controversially discussed. The purpose of the present controlled laboratory study was to evaluate whether a polydioxansulfate (PDS®) cord augmentation with separate reconstruction of the coracoclavicular (CC) ligaments and the acromioclavicular (AC) complex provides sufficient vertical stability in a biomechanical cadaver model.

Methods Twenty-four shoulders of fresh-frozen cadaveric specimen were tested. Cyclic loading and load to failure protocol was performed in vertical direction on 12 native AC joints and repeated after reconstruction. The reconstruction of the coracoclavicular ligament was performed using two CC PDS cerclages and an additional AC PDS cerclage.

Results In static load testing for vertical force, the native AC joint complex measured 590.1 N (±95.8 N), elongation 13.4 mm (±2.1 mm) and stiffness 48.7 N/mm (±12.0 N/mm). The mean maximum load to failure in the reconstructed joints was 569.9 N (±97.9 N), elongation 18.8 mm (±4.7 mm) and stiffness 37.9 N/mm (±8.0 N/mm). During dynamic testing of the reconstructed AC joints, all specimens reached the critical elongation of 12.0 mm, defined as clinical failure between 200 and 300 N. The mean amount of repetitions at clinical failure was 305. A plastic deformation of the reconstructed specimens throughout cyclic loading could not be detected.

Conclusion The AC joint reconstruction with acromioclavicular and coracoclavicular PDS cord cerclages did not provide the aspired vertical stability in a cadaver model.

Level of evidence Basic Science Study.

Keywords AC joint injuries · AC joint dislocation · AC joint reconstruction · PDS augmentation · Acromioclavicular · Coracoclavicular

Introduction

Acromioclavicular joint dislocation represents a common injury of the superior shoulder suspensory complex comprising different injuries to the acromioclavicular and coracoclavicular ligaments. Most commonly, the mechanism of this injury is a direct force from a fall on the lateral aspect of the shoulder with the arm in an abducted position. Thereby, different forces are responsible for a different type of injury. These injuries have been classified by Rockwood [54] into type I through VI. Typically, type I

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and II injuries are treated non-operatively, and the vast majority of these patients return to pre-injury status [10, 13, 32]. For acute type III injuries, the favourable treatment is still controversially discussed in the literature, while clinical studies showed similar results for surgical and non-operative treatment [3, 29]. However, in young and active patients as well as high-level athletes and manual workers, surgical intervention is often preferred to allow more rapid rehabilitation and to enable an early return to daily activity [17]. In terms of acute high-grade injuries, typically types Rockwood[54] IV through VI, most authors recommend surgical treatment, as non-operative treatment may lead to residual symptoms like pain, stiffness or decreased range of motion and weakness [1, 3, 10, 24, 29, 32, 36, 45, 46, 52, 55].

The literature is replete with surgical techniques to address acromioclavicular dislocations, including ligament reconstruction or transfer [28, 33, 36, 51], augmentation with absorbable/non-absorbable sutures [15, 20, 27, 31, 53] or tendon grafts [26, 46] as well as with rigid materials like plates [11, 25, 41, 42] or CC screws [5, 49]. Since arthroscopic surgery has highly advanced in recent years, several minimally invasive techniques with suture anchors [6–8, 12, 39, 53] or suture buttons have been invented [21, 38, 43, 44, 50]. Furthermore, combinations of these techniques are also described in the literature [4, 17, 21].

However, despite modern minimally invasive and arthroscopically assisted treatment options for anatomic reconstruction of the coracoclavicular ligaments, there is still no well-defined gold standard treatment for acromioclavicular joint separations.

Since 1972, when Weaver and Dunn [51] published their popular technique, several biomechanical studies have reported on the latest fashion of AC joint augmentation providing an increasing stability of the reconstructed complex [12, 16, 30, 33–35, 37, 48] and finally equal or even more stability than native ligaments [50].

Therefore, it seems that future belongs to recently described, minimal invasive techniques, using anchors or buttons with or without tendon grafts, even though long-term results that might point out unknown complications are still missing. To date, open techniques like reconstructions with absorbable or non-absorbable suture cerclages are still in use for acute AC joint separations and show reliable and good to excellent clinical results, even though slight re-dislocations are reported [14, 15, 27, 31].

The purpose of the current study was to evaluate the vertical stability of our AC joint reconstruction technique for acute AC joint injuries, using coracoclavicular PDS cerclages and an additional acromioclavicular PDS cerclage augmentation. We hypothesized that this technique provided sufficient vertical stability to prevent a vertical re-dislocation during the healing process.

Materials and methods

Shoulders ($n = 24$, 16 female, 8 male) were obtained from 12 human cadavers. The average age of all specimens was 79 years (range 65–96 years). All tested specimens were free from systematic disease or previous injury to the AC joint. Until testing, shoulder specimens were stored at −20 °C and then thawed at room temperature for 24 h before use. Before testing, the glenohumeral joint was disarticulated, and all the soft tissue was removed from the clavicle and scapula except of the capsule–ligament apparatus of the AC joint and the coracoclavicular ligament complex.

The biomechanical capability of the native capsule–ligament complex of the AC joint was evaluated in 12 specimens (8 female, 4 male), whereas left and right shoulders were alternately tested. Comparative tests were performed with the reconstructed contralateral shoulder of the same specimens using a polydioxansulfate (PDS) cerclage augmentation. The detailed reconstruction technique is described below. All specimens were loaded along a vertical-oriented axis using a material testing machine (Zwick 2.5 TN, Zwick-Roell, Ulm, Germany). This machine provides a load accuracy of 0.1 N. Data were recorded with dedicated software (Textexpert 8.1, Zwick-Roell) and compiled using a desktop computer and Excel software (Microsoft Corp, Redmond, Washington). The scapula was embedded in synthetic epoxy resin (Ureol FC 52 Polyol, Vantico, Wehr, Germany) in a custom block mould from the inferior angle to the edge of the glenoid and fixed to the base of the testing device. With a metal fixation, the clavicle was attached to the load cell of the material testing machine. Flexible mounting minimized mechanical constraints on the motion of the clavicle. The appropriate anatomic position between the clavicle and the scapula was retained. Attention was paid to ensure that the coracoclavicular ligament complex and corresponding PDS augmentations were in line with the loading axis of the testing machine. The designed set-up guaranteed stable mounting of the scapula and clavicle to the testing machine and provided standardized experimental procedure (Fig. 1).

Reconstruction technique

A PDS cerclage reconstruction was performed in a modified technique to previously published literature [2, 22]. After completely sectioning the capsule–ligament apparatus of the AC joint and the coracoclavicular ligaments, two parallel 2.5-mm-diameter holes were vertically drilled through the distal third of the clavicle in cranio-caudal direction. The exact position of the clavicular tunnels was determined according to Rios et al. [40], who assigned the attachment sites of the trapezium and conoid ligament to two regions located 17 and 30 % of the total clavicle length

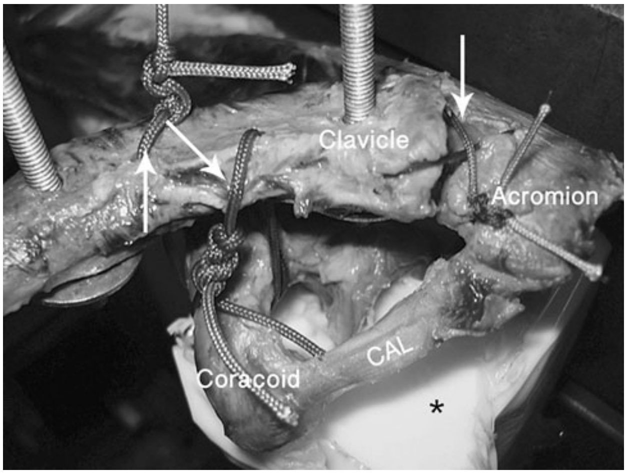

Fig. 1 Testing set-up with embedded scapula in epoxy resin (*) and metal clavicle fixation. AC joint reconstruction with two coracoclavicular PDS cerclages (*white arrows*, *left*) and one additional acromioclavicular PDS cerclage (*white arrow*, *right*). *CAL*, coracoacromial ligament

medial from the lateral clavicle end. According to Baker et al. [2], the drill holes were placed into the anterior third of the clavicle, in order to minimize the anterior displacement. The CC ligament complex was repaired using two 1.5-mm-braided PDS cord cerclages. The two PDS cords were guided around the base of the coracoid and then passed through one of the vertical drill holes. Subsequently, reduction of the AC joint was performed by cranio-caudal force using a ball spike, and the sutures were securely tied using a standard surgeon's knot followed by five square knot ties. Next, a 1.5-mm-diameter hole was drilled in horizontal direction from ventral to dorsal through the distal clavicle and the acromion, at a distance of approximately 1 cm from the AC joint. Finally, a 1.0-mm-braided PDS cord was passed through these drill holes securing the AC joint in an eight-shaped configuration (Figs. 1, 2) and knotted as described above.

Biomechanical testing protocol

First native shoulders ($n = 12$) were tested under static conditions. The specimens were fixed to the testing machine as previously described and loaded until failure. Initially, a preload of 5 N was applied to ensure a consistent starting point. Next, the applied force was continuously increased with a rate of 25 mm/min until failure according to previous published studies [19, 50]. Load to failure, stiffness and elongation at load to failure and failure mode were evaluated. Load to failure was considered when the testing machine stopped at a drop in force of 50 % from the applied maximum force ($F^{\max}$ 50 %). The recorded $F^{\max}$ was equated with the load to failure. Stiffness was calculated from the slope of the linear portion of the load–displacement curve provided by the software of the testing machine, and the mode of failure was visually analysed.

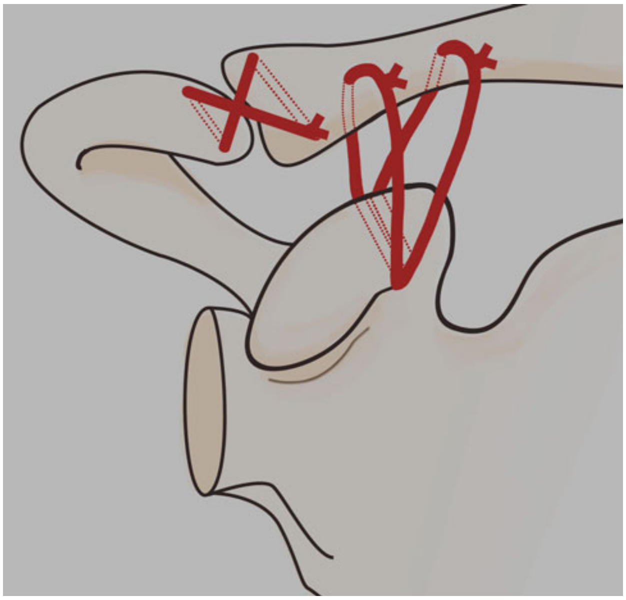

Fig. 2 Schematic drawing of our fixation technique with double cc cerclage and ac cerclage PDS augmentation. For our performed technique, one PDS cerclage was guided in front of the clavicle and one behind it

For the reconstructive shoulders ($n = 12$), a dynamic testing protocol was run before load to failure testing. Load was applied in a cyclic manner at 1.5 Hz between 10 and 100 N, 100 and 200 N, 200 and 300 N, etc. For each force, 100 repetitions were performed. An initial preload of 10 N was applied. The gradual increase in load of about 100 N after 100 cycles was continued until clinical failure was detected. Clinical failure was defined as elongation of 12 mm (ca. 1 mm less than elongation at failure of the native ligaments). At this point, the number of carried out cycles was noted. Data were recorded permanently to analyse the elongation amplitude of the PDS reconstruction at any time. After a 1-min break, specimens were loaded again with 100 cycles from 10 to 100 N. By comparing elongation during initial 100 cycles and these additional 100 cycles, the kind of PDS deformation was detected. Subsequently, the reconstructed shoulders were tested until failure using the same testing protocol as for native ligament complex.

Statistical analysis

All of the investigated outcomes were assessed on a metric scale. A corresponding visualization by scatter plots showed no severe deviations from the normal distribution. Therefore, descriptive statistics are given by mean ± standard deviation as measures of location and variability.

Table 1 Results from static testing

	N	Load to failure (N)	Elongation to failure (mm)	Stiffness (N/mm)	Mode of failure
Native tendon	12	590.1 (±95.8)	13.4 (±2.05)	48.7 (±12.0)	9 ligament rupture 3 coracoid fracture
PDS augmentation	12	569.9 (±97.9)	18.8 (±4.7)	37.9 (±8.0)	12 coracoid fracture
P value		n.s.	0.003	0.021	

Median (range) of the measurements for the native and reconstructed specimens is reported together with *P* values

Accordingly, group comparisons of native to reconstructed shoulders were performed by Student's *t* test for paired samples. All statistical tests were two-sided and conducted in an explorative manner on a significance level of 0.05. Statistical analysis was performed with *R* for statistical computing.

Results

Static testing: native shoulders versus reconstructed shoulders

For static load to failure testing of native AC joint ligaments ($n = 12$), the mean load to failure was 590.1 N (±95.8 N) at a mean elongation of 13.4 mm (±2.1 mm). The calculated stiffness of the native ligaments was 48.7 N/mm (±12 N/mm). Out of 12 native shoulders, 9 failed due to coracoclavicular ligament insertion pull-out and 3 showed a fracture of the coracoid process.

Mean load to failure for the PDS-reconstructed specimens ($n = 12$) was 569.9 N (±97.9 N), elongation 18.8 mm (±4.7 mm) and stiffness 37.9 N/mm (±8 N/mm). All 12 reconstructed shoulders failed due to fracture of the coracoid process.

No significant difference between the native shoulders and the PDS-reconstructed group was seen for load to failure (n.s.) (Fig. 2). Significant differences were seen in elongation at load to failure ($P = 0.003$) and stiffness ($P = 0.021$) (Table 1).

Dynamic testing: reconstructed shoulders

Progressive dynamic testing was stopped when an elongation of 12 mm was detected, which was defined as clinical failure, due to PDS properties. All reconstructed specimens reached 12 mm elongation between 300 and 400 N of cyclic loading. In average, there was a mean of 305 repetitions (±5.7 repetitions) until clinical failure. Elongation was noted at preliminary test load of 10 N and after 100 cycles before load increasing. Comparing elongation after initial 100 cycles (10–100 N) (5.7 mm) to elongation after final 100 cycles (10–100 N) (5 mm), performed after a 1-min break, there was no plastic deformation of the reconstructed specimens throughout cyclic loading. The structural quality of PDS augmentation was not reduced, and the elongation until 12 mm was completely reversible (Table 2).

Discussion

The most important finding of the present study was that the PDS reconstruction with additional AC cerclage for complete AC joint separations did not reach the aspired vertical stability in our cadaver model. The optimal surgical method for complete AC joint dislocations is still a matter of debate. Several biomechanical studies in the literature already aimed at showing the best possible or most stable treatment option. In the present cadaver study, the described technique for AC joint reconstruction, using AC

Table 2 Results from dynamic testing

	Elongation I (mm)	Increase in elongation I (mm)	Break	Elongation II (mm)	Increase in elongation II (mm)
Preliminary test load 10 N	2 (±0.6)	2 (±0.6)		1.6 (±0.1)	1.6 (±0.1)
100 cycles for 10–100 N	5.7 (±0.8)	3.7 (±0.5)		5 (±0.4)	3.3 (±0.3)
100 cycles for 100–200 N	8.3 (±0.4)	2.6 (±0.5)	1 min		
100 cycles for 200–300 N	10.9 (±0.3)	2.6 (±0.3)			
100 cycles for 300–400 N	12	1.1 (±0.3)			

Median (range) of the measurement of elongation and increase of elongation for the reconstructed specimens is reported until clinical failure (12 mm) and after a 1 min break and CC cerclages, turned out to not have the aspired biomechanical properties.

Surgical treatment of acromioclavicular joint injuries is typically reserved for complete dislocations such as Rockwood type IV and V injuries. Optimal treatment of type III injuries is still controversially discussed, since clinical studies showed no significant benefits for either treatment [3, 29, 47]. More than 80 surgical procedures have been proposed for acute or chronic AC joint repair with no specific indications for their respective use. The most popular procedure is the coracoacromial ligament transfer, as described by Weaver and Dunn in 1972 [51]. However, biomechanical properties and strength of this technique have been called into question, as clinical data reported subluxation or even dislocation occurring in the chronic setting as high as 30 % [51, 52]. Therefore, many surgeons considered other possibilities to reconstruct the CC ligament complex, and several biomechanical studies on different reconstruction techniques exist.

Bearing in mind that AC capsule and ligaments mainly contribute to horizontal stability, whereas the coracoclavicular ligaments limit vertical translation [6], and regarding the different roles of each coracoclavicular ligament in providing AC joint stability [9, 18], it has lately been recommended to treat acute AC joint dislocations of Rockwood type IV through VI by addressing the coracoclavicular ligaments separately in an anatomic manner [19, 22, 40]. Furthermore, optimal treatment and anatomic reconstruction would include restoring the AC complex as well as the coracoclavicular ligaments [9, 16, 19, 22, 33]. To account for that, we use an additional AC cerclage in our technique.

A study by Breslow et al. [6] showed similar stability for suture repairs compared to suture anchors techniques. However, they concluded that the access to the top of the coracoid process to be easier when using anchors. Therefore, more and more minimally invasive or arthroscopic techniques with drill guides were developed during the following years [7, 8, 50]. In 2006, Chernchujit et al. [7] evaluated the mean ultimate tensile strength for a double anchor system (FiberWire® No. 5) at 767 N, achieving a greater tensile strength than measured for native coracoclavicular ligaments (578 ± 111 N). Walz et al. [50] reported in 2008 on an anatomic AC joint reconstruction using 2 TightRope® devices. They could show an improved vertical (mean 982 N) and horizontal (mean 627 N) stability for the reconstructed group compared to the native ligaments and reconstructions in former studies, except the bicortical coracoclavicular screw fixation. Stiffness for the reconstructed specimens showed to be only little less than for the native ligaments. Walz et al. [50] concluded that they found a reconstruction method for AC joint dislocations, which is a stable and functional anatomic reconstruction method. However, when reconsidering the requirements for an anatomic reconstruction, namely restoring the AC as well as CC ligaments, whereas the CC ligaments are addressed separately, most of the existing reconstructions are not completely anatomic.

The use of a suture or tape cerclages passed around the base of the coracoid and around or through the clavicle has already been investigated and supported in several cadaveric studies [22, 23, 37]. Therefore, studies have already shown greater laxity, respectively, lower stiffness for the suture cerclages, using No. 5 non-absorbable polyester sutures or No. 5 Ethibond, compared to the native ligaments [12, 22].

Biomechanical studies have also reported on AC joint reconstructions using PDS cerclages in different ways. In a porcine metatarsal model, Wellmann et al. [53] compared the tensile fixation strength of 4 different minimally invasive AC joint repairs including 1.3-mm single PDS cerclage with a subcoracoidal flip button fixation and 1.3-mm single PDS cerclage fixation. They found no significant difference between the 2 PDS repairs assessing an ultimate load of 646 N for the flip button repair and 663 N for conventional PDS banding. Motamedi et al. [37] found no significant difference for mean failure loads between the intact ligament complex (725 N) and augmentations performed with braided polydioxanone (PDS) (677 N) or braided polyethylene (placed through (986 N) or around (763 N) the clavicle). Nevertheless, they pointed out a decreased stiffness for the PDS augmentations compared to the native ligaments or the polyethylene reconstructions. However, none of the presented studies used an additional acromioclavicular cerclage.

Regarding the results of the present study, the strength of the reconstructed AC joints is somewhat lower (580 N) than mentioned in former studies [37, 53]. The higher mean specimen age in our study describing a kind of “worst case scenario” and the fact that we ran a dynamic testing protocol up to 300–400 N before static load to failure testing may account for these differences. The poor stiffness of the PDS construct in our study (38 N/mm) agrees with the results of Motamedi et al. [37](27 N/mm) and Wellmann et al. [53] (25 N), as they reported a relatively low stiffness and increased tendency to stretch for PDS repairs. As a result of the low stiffness, clinical failure was reached in all specimens between 300 and 400 N of cyclic loading after an average of 305 cycles. Even the present technique with double CC cerclage and additional AC cerclage did not better this situation.

The present study design has the advantages of being rigorous, well controlled and reproducible, but it contains the immanent limitations associated with applying a cadaveric biomechanical examination to a clinical problem. In practice, we have not assessed parameters such as failure under anterior–posterior loading and rotational motion, as the goal of the study was to investigate the vertical stability of our PDS suture repair technique. Furthermore, the mean specimen age (79 years; range 65–96 years) in our study was higher than in some previous investigations, and it is likely to be higher than the age of young athletes, in which acromioclavicular joint dislocations usually occur. Since age may have an effect on bone and ligament properties [37], this might also be a limitation of the present study and might account for the high amount of coracoid fractures in the repair group, which we do not see in clinical use. However, in clinic, shoulders are not exposed to the same high loads during rehabilitation.

Finally, the results of the present study indicate that PDS augmentations might lead to excessive vertical loading of the repaired AC joint complex and subsequent failure of the reconstruction, respectively, vertical re-dislocation. Therefore, this study has changed our technique for AC joint reconstruction performed in the daily clinical practice.

Conclusion

In conclusion, the hypothesis could not be corroborated by this study. It was demonstrated that PDS reconstruction with additional AC cerclage did not reach the aspired stability in our cadaver model. Since there was still a considerable amount of elongation with the AC and CC cerclages (3 PDS cords) technique, it appears that the biomechanical properties of the PDS sutures account for this problem rather than the surgical technique. Therefore, the use of suture materials with different material properties should be reconsidered from a biomechanical point of view.

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