Biomechanical Comparison of Anatomic and Extra-Anatomic Reconstruction Techniques Using Local Grafts for Chronic Instability of the Acromioclavicular Joint

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Background: Anatomic reconstruction techniques are increasingly used to address cases of acromioclavicular (AC) joint chronic instability. These usually involve an additional surgical site for autograft harvesting or an allograft.

Purpose: To describe a triple-bundle (TB) anatomic reconstruction using on-site autografts, the semiconjoint tendon (SCT) and the coracoacromial ligament (CAL), and compare its primary stability to the native AC joint ligamentous complex and to a modified Weaver-Dunn (WD) reconstruction.

Study Design: Controlled laboratory study.

Methods: Intact AC joints of 12 paired cadaveric shoulders were tested for anterior, posterior, and superior translations under cyclic loading with a servo-hydraulic testing system. One shoulder from each pair was randomly assigned to the TB group, where 2 SCT strips were used to reconstruct the coracoclavicular ligaments while the distal end of the CAL was transferred to the distal extremity of the clavicle to reconstruct the AC ligaments; the other shoulder received a modified WD reconstruction. After reconstruction, the same translational testing was performed, with an additional load-to-failure test in the superior direction.

Results: In both the TB and the WD groups, no significant differences were found before and after reconstruction in terms of joint displacements after cyclic loading, in all 3 directions. Compared with the WD reconstruction, the TB repair resulted in significantly lower displacements in both the anterior (ie, 2.59 ± 1.08 mm, $P = .011$) and posterior (ie, 10.17 ± 6.24 mm, $P = .014$) directions, but not in the superior direction. No significant differences were observed between the 2 reconstructions during the load-to-failure testing, except for the displacement to failure, which was significantly smaller (ie, 5.34 ± 2.97 mm) in the WD group ($P = .037$).

Conclusion: Anterior, posterior, and superior displacements after an anatomic reconstruction of the AC joint complex using the SCT and CAL as graft material were similar to those of native AC joints and significantly smaller in the axial plane than those of AC joints after a WD repair.

Clinical Relevance: An anatomic reconstruction is achievable using the CAL and the SCT as on-site graft materials, providing satisfactory initial stability and thereby allowing earlier mobilization.

Keywords: acromioclavicular joint; anatomic reconstruction; biceps; conjoint tendon; coracoacromial ligament

In addition to the dynamic stability ensured by the deltoid and trapezius muscles, the static stability of the acromioclavicular (AC) joint relies primarily on 3 ligamentous structures.[11] Considered as one functional unit, the AC ligaments represent the major restraint to large displacements in the posterior direction. The coracoclavicular (CC) ligaments play a primary role in restraining large displacements in the anterior and superior directions, which can be attributed to the conoid ligament medially, and in axial compression of the clavicle toward the acromion process, attributed to the trapezoid ligament laterally.[13]

Despite these anatomic constraints, the AC joint is commonly subject to traumatic dislocations, due to its particularly exposed location. Indeed, such separations represent 3.2% of all injuries involving the shoulder girdle and are primarily caused by a direct impact to the shoulder, especially during contact sports.[3] In high-grade injuries, both AC and CC ligaments fail and surgical management is usually recommended (ie, reduction and stabilization).[32] Additionally, in cases of delayed diagnosis or failure of primary joint stabilization, inflammatory changes in ligamentous

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tissues decrease their healing potential over time.[7,8,23,25] Subsequently, after a preoperative delay ranging between 10 and 21 days, an additional biological graft is recommended.[1]

Early AC ligamentoplasty techniques were performed using local grafts, pedicled anteriorly onto the coracoid process and secured posteriorly onto the distal clavicle. In 1942, Vargas[40] reported on the use of the lateral part of the semiconjoint tendon (SCT) corresponding to the short head of the biceps tendon; 30 years later, Weaver and Dunn[42] proposed an intramedullary fixation of the coracoacromial ligament (CAL) into the shaft of the distal clavicle. However, such reconstructions do not restore the complex anatomic and biomechanical properties of the AC static stabilizers; subsequently, inconsistent radioclinical outcomes have been reported.[10,39,43] New anatomic techniques have been developed more recently, reconstructing the native ligamentous lines of action close to the original anatomic structure, and have been shown to provide better biomechanical and clinical results.[26,28,38,41] However, tendon grafts currently used to perform such reconstructions (ie, hamstrings, long toe extensor, wrist flexors) usually require additional surgical sites that increase the graft's morbidity.[14,24] Use of an allograft may prevent such limitations. However, this material is expensive, may not be routinely available in some countries, and adds the potential risk of disease transmission.[2,6]

The purpose of this study was to assess the biomechanical properties (ie, translational displacements, ultimate load to failure, maximal displacement to failure, and stiffness) of an anatomic triple-bundle (TB) reconstruction performed with the SCT and the CAL and to compare them with the native AC ligamentous complex and with an extra-anatomic reconstruction also using an on-site graft, that is, the Weaver-Dunn (WD) procedure. Our hypothesis was that there would be no significant difference in the biomechanical parameters between the TB ligamentoplasty and the native joint and that both would be superior to the WD reconstruction.

METHODS

Specimen Preparation

Twelve paired, fresh-frozen cadaveric shoulders were obtained by our institutional anatomic bequest program with Biospecimens Committee approval. The mean age of the donors (4 men, 2 women) was 76.4 ± 18.1 years (range, 39-92 years). Specimens were thawed overnight at room temperature. The glenohumeral joint was disarticulated, and all cutaneous, fatty, and muscular tissues surrounding the AC joint and the CC interval were removed except for the AC and CC ligaments, which were left intact, along with the conjoint tendon and the CAL. Before the native joint was tested, the specimens were visually ascertained to be free of any previous alterations of the AC and CC ligaments, conjoint tendon and CAL, scapula, and clavicle. Before reconstruction, the AC joints were dissected and inspected for degenerative disease. Specimens presenting any signs of such alterations were excluded from the study.

Throughout all phases of preparation and testing, the specimens were kept moist by use of a 0.9% saline solution. The proximal quarter of the clavicle shaft and the inferior third of the body of the scapula were trimmed with an oscillating saw to facilitate further potting and mounting. The scapula was potted in a 15-cm (length) × 5-cm (width) × 8-cm (height) custom block mold with urethane resin (Smooth-Cast 65D; Smooth-On Inc), such that the glenoid articular surface was perpendicular to the floor along with its inferior-superior axis. The clavicle was potted in a 5-cm (diameter) × 6-cm (length) acrylic tube such that its long axis was centered into the pipe. The potted scapula was then mounted onto a vise that was secured to the base of the servo-hydraulic test frame (858 Mini Bionix II; MTS Systems), while the potted clavicle was secured to the system's linear actuator with a custom aluminum clamp. Both scapular and clavicular clamps allowed rotations of each part of the specimen around 3 axes (ie, posterior-anterior, medial-lateral, and inferior-superior); the specimen was successively placed in such a way to generate 3 clavicular translation directions, assessed relative to the scapula, which included anterior, posterior, and superior orientations (Figure 1). To test the anterior laxity, the distal clavicle was positioned so that its superior surface was perpendicular to the test machine base and its anterior edge was parallel to the base; the inferior-superior axis of the glenoid was positioned parallel to the base, with the scapular plane forming an angle with the base ranging from 30° to 45°, depending on the specimen's anatomic features; the linear actuator was then displaced upward to load the joint. For posterior laxity testing, the specimen position was the same as in the anterior testing, but the actuator was displaced downward. To test the superior laxity, the inferior-superior axis of the glenoid was positioned perpendicular to the test machine base, and the superior

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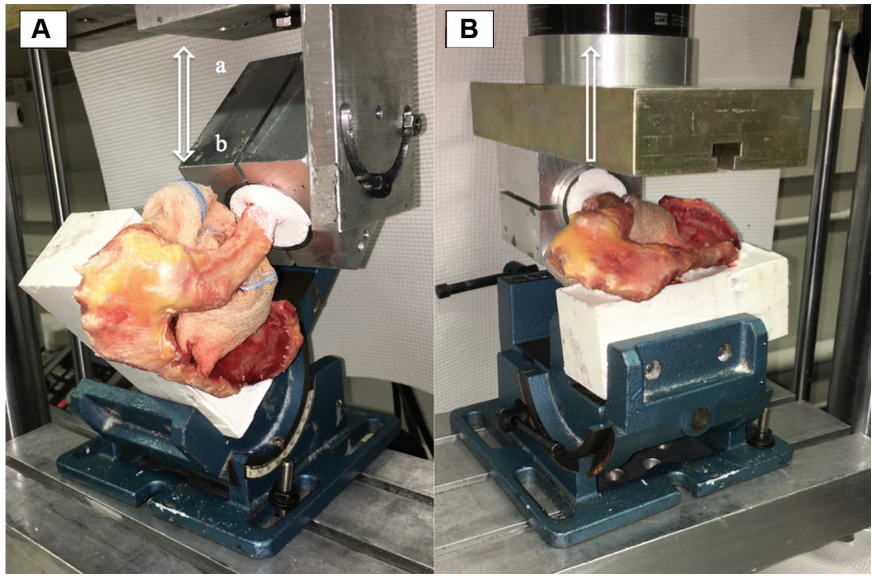

Figure 1. Intact potted left specimen set in the MTS servo-hydraulic testing system. (A) The specimen was set with the anterior edge of the distal clavicle parallel to the floor so that the scapula formed a 30° angle with the MTS base; anterior displacement was tested first by moving the actuator upward (*a*), and then posterior displacement was tested by moving the actuator downward (*b*). (B) Superior displacement was evaluated after setting the specimen with the glenoid surface perpendicular to the base, with the actuator moving upward.

surface of the distal clavicle was parallel to the base. The relative positions of the acromion and the clavicle were adjusted to reproduce the anatomic features through visual assessment and palpation; once anatomic positioning was achieved, the MTS machine was tared and both clamps were securely tightened.

An optical marker tracking system (Metria Innovation Inc) was used to assess 3D displacements during testing, to more directly assess changes in the AC joint space during loading (ie, accuracy of 1/2500 of the measurement distance[27]; in this experiment, the camera was positioned 0.5 m away from the markers, yielding a 0.2-mm accuracy). Each specimen received 2 markers, 1 marker on the clavicle side and 1 marker on the scapula side. The markers were fixed to the resin blocks, and not directly to the bones, to avoid the inevitable weakening of the specimen that would be caused by the insertion of posts for mounting the markers. This was deemed acceptable considering that the bending of the bony structures was previously demonstrated to be negligible with loads less than 70 N.[4] One digitizing camera along with built-in software measured the 3D position and orientation of each marker, with automatic calculation of 3D displacements of one marker over the other.

Intact specimens were first tested to assess their physiological laxity in all 3 directions. The AC and CC ligaments were then excised, and one shoulder of each pair was randomly assigned to a reconstruction group (ie, TB or WD), while the contralateral shoulder received the other reconstruction. Specimens were tested again after reconstruction, with the same translational testing and an additional load-to-failure testing in the superior direction.

Surgical Reconstructions

The TB group received an anatomic triple-bundle reconstruction, using the SCT and the CAL as grafts to replace the CC and AC ligaments, respectively (Figure 2).

The lateral part of the conjoint tendon was used for the CC ligament reconstruction. The anterior and superficial layer of the SCT (ie, tendinous layer) was isolated from the muscle fibers that were sharply dissected away, to obtain a 12-mm (width) × 80-mm (length) tendinous band pedicled proximally onto the lateral part of the coracoid tip.[35] In a preliminary anatomic study, these dimensions were determined to be sufficient for the reconstruction.[22] This lateral SCT band was then divided longitudinally into two 6 mm–wide strips, and each of them was prepared with a No. 2 suture (FiberWire; Arthrex) in a Krackow fashion. Two 4-mm tunnels were drilled in the distal clavicle at the insertion sites of the CC ligaments. Based on the anatomic study by Rios and colleagues,[31] the medial tunnel was drilled 35 mm medial to the lateral edge of the clavicle, in the posterior half of the clavicle; the lateral tunnel was drilled 25 mm medial to the clavicle lateral edge, centered in the anteroposterior thickness of the clavicle. An additional 5-mm tunnel was created, centered through the coracoid base. The 2 SCT strips were then flipped below the coracoid process, shuttled throughout its base, blocked with a 4-mm (diameter) × 10-mm (length) tenodesis screw (Bio-Tenodesis Screw; Arthrex), and then separated with one strip inserted into each clavicular tunnel. Regarding the AC bundle reconstruction, the distal 10 mm of the clavicle was resected. Two 1.6-mm holes were drilled into the superior cortex of

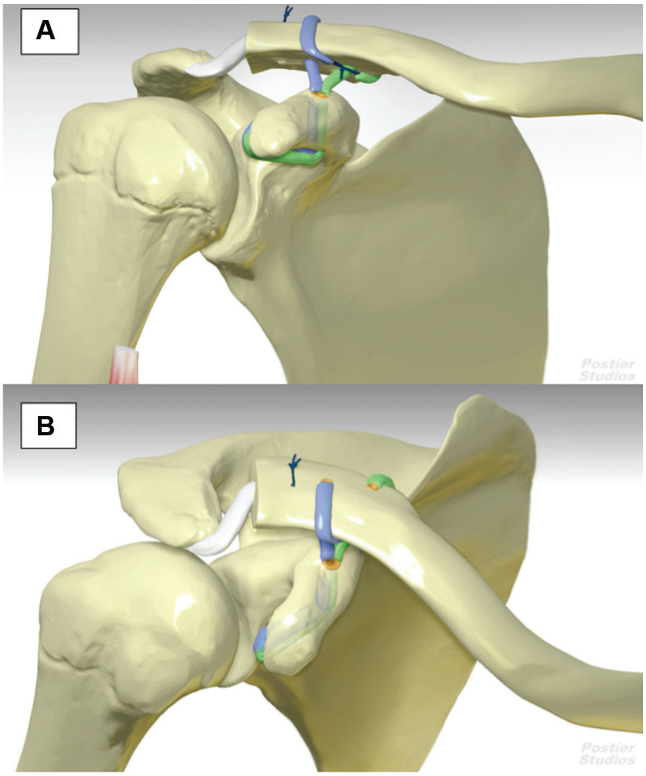

Figure 2. Drawings representing (A) anterior and (B) antero-superior views of the anatomic triple-bundle reconstruction of the right acromioclavicular joint ligamentous complex, with 2 semiconjoint tendon strips, one medial (green) and one lateral (blue), used to reconstruct the conoid and trapezoid coracoclavicular ligaments, respectively, while the coracoacromial ligament (white) was used to reconstruct the acromioclavicular ligaments.

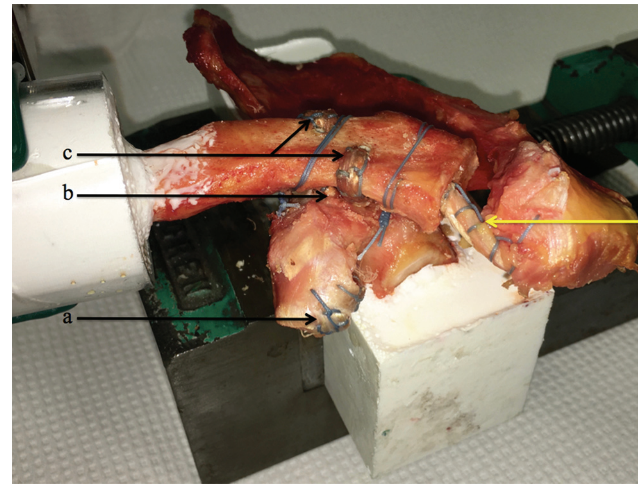

Figure 3. Dissection of the left shoulder showing the triple-bundle reconstruction of the acromioclavicular joint, with two 6-mm strips of semiconjoint tendon (black arrows) flipped inferiorly and posteriorly under the coracoid process (*a*), passed through the coracoid base and exiting centered on its superior surface (*b*), and finally passed through 2 clavicular tunnels (*c*) corresponding to the insertion site area of the conoid (medial) and trapezoid (lateral) coracoclavicular ligaments. In addition, the coracoacromial ligament (yellow arrow) was detached from the coracoid and transferred intramedullarily into the distal clavicle shaft.

the clavicle through the medullary canal, 10 mm from the distal end and with a 10 mm–wide bone bridge preserved between the 2 holes. The CAL was detached from the lateral aspect of the coracoid process and retained on the acromion. The CAL free end was then prepared with a No. 2 suture in a Krackow fashion and transferred to the remaining distal clavicle, with the two free ends of the suture passed into the drill holes. The clavicle was then reduced to be flush with the acromion, with adequate tension on the construct. Both SCT strips were secured into their respective clavicular tunnels with 4 × 10–mm tenodesis screws, and the CAL suture ends were tied together over the distal clavicle (Figure 3).

The WD group received a WD reconstruction with Zooker's modification (Figure 4).[45]

The distal clavicle preparation was the same as previously described for the TB group. Retained onto the coracoid tip, the CAL was detached from the acromion to be transferred into the medulla of the remaining distal clavicle; a Krackow stitch was used to weave a No. 2 suture through the CAL, the ends of which were passed through the drill holes in the distal clavicle. A double-button device (TightRope; Arthrex) was then used to augment the WD sutures. Once the clavicle was placed in a reduced position (ie, superior surfaces of the distal clavicle and anterior acromion brought together flush), a 2.4-mm pin was used to drill through the distal clavicle and the coracoid base starting 20 mm from the edge of the distal clavicle excision (ie, 30 mm from the native lateral edge of the clavicle). A 4-mm cannulated drill was then used to overdrill the guide pin. A suture passer was used to pass the oblong button through the clavicle and the coracoid, to be reoriented and stabilized under the coracoid base while the round button was applied on the superior aspect of the distal clavicle. Both the clavicular and coracoid buttons' orientations were verified before tensioning the device. Tightening of the reconstruction started with the adjustable loop of the double-button device and was completed with the sutures of the WD, using the same landmarks as in the TB reconstruction to obtain satisfactory tensioning (Figure 5).

Biomechanical Protocol

To evaluate the laxity of the native joints and of the reconstruction techniques, translational testing of all specimens before and after reconstruction was performed in the anterior, posterior, and superior directions. Preconditioning was performed by cycling the AC joint between 0 and 25 N over 10 cycles; the specimens were then loaded to an amplitude of 70 N over 1000 cycles at a frequency of 1 Hz. Displacement at peak force was documented at 1 and 1000 cycles. At the conclusion of cyclic testing, reconstructed joints were loaded

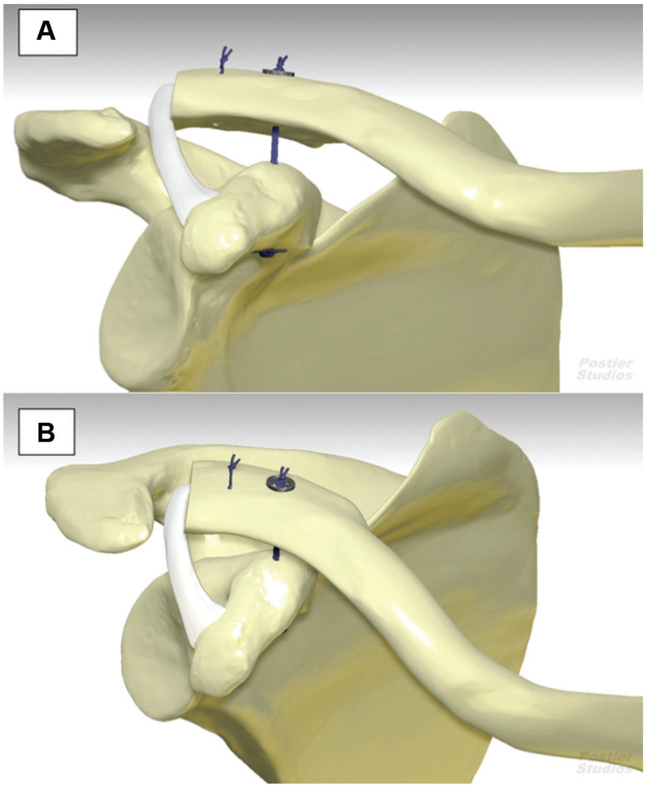

Figure 4. Drawings showing (A) anterior and (B) anterosuperior views of the Weaver-Dunn reconstruction of the right acromioclavicular joint ligamentous complex, with the TightRope augmentation.

to failure in the superior direction at a constant distraction rate of 1 mm/s to assess the maximal tensile loading capacity and the displacement to failure of each technique; the corresponding stiffness was calculated from the slope of the linear region of the force-displacement curve. Failure was defined as construct breakage with interruption of the linear progression of the slope of the force-displacement curve. Data analysis was conducted with a custom MatLab algorithm (MathWorks).

Statistical Analysis

An a priori power analysis showed that a sample size of 6 specimens in each group could detect differences in means that were 1.8 SDs or larger, with 80% power and 95% confidence. An analysis of variance was performed to compare mean values of the intact and reconstructed groups; Tukey honestly significant difference test was applied if significant differences were identified. Anterior, posterior, and superior displacement means were compared at 1 cycle of loading and at 1000 cycles of loading. Mean ultimate tensile load, displacement to failure, and stiffness were compared after 1000 cycles of loading. Results were presented as mean ± SD. The level of significance was defined as $P < .05$ for all tests.

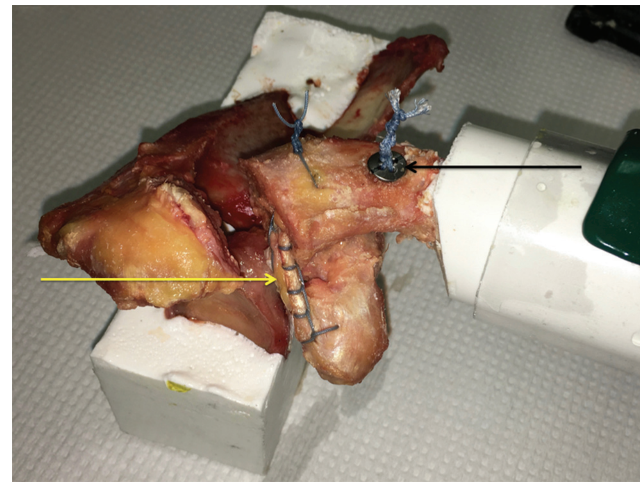

Figure 5. Dissection of the right shoulder showing a modified Weaver-Dunn reconstruction augmented with the TightRope device (black arrow), with the coracoacromial ligament (yellow arrow) detached distally, reinforced with a No. 2 FiberWire suture, and transferred intramedullarily into the distal clavicle shaft.

RESULTS

Translational Testing

After 1 loading cycle, significant differences were noted in mean anterior, posterior, and superior displacement (P = .0029, P = .0276, and $P < .001$, respectively). After 1000 loading cycles, significant differences were noted in mean anterior and posterior displacement but not superior displacement (P = .011, P = .024, and P = .065, respectively). Post hoc testing showed that mean joint displacement of both the TB and WD groups was not significantly different before and after the reconstructions in either the anterior, posterior, or superior directions after cyclic loading (Table 1).

The comparison between the 2 repair groups demonstrated significantly smaller displacements after cyclic loading in the anterior and posterior directions after the TB reconstruction (P = .011 and P = .014, respectively); no significant difference was observed in the superior direction between the 2 constructs.

Load-to-Failure Testing

TB reconstructions had significantly greater displacement to failure than WD reconstructions (P = .037, Table 2). However, no significant difference was found in the ultimate tensile load or stiffness between the 2 constructs. The modes of failure of the TB reconstruction entailed rupture of the SCT strips in the CC interval in 4 specimens, pullout of the coracoid screw in 1 specimen, and coracoid fracture in 1 specimen. In the WD group, 5 specimens failed because the oblong button of the adjustable loop pulled through the coracoid, and 1 specimen failed due to suture breakage of the loop; failures of the CAL transfer

TABLE 1
Translational Testing[a]

Directions of Displacement	TB Group			WD Group			TB vs WD		
	Intact	TB	*P* Value	Intact	WD	*P* Value	TB	WD	*P* Value
Anterior displacement, mm									
Preloading	3.11 ± 1.16	1.09 ± 0.18	.004	2.08 ± 0.68	2.87 ± 1.09	.419	1.09 ± 0.18	2.87 ± 1.09	.010
Postloading	4.71 ± 2.08	2.80 ± 0.87	.076	3.65 ± 0.77	5.39 ± 0.94	.119	2.80 ± 0.87	5.39 ± 0.94	.011
Posterior displacement, mm									
Preloading	8.30 ± 4.80	3.14 ± 2.44	.243	6.32 ± 3.35	11.83 ± 6.69	.196	3.14 ± 2.44	11.83 ± 6.69	.019
Postloading	9.14 ± 4.65	3.84 ± 2.50	.316	7.99 ± 4.85	14.01 ± 7.49	.218	3.84 ± 2.50	14.01 ± 7.49	.014
Superior displacement, mm									
Preloading	2.60 ± 0.54	0.80 ± 0.30	.005	2.64 ± 1.37	1.04 ± 0.67	.014	0.80 ± 0.30	1.04 ± 0.67	.967
Postloading	3.84 ± 1.42	2.65 ± 2.34	.568	3.25 ± 1.40	1.33 ± 0.60	.178	2.65 ± 2.34	1.33 ± 0.60	.477

[a]Mean postloading posterior displacements after triple-bundle (TB) anatomic repair were less than in the intact state or after modified Weaver-Dunn (WD) repair; mean postloading superior displacements after WD reconstruction were less than in the intact state. All data are reported as mean ± SD. Displacement values were recorded after 1 cycle (ie, preloading) and after 1000 cycles (ie, postloading); comparisons were made before and after reconstruction for each specimen and then between reconstructions for each pair of shoulders.

TABLE 2
Load-to-Failure Testing[a]

	TB	WD	*P* Value
Ultimate tensile load, N	472 ± 123	516 ± 371	.787
Displacement to failure, mm	10.47 ± 4.6	5.13 ± 2.32	.037
Stiffness, N/mm	85.05 ± 23.56	144.71 ± 86.02	.155

[a]Mean displacement to failure was greater after triple-bundle (TB) reconstruction (which entailed triple-bundle anatomic repair, using the semiconjoint tendon and the coracoacromial ligament) than after Weaver-Dunn (WD) reconstruction (which entailed modified WD repair with TightRope augmentation). All data are presented as mean ± SD.

occurred after the double-button device failure in all cases and were not considered since the load value was inferior to the coracoid failures or suture breakage.

DISCUSSION

In this study, we described a reconstructive technique to address chronic cases of AC joint separations by using onsite grafts (ie, SCT and CAL) to reconstruct the CC and the AC ligaments, respectively, and compared its biomechanical properties with a modified WD technique augmented with a double-button device. Translational testing demonstrated significantly less mean displacement in the TB group in the anterior and posterior directions, but no significant difference was observed in the superior direction. Load-to-failure testing in the superior direction demonstrated greater displacement to failure in the TB group; no significant differences were noted between the 2 constructs in terms of ultimate tensile load and stiffness.

To enhance the weak initial fixation that the CAL provides in the WD reconstruction, numerous augmentation techniques have been proposed to act as an additional and stronger link between the coracoid process and the distal clavicle during the biological healing of the CAL. The most commonly reported method is a cerclage with suture or tape, but other augmentations such as screws and suture anchors have also been described.[10,15,16,29] More recently, Zooker and colleagues[45] reported on the biomechanical properties of the double-button augmentation method, which demonstrated greater stability over tape cerclage in both the superoinferior and anteroposterior directions. Additionally, the investigators compared translations between intact and reconstructed specimens, demonstrating a better superior stability after WD reconstruction with double-button augmentation than in the intact group, with a mean translation similar to our findings (ie, 2.1 ± 0.1 mm of translation after 2000 cycles). Zooker and colleagues[45] also reported greater horizontal stability in the intact group than after reconstruction, with similar translation as well. They concluded that the double-button augmentation failed to maintain normal anteroposterior translation after cyclic loading compared with native AC joint ligamentous complex.[45] By providing a vertical link between the inferior surface of the clavicle and the superior aspect of the coracoid base, double-button fixation may be the augmentation method that most accurately reproduces the anatomic features of the native CC ligaments. However, since no repair of the AC complex is attempted in the WD reconstruction, greater anteroposterior translations seem inevitable.[13]

Motta et al[30] highlighted the potential consequence of an increased anteroposterior laxity of the TightRope device in acute cases. In 4 patients with joint hyperlaxity and high-grade acute AC joint separations treated with a single double-button device, the authors described a nontraumatic, painless, complete recurrence of the shoulder deformity without any signs of implant migration on radiographs but with a trapezoid-shaped resorption of the clavicular tunnel. The authors concluded that the lack of anteroposterior stability was responsible for a windshield-wiper effect of the double-button sutures against the sharp edges of the bone tunnels, which produced shear abrasive forces accounting for these early failures. Facing similar complications with the use of a single device, Scheibel et al[33] switched to the double TightRope technique in acute cases, which seemed to prevent such shortcomings.

In chronic cases, when double-button fixation was used to augment the CAL transfer, Boileau and colleagues[6] did not report any loss of reduction in their original study of 10 patients. One patient's outcome was particularly noteworthy, considering that a lateral migration of the coracoid button was noted 6 months after surgery on follow-up radiographs, which Boileau et al[6] considered to be a coracoid monocortical fracture. Since no loss of reduction was reported, this supports the hypothesis that satisfactory biomechanical properties may be obtained after biological healing of the CAL transfer. However, since the authors did not perform comparative dynamic imaging, the accuracy of their postoperative assessment of the AC joint's horizontal and vertical stability may be limited.[36,37] More recently, Kocaoglu and colleagues[20] conducted a comparative study involving the WD technique with a double-button augmentation only (ie, TightRope device; Arthrex) and a single-bundle anatomic repair of the CC ligaments using palmaris longus graft inserted in another double-button device (GraftRope; Arthrex). Better clinical outcomes were reported with the anatomic reconstruction, with a greater vertical stability ascertained on anteroposterior comparative stress views; however, no axillary comparative stress views were available, and thus it was not possible to compare the horizontal stability of the 2 techniques.[37]

First described by Vargas[40] in 1942, the short head of the biceps is another local autograft that may be used to stabilize chronic AC joint dislocation. In his original report, Vargas[40] left the tendon proximally attached to the coracoid tip, flipped it superiorly and posteriorly, and sutured the tendon to itself after passing it through a single tunnel drilled in the distal clavicle. Different modifications have hitherto been proposed, such as the intramedullary fixation of the distal end of the tendon into the clavicle shaft, as recommended by Jiang et al,[17] or the arthroscopic approach described by Kany and colleagues.[18] Kim et al[19] transferred both SCT and CAL distal ends to the conoid and trapezoid tuberosities, respectively, advocating for an anatomic double-bundle reconstruction.

With constructs similar to the WD reconstruction, none of these previous techniques seem to accurately reconstruct the anatomic lines of action of the native CC ligaments; subsequently, unsatisfactory biomechanical outcomes could be expected.[35] In fact, the CC ligaments are tightened between the superior surface of the coracoid base and the inferior aspect of the distal clavicle.[31] In our study, the coracoid tunnel constrained the SCT to mimic closely the lines of action of the native CC ligaments, thus providing similar translational restraints to the distal clavicle as demonstrated herein. In a preliminary anatomic study that we conducted in 12 paired cadaveric shoulders, the SCT graft was found to be long enough in all specimens to reconstruct both CC ligaments in such a fashion, with a mean excess length of 39.9 ± 5.7 mm (range, 32.2-47 mm) medially and 37.6 ± 5 mm (range, 31-45.1 mm) laterally.[22] These findings were confirmed during the present study, since the reconstruction could be performed in all cases. In addition, with the SCT restoring the CC complex, the CAL may be used to reconstruct the AC ligamentous complex, with its proximal end detached from the coracoid tip to be transferred posteriorly to the distal clavicle. In the present TB technique, the resection of the distal end of the clavicle is mandatory to perform the CAL transfer. Since Beitzel et al[5] demonstrated that such resection led to increased horizontal translation, this may appear as a limitation when compared with the TB reconstruction described by Tauber and colleagues.[38] However, no significant differences were found in the TB group between the intact state and after the reconstruction in the anterior and posterior directions (Table 1). This appears to confirm the conclusion from Beitzel et al,[5] who stated that "if [a violation of the AC capsule is] indicated in AC joint dislocations, a reconstruction of the AC joint capsule should be considered." In contrast to the original WD technique, this new line of action of the transferred CAL seems to achieve a satisfactory horizontal stabilization of the distal clavicle, as previously demonstrated by Shu et al.[34] Moreover, as reported by Lafosse et al[21] for the CAL and by Kany et al[18] for the SCT, both grafts may be harvested arthroscopically to decrease the morbidity of the technique. However, Kany et al[18] described a 3 cm–long graft harvest, whereas a longer graft was needed in the present study (ie, 8 cm); such harvest may be technically challenging with the use of an arthroscope, and its feasibility remains to be demonstrated.

Despite adequate biomechanical properties, 2 potential drawbacks of this technique need to be addressed. The contribution of the CAL to static glenohumeral stability has been well established, and sectioning it may alter kinematics of the glenohumeral joint[9]; however, no functional consequences of such harvesting have been outlined, except in cases with major alterations of the dynamic glenohumeral stabilizers.[12,44] Regarding the conjoint tendon, only the lateral part needs to be harvested to obtain an adequate length to reconstruct the CC ligaments without any significant damage to the underlying neuromuscular structure. With a cautious and sharp retrograde elevation of the superficial layer of the tendon, the biceps integrity is preserved since muscle fibers are retained on its deep layer; likewise, the musculocutaneous nerve runs deep into the muscle belly, and such a superficial dissection is thus safe. This recommendation has been confirmed clinically in several studies using this graft, openly and arthroscopically; in fact, no author seems to have encountered any substantial shortcoming such as biceps impairment or musculocutaneous nerve injury.[17-19,40]

The present study and its findings should be considered in light of its inherent limitations. This cadaveric model does not allow testing of the postoperative biological healing that can be expected in patients, which subsequently limits the relevance of our conclusions to the primary stability of the reconstruction. Further, most of our specimens were issued from elderly donors with poor bone quality, which limited our experiments and their interpretability. For economic reasons, bone density testing could not be conducted in our specimens to accurately identify osteopenia, but experimental evidence of such condition was outlined. In a pilot study of 2 pairs of shoulders, we encountered 3 coracoid fractures during load-to-failure testing of the native ligaments; furthermore, the coracoid-related failure rate was unusually high compared with similar studies, especially in the WD group.[4,26,45] The protocol was consequently modified and the load to failure was performed only after reconstruction, which precluded any comparison with the ultimate tensile load of the native AC joints. In addition, optical markers were not positioned directly on the bony structures but were placed on the resin blocks to avoid any additional weakening of the specimens. Since the markers were positioned in similar fashion in all of our specimens, we considered that alterations of translational measurements at the AC joint space, if any, were similar in all specimens. Moreover, based on the report from Beitzel et al,[4] measurement variations due to bending of bony structure may be considered negligible. The small sample size is another shortcoming of the present study. Comparisons of means for some parameters (ie, joint displacements before and after reconstructions, ultimate tensile loads and subfailure stiffness of each construct) may be subject to statistical type II errors, putting their validity into question. However, such a small sample was sufficient to demonstrate that the TB reconstruction can provide adequate horizontal and vertical stability to the AC joint and that this construct was superior to the WD technique in terms of horizontal stability. Finally, translational testing and load-to-failure testing as conducted herein are broadly used protocols, allowing for clarity and comparability of outcomes. However, considering that the AC joint contributes to multiple shoulder motions and is thus subjected to forces in variable directions, such testing hardly reflects the in vivo conditions of this joint.

CONCLUSION

A triple-bundle anatomic reconstruction of the AC joint is feasible by combining the SCT and the CAL to reconstruct the CC and AC ligaments, respectively. When compared with native AC joints, the AC joints with TB repair demonstrated satisfactory stability in all directions (ie, anterior, posterior, and superior). Furthermore, smaller horizontal translations were observed in comparison with the WD reconstruction augmented with a double-button device.

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