

Biomechanical Evaluation of a Novel Reverse Coracoacromial Ligament Reconstruction for Acromioclavicular Joint Separation

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Background: Enhancing anterior-posterior (AP) stability in acromioclavicular (AC) reconstruction may be advantageous.

Purpose: To compare the initial stability of AC reconstructions with and without augmentation by either (1) a novel “reverse” coracoacromial (CA) ligament transfer or (2) an intramedullary AC tendon graft.

Hypothesis: Reverse CA transfer will improve AP stability compared with isolated coracoclavicular (CC) reconstruction.

Study Design: Controlled laboratory study.

Methods: Six matched pairs of cadaveric shoulders underwent distal clavicle resection and CC reconstruction. Displacement (mm) was measured during cyclic loading along AP (± 25 N) and superior-inferior (SI; 10-N compression, 70-N tension) axes. Pairs were randomized to receive each augmentation and the same loading protocol applied.

Results: Reverse CA transfer (3.71 ± 1.3 mm, standard error of the mean [SEM]; $P = .03$) and intramedullary graft (3.41 ± 1.1 mm; $P = .03$) decreased AP translation compared with CC reconstruction alone. The SI displacement did not differ. Equivalence tests suggest no difference between augmentations in AP or SI restraint.

Conclusion: Addition of either reverse CA transfer or intramedullary graft demonstrates improved AP restraint and provides similar SI stability compared with isolated CC reconstruction.

Clinical Relevance: Reverse CA ligament transfer may be a reasonable alternative to a free tendon graft to augment AP restraint in AC reconstruction.

Keywords: acromioclavicular reconstruction; coracoclavicular reconstruction; acromioclavicular separation; Weaver-Dunn

Acromioclavicular (AC) separation is very common in the active population and accounts for more than 40% of all shoulder injuries in athletes.^{17,21,28,31,34} Reconstructive options for chronic, symptomatic high-grade injuries, particularly in athletes and laborers, continue to be employed and debated. Even when AC joint reconstruction is distinctly indicated, there is no obvious consensus in technique, and an evolving understanding of the AC joint has

given rise to a multitude of described procedures and biomechanical studies.

The goal of AC joint reconstruction is to closely approximate natural AC ligament geometry and biomechanical function. This requires the reconstruction to adequately reduce the joint, provide superior-inferior (SI) and anterior-posterior (AP) translational restraint similar to an intact state, reduce or eliminate pain, and possibly prevent or delay joint posttraumatic and degenerative arthritis.³¹ An important consideration is also to diminish complications directly related to surgical intervention, including hardware failure, fracture, infection, and aseptic foreign body or allograft reaction.^{11,12,32} Two recent reports in the literature highlight fracture and suture breakage as not infrequent problems and cite between 20% and 40% complications after use of newer techniques.^{27,30}

Coracoclavicular (CC) reconstruction alone may not be sufficient to adequately stabilize the AC joint in the AP plane.^{7,8,15,19} The purpose of this study was to evaluate a novel technique used to improve AP stability with minimal morbidity in the surgical management of AC joint separation.

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We hypothesized that a reverse coracoacromial (CA) ligament transfer will improve AP stability compared with isolated CC reconstruction and comparably with a previously described intramedullary AC free tendon loop technique.

MATERIALS AND METHODS

Specimens

Six matched pairs of fresh-frozen human cadaveric shoulders (average age, 79 years; range, 63-94 years; 3 male and 3 female) were disarticulated at the glenoid and sternoclavicular joint. All specimens were inspected for intact AC joints and supporting ligaments. Scapulae and clavicles were dissected free of all overlying soft tissue and muscle, leaving the AC capsule, CA ligament, and CC ligament intact. To address future application of this technique, the CA ligament was measured and recorded for each specimen with a standard ruler. Over the course of experimentation, saline was periodically applied to specimens to prevent desiccation.

All scapulae were potted in aluminum boxes up to the level of the inferior glenoid using set screws and polymethyl methacrylate (PMMA) bone cement to lock scapular translational and rotational movement. Scapulae were visually aligned and potted in an orientation such that the AC joint axis was set perpendicular to the potting box, ensuring that mechanical testing would closely mimic physiological biomechanics with anatomic AP and SI loading (Figure 1). Clavicles were potted proximally starting 80 mm medial to the conoid ligament attachment site on the clavicle. Clavicles were potted in 1.25-inch (31.75 mm) polyvinyl chloride (PVC) pipe using 3 set screws and PMMA bone cement to secure bones against longitudinal, rotational, and bending movement.

Porcine tendons were harvested from the flexor tendons of fresh-frozen posterior leg shanks for anatomic CC and AC graft reconstructions. The tendons were sized to 6 mm and pretensioned manually before use. These tendon segments were used to simulate biomechanical function of semitendinosus human grafts, as previously described.²⁵

Surgical Reconstruction

After potting, a 10-mm distal clavicle excision was performed with the AC joint capsule incised longitudinally and repaired with 3 figure-of-8 No. 2 FiberWire (Arthrex Inc, Naples, Florida) sutures. Each CC ligament was completely resected (both conoid and trapezoid) and reconstructed with a porcine free tendon loop around the clavicle and coracoid supplemented by a coracoid anchor (Figure 2). The anchor (Mitek SuperAnchor 2.9 mm, DePuy Mitek Inc, Raynham, Massachusetts) was double loaded with 2 sutures, No. 2 FiberTape (Arthrex Inc) and No. 2 OrthoCord (DePuy Orthopaedics Inc, Warsaw, Indiana), and then was placed at the anterior extent of the CC ligament complex origin on the coracoid. Two 1.5-mm drill holes approximating the anatomic insertions of the conoid and trapezoid attachments to the clavicle were made on the superior clavicle at least 15 mm apart in a manner consistent with Grutter and Petersen's description

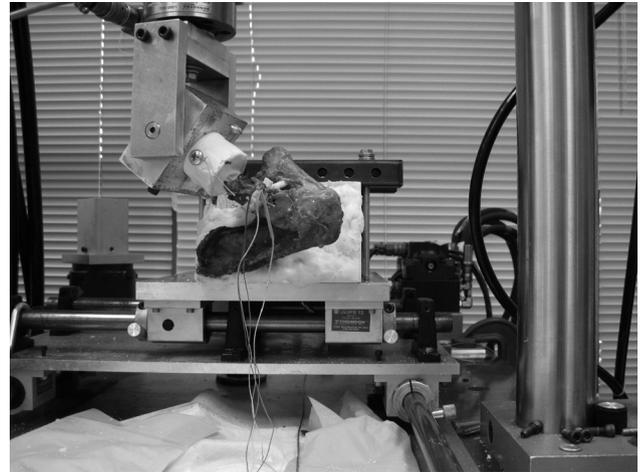


Figure 1. Setup of scapula and clavicle secured to the materials testing machine.

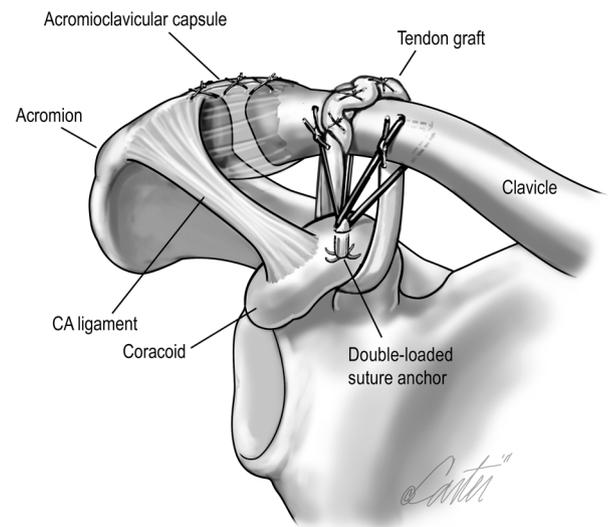


Figure 2. Isolated coracoclavicular reconstruction with double-loaded suture anchor and allograft augmentation.

for anatomic bone tunnels.¹⁴ The sutures were then tied over the anterior clavicle. A No. 2 FiberTape (Arthrex Inc) was used for the “conoid” and No. 2 OrthoCord suture (DePuy Orthopaedics Inc) for the “trapezoid” re-creation of CC ligament insertion sites on the clavicle. A 150-mm by 6-mm porcine tendon was then looped around the base of the coracoid, with the medial limb posterior and lateral limb anterior to the clavicle and secured with 3 figure-of-8 No. 2 FiberWire sutures (Arthrex Inc) in a Pulvertaft weave fashion.

After load-displacement testing (as described in Mechanical Testing Protocol below) following isolated CC reconstruction, matched pairs were randomized to a second treatment augmentation, receiving either reverse CA ligament transfer or intramedullary tendon graft (Figure 3). Contralateral shoulders received the other augmentation

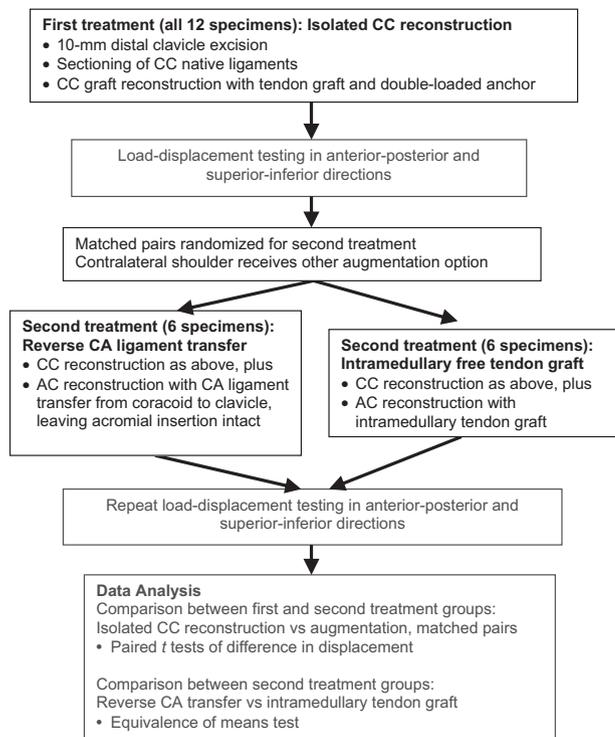


Figure 3. Flow diagram of experimental methods.

option. The initial CC reconstruction was maintained throughout the testing of the AC reconstruction.

For the reverse CA transfer group, the CA ligament was released from the coracoid and delivered to the distal clavicle, maintaining its attachment to the acromion. A No. 2 FiberWire suture (Arthrex Inc) was placed in a Krackow fashion in the coracoid side of the ligament and passed through two 1.5-mm transosseous drill holes in the distal clavicle at least 10 mm apart and 8 mm from the edge of the distal clavicle, and the sutures were secured over the distal clavicle bone bridge (Figure 4).

For the intramedullary group, we used Freedman et al's technique.^{9,24} Porcine tendons 50-mm long by 6-mm wide were looped and secured with No. 2 FiberTape Krackow sutures (Arthrex Inc), leaving one end of the suture tail longer. A loop of No. 5 Ethibond (Ethicon Inc, Somerville, New Jersey) was then placed through the tendon loop for future suture shuttling. The No. 5 Ethibond (Ethicon Inc) served as a suture passer for the No. 2 FiberTape suture (Arthrex Inc) through the graft and bone. The AC joint was prepared to receive the graft by drilling out 2 blind-ending, collinear, 15-mm-deep by 6-mm-wide intramedullary tunnels in the distal clavicle and acromion. Transosseous 1.5-mm holes were then drilled toward the blind tunnel ends from the most anterior and posterior aspects of the superior surfaces. The graft was pulled taut into the collinear tunnels. The No. 5 Ethibond (Ethicon Inc) was used to pull the long limb of No. 2 FiberTape (Arthrex Inc; from the clavicle side) into the opposite tunnel and through the tendon loop, allowing for the tape to be tied in a cruciate fashion across the superior aspect of the AC joint (Figure 5).

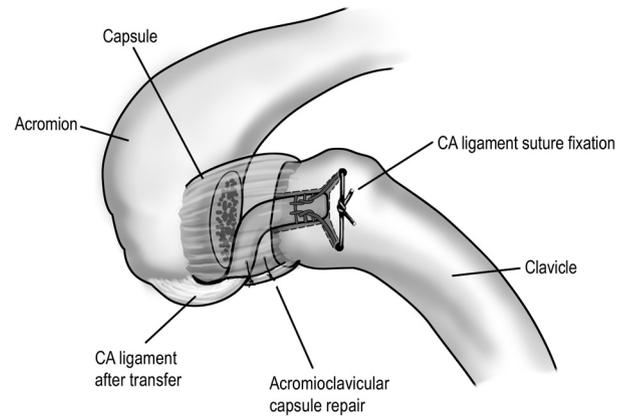


Figure 4. Acromioclavicular reconstruction with reverse coracoacromial ligament transfer from the coracoid to distal clavicle, keeping the acromial insertion intact.

Mechanical Testing Protocol

For load-displacement testing, specimens were mounted into a materials testing machine (MTS 858 Bionix, MTS Systems Corp, Eden Prairie, Minnesota), such that machine loading would be applied along the AP AC joint axis. The PVC potted end of the clavicle was secured into the loading ram of the MTS machine through a custom fixture, while the box in which the scapula was potted was secured horizontally (posterior surface of the scapula facing down) on a 2-axis moveable table.

After proper positioning was confirmed, all translational and rotational axes of both the clavicle and scapula were locked so that translation could only occur along the loading axis (vertical machine axis, AP joint axis). Each specimen was then loaded for 20 cycles in both the anterior and posterior directions. For each AP cycle, the scapula was held stationary, and the clavicle was displaced in both the anterior and posterior directions at a rate of 3.3 mm/s to 25-N end points. Displacement measurements were acquired at a rate of 51.2 Hz. The final cycle's maximum displacements were compared for similarity to preceding cycles and recorded as the displacement range for the trial.

After AP testing, without altering specimen setup, the loading ram was positioned and locked at zero load (anatomic joint position). Next, the SI axis of scapular motion (relative to the fixed clavicle) was unlocked so that the table on which the scapula box was mounted could move freely in the SI direction in response to load. The "zero" position of the scapula was recorded, and all subsequent displacement measurements were made with a dial indicator (model 3058 [0- to 50-mm range, 0.01-mm resolution], Mitutoyo, Kawasaki, Japan). Specimens were then loaded in the SI direction using a pulley system with fixed weights. Each specimen was first loaded by displacing the scapula in the superior direction using a load of 10 N to create compression across the joint. Subsequently, the scapula was loaded in the inferior direction, creating

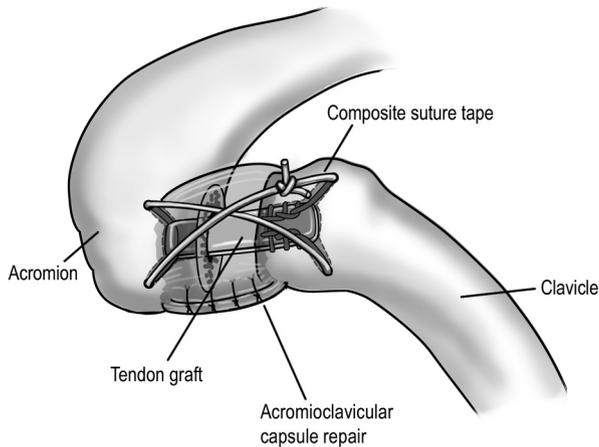


Figure 5. Acromioclavicular reconstruction with intramedullary free tendon graft.

tension across the joint, using a load of 70 N. These methods and loads are consistent with the manner described by Zooker et al.³⁵ A minimum of 3 loading cycles were completed to ensure proper equilibration of displacements. Maximum displacements were recorded within 3 to 5 seconds after each load was applied and displacement had reached equilibrium, while new neutral point readings were recorded after each load was removed to account for specimen creep. The maximum displacement range was calculated and recorded for each specimen. This protocol thus allowed for both AP and SI load-displacement testing of reconstructions without altering specimen positioning. Loading magnitudes and protocols were based on previously published protocols, which determined these magnitudes to be physiologically meaningful and within the elastic range for involved ligament structures.^{4,18,24,35}

Data Analysis

Data were analyzed with paired *t* tests and equivalence tests. Each specimen was tested after the first treatment of CC reconstruction with distal clavicle resection and AC capsular repair. Paired specimens were then retested after a second treatment of either reverse CA ligament transfer or intramedullary graft, with re-repair of the AC capsule (Figure 5). Therefore, each specimen served as its own control compared with isolated CC reconstruction. Statistically significant ($\alpha = .05$) changes in clavicle load displacement between first and second treatment groups for both augmentation methods were evaluated. Specifically, differences in displacement were compared with paired *t* tests.

A test of equivalence of means was used to evaluate whether the effects of the 2 augmentations were statistically equivalent ($\alpha = .05$), with an equivalence threshold of 5 mm.¹ Because of the small sample size and attendant concerns regarding parametric assumptions, nonparametric

bootstrap 90% confidence intervals were also calculated for AP and SI. Our hypothesis was that the improvement produced by the 2 augmentations would be equivalent in AP and SI load-displacement behavior.

RESULTS

After CC reconstruction alone, the average AC joint SI displacement was 6.19 ± 0.9 mm for the reverse CA group and 6.60 ± 0.3 mm for the intramedullary graft group. After AC augmentation, the average SI displacement was 4.79 ± 0.6 mm for the reverse CA group and 4.90 ± 0.7 mm for the intramedullary graft group. After CC reconstruction alone, the average AC joint AP displacement was 11.74 ± 2.4 mm for the reverse CA group and 11.28 ± 1.7 mm for the intramedullary graft group. After AC augmentation, the average AP displacement was 8.00 ± 1.7 mm for the reverse CA group and 7.85 ± 1.1 mm for the intramedullary graft group.

Paired *t* tests evaluating differences in displacement showed that reverse CA ligament transfer significantly improved AP stability compared with CC reconstruction alone (3.74 mm \pm 1.3 mm SEM; 95% confidence interval [CI], 0.46-7.01; $P = .033$). Intramedullary AC tendon graft augmentation also significantly decreased AP translation (3.43 mm \pm 1.1 mm; 95% CI, 0.52-6.35; $P = .029$) (Table 1, rows E and G).

The SI stability did not show a statistical difference between isolated CC reconstruction and augmentation with either reverse CA ligament transfer or intramedullary graft in this study, although a trend toward increased constraint was seen in both augmentation groups.

Using a clinically significant displacement value of 5 mm in all directions, a test of equivalence of means supports that there is no difference between reverse CA ligament transfer versus intramedullary tendon graft in AP or SI stabilizing effect ($\alpha = .05$; CI for AP difference, -1.46 to 0.85 ; CI for SI difference, -3.04 to 3.63). The non-parametric bootstrap CIs ($\alpha = .05$; AP difference, -1.17 to 0.54 ; SI difference, -2.85 to 2.34) confirmed this finding. That is, despite this study's small sample size, nonparametric and parametric tests yielded the same result: the difference in displacement between the 2 augmentation methods was less than 5 mm. Therefore, both second treatment groups displayed equivalent improvement to AP stabilization and equivalent equivocal improvement to SI stabilization (Table 2). The average measured CA ligament intact length was 30.2 mm \pm 2.6 mm SEM.

DISCUSSION

Before Bosworth³ published his 8-year results on temporary screw fixation of the clavicle to the coracoid in 1948, fascial suture, Kirschner wire fixation, and distal clavicle excision were commonly performed for complete AC dislocation. In 1972, Weaver and Dunn³³ described transfer of the acromial limb of the CA ligament to the distal clavicle. Soon, modification with synthetic tape or material between

TABLE 1
Comparison Between First and Second Treatment Groups' Difference in Displacement Using Paired *t* Tests^a

Row	Direction of Clavicular Displacement	Difference in Displacement (\pm SEM), mm	
		Reverse CA	Intramedullary Graft
E	Difference in AP displacement (row A-C)	3.74 \pm 1.3	3.43 \pm 1.1
F	Difference in SI displacement (row B-D)	1.40 \pm 1.1	1.69 \pm 0.7
P Value, Paired <i>t</i> Test			
G	Paired <i>t</i> test of AP difference (row E)	.033	.029
H	Paired <i>t</i> test of SI difference (row F)	.271	.058

^aSEM, standard error of the mean; AP, anterior-posterior; SI, superior-inferior; CA, coracoacromial.

TABLE 2
Comparison Between Second Treatment Groups, Reverse Coracoacromial Transfer Versus Intramedullary Tendon Graft, Using Equivalence Tests With a Clinically Significant Displacement Value of 5 mm

Row	Direction of Displacement	Equivalence Test: Confidence Interval for $\alpha = .05$		
		Equivalence of Means	Nonparametric Bootstrap	Equivalent at 5-mm Displacement?
I	Anterior-posterior (row E)	-1.46 to 0.85	-1.17 to 0.54	Yes
J	Superior-inferior (row F)	-3.04 to 3.63	-2.85 to 2.34	Yes

the coracoid and clavicle became common.²² Autogenous tendon graft as a salvage procedure was introduced by Jones et al¹⁶ in 2001, and various tendon reconstructions, including allograft, have become popular. Mazocca et al^{23,24} proposed anatomic reconstruction with bone tunnels for tendon graft in the coracoid and clavicle.

Biomechanical studies have analyzed the structure and function of the AC joint capsule, AC ligaments, and CC ligaments. By comparing clavicle-scapula force-displacement relationships in cadaveric specimens with intact and sectioned capsule and ligaments, researchers have demonstrated that the AC capsule and its reinforcing ligaments are the primary restraint along the AP axis and are also most important to joint stability in all directions at small loads.^{5-9,29} In contrast, the CC ligaments are the primary stabilizers to SI motion and compression-induced translations. The CC ligaments are most important at larger loads with greater displacement.^{5,6,8,9}

Interest in improving existing repair techniques has paralleled our understanding of ligament biomechanics, with recent focus on restoring AP constraint. The inability of the CC ligament, even when reconstructed, to fully compensate for the AC joint capsule and ligaments after AC capsule resection was highlighted by Debski et al.^{6,7,15} In addition, Blazar et al² reported a significant association between postoperative pain scores and increased AP range of motion of the distal clavicle following distal clavicle resection.

Existing dominant techniques have primarily concentrated on reconstruction of the CC ligaments with tendon graft, suture, flip button, or a combination of these to significantly restrain SI translation and joint malreduction superiorly. The CC reconstruction technique tested with

this study is the one employed by the senior author over the past decade to limit potential complications of suture implant cutout or fracture.

Graft and/or suture limbs that pass purposefully around the clavicle have been proposed to support AP constraint.³² Techniques that directly consider the AC ligaments and capsule are less common and include suturing the intact CA ligament up to reinforce direct repair of the AC ligaments, tendon graft passage from a CC reconstruction to the acromion and sutured over a bone bridge in the lateral acromion, AC banding with suture cord, and intramedullary AC free tendon graft.^{4,9,14,22} Deltotrapezial fascia closure has also long been considered paramount, as these muscles are important dynamic stabilizers.²²

Complications associated with bone tunnels and transosseous drill holes, use of anchors in the coracoid, suture and synthetic material fixation, and hardware have all been described.^{11,13,22,25-27,30,32} Early fracture can compromise the reconstruction entirely, possibly requiring reoperation, whereas even late fractures, which may be treated with activity restriction, may give rise to unacceptable symptoms and a poor result. In a small series of 7 anatomic CC reconstructions in which the tendon graft was placed through 2 clavicular bone tunnels, 3 patients had clavicular fracture as a complication.³² Clavicle and coracoid fracture secondary to synthetic fiber mesh cerclage loop has been described.³⁰ Suture button pulled through the coracoid, loss of reduction because of clavicular osteolysis under the superior button, as well as fracture through the coracoid and clavicle have also been published.^{11,27} A recent series of 20 suture button repairs reported 4 cases of loss of reduction because of rupture of the suture; the authors questioned if hyperlaxity may have increased

risk of failure.²⁷ In one biomechanical study, failure secondary to an inadequate-sized bone bridge was reported.²⁰ Fracture because of small transosseous drill holes was not identified by this author group but certainly may be an occult occurrence and affect AC joint reduction, and loss of reduction is still the most common complication.^{22,30,31}

Our technique directly addresses both the CC ligaments and AC ligaments by augmenting a standard CC tendon graft reconstruction with a novel reverse CA ligament transfer. We purposefully avoided transosseous tunnels and reduced the number of drill holes, excess allograft, and hardware. Our results show that addition of a reverse CA ligament transfer to a standard CC graft reconstruction significantly improved AP restraint compared with isolated CC reconstruction. The intramedullary tendon graft augmentation also significantly reduced AP motion. That is, both were superior to isolated CC reconstruction in constraining AP displacement. Comparing matched pairs using an equivalence of means test with an equivalence threshold of 5 mm confirms that the 2 augmentation methods were not different but the same; that is, they are comparable in improving AP restraint.¹

The SI stability did not show a statistical difference between isolated CC reconstruction and augmentation with either reverse CA ligament transfer or intramedullary graft in this study, although a trend toward increased constraint was seen in both augmentation groups. Equivalence of means testing shows no difference; that is, SI stability is comparable between reverse CA ligament and intramedullary graft groups.¹ Therefore, isolated CC, CC plus reverse CA transfer, and CC plus intramedullary tendon graft all performed equally well in providing SI constraint.

A clinically significant displacement value for the AC joint in each plane was not established. Five millimeters was chosen as the equivalence threshold instability in this study because it is measurable on clinical examination and there is support in the literature.^{2,8,10,18,35} Separate author groups have reported in clinical and biomechanical studies that the average laxity of a native intact joint in the AP direction is in the approximate range of 8.5 to 10.5 mm with a range of ± 1 to 3 mm and the SI laxity 3 to 5 mm with a range of 0.5 to 1.5 mm.^{2,8,10,18,35}

Specifically comparing our data with Freedman et al's findings is appropriate given the choice of utilizing their intramedullary tendon graft as the comparison to direct AC joint reconstruction augmentation.⁹ Although their average translational motion numbers were smaller across the board, this may be related to their use of smaller loads as required by their specialized testing setup. Overtightening compared with the intact state may also have been a concern for their technique, as exhibited by decreased translation after reconstruction compared with an intact state. We are unable to assess this in our study, as the intact state was not tested. However, when comparing our data with previously published biomechanical studies utilizing similar or greater loading protocols, our data are consistent with restoring the translational characteristics of the native AC joint.^{8,10,18,35}

An alternative technique of free graft intramedullary AC reconstruction using suture buttons was recently described by Gonzales-Lomas et al,¹³ which also showed improved AP restraint compared with CC reconstruction alone. Further investigation is needed to see how this technique compares to the reverse CA transfer described in our study.

In our protocol, a 10-mm distal clavicle resection was performed on all specimens, including the intramedullary graft reconstructions. This is in contrast to how Freedman et al described their technique.⁹ We believe that re-apposition of the AC joint without distal clavicle excision is often possible in the acute setting and is preferred by the senior author to enhance AC joint stability. In the subacute or chronic setting, however, distal clavicle excision is often implemented to limit symptoms of posttraumatic AC joint arthritis. In our study, we found that stabilization of the joint using the intramedullary graft technique with distal clavicle resection could still achieve excellent AP stability. Further, reverse CA ligament transfer achieved similar AP constraint with less suture material, smaller drill holes, and avoidance of additional allograft tissue.

For uniformity, in this study, 10 mm was resected for all specimens. The amount of AC capsule and ligaments remaining after careful resection did vary conspicuously as other investigators have previously described.^{4,27} Although capsular repair was part of our reconstruction technique, it was not a consistent repair because of the disparities in anatomy. This may account for a larger range among AP translation between specimen pairs. Because each specimen did serve as its own control and a limited re-repair of the capsule was performed after the second treatment, improvement of AP displacement achieving statistical significance confirms that the augmentation was responsible.

Our CC reconstruction technique differs from previous studies, utilizing a double-loaded suture anchor in the coracoid and 2 "anatomic" small drill holes in the clavicle, in addition to a free tendon graft around the coracoid and clavicle. It is possible that this could skew the control findings in comparison with previous studies. The senior author (T.R.M.) has successfully utilized this technique clinically for the past decade for 3 main reasons: First, static suture restraint limits early clinical stretch of the graft material before biological incorporation. Second, if the sutures were to cut out one or both drill holes in the clavicle, then it would cause an incomplete fracture (anterior half only), which would remain stable. Finally, the coracoid anchor limits the risk of coracoid fracture when the suture is passed around the entire coracoid. The anchor used in this study comes loaded with 2 No. 2 OrthoCord sutures (DePuy Orthopaedics Inc). We have routinely exchanged one of the OrthoCord sutures (DePuy Orthopaedics Inc) with a No. 2 FiberTape (Arthrex Inc) because it is stronger and broader. The eyelet size of this particular anchor device makes it difficult to double load with 2 No. 2 FiberTapes (Arthrex Inc), and so only one OrthoCord (DePuy Orthopaedics Inc) is exchanged, which still allows smooth sliding of the suture material.

Other limitations of this study include no testing of the intact state, elderly age of specimens, and as with all cadaveric studies, the ability to test only immediate

stability without the possible benefits of dynamic stabilizers or tendon graft healing.

CONCLUSION

The AP stability is a concern that needs to be addressed in CC reconstruction of the shoulder. This cadaveric study describes a novel reverse CA ligament transfer that demonstrates improved AP stability compared with isolated CC reconstruction and comparable with the intramedullary tendon allograft technique. Benefits of the reverse CA ligament transfer may be decreased graft burden, suture tape bulk, and small drill holes with less structural violation of the AC joint.

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