Cyclical Loading of Coracoclavicular Ligament Reconstructions

A Comparative Biomechanical Study

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Background: Reconstruction for injuries to the acromioclavicular joint remains controversial.

Hypothesis: A coracoclavicular ligament reconstruction with a semitendinosus tendon would have superior performance to the classic coracoacromial ligament transfer with or without augmentation.

Study Design: Controlled laboratory study.

Methods: Five cadaveric shoulders were used to reconstruct the coracoclavicular ligaments with 3 methods: coracoacromial ligament transfer without augmentation, coracoacromial ligament transfer augmented with No. 5 Ethibond suture, and a semitendinosus tendon. Each reconstruction was cyclically loaded at 40 N to 80 N for 2500 cycles, then from 40 N to 210 N for 2500 cycles, followed by loading to failure. The number of cycles to 50% and 100% loss of acromioclavicular joint reduction were recorded.

Results: During the 40 N to 80 N–loading cycle, the coracoacromial transfer without augmentation failed (15 ± 16 cycles). The augmented coracoacromial ligament transfer and the semitendinosus reconstruction did not fail (P = .008). During the 40 N to 210 N–loading cycle, the augmented coracoacromial ligament transfer failed (207 ± 399 cycles). The semitendinosus reconstruction survived through both loading cycles (P < .01).

Conclusion: Coracoclavicular ligament reconstruction with a semitendinosus graft is a biomechanically superior construct in a cyclically loaded setting to a coracoacromial ligament transfer augmented with a No. 5 Ethibond suture.

Clinical Relevance: The semitendinosus graft is a strong, biologic option for reconstruction of the coracoclavicular ligaments.

Keywords: acromioclavicular joint; coracoacromial ligament transfer; semitendinosus graft

Injury to the acromioclavicular joint is a common problem, with an incidence of 3 to 4 out of 100 000 in the general population. Young men are most commonly affected, and 25% to 52% of these injuries occur during sporting activities.[‖] Injury to the acromioclavicular joint can occur directly or indirectly. Classically, a direct blow to the shoulder with the arm adducted causes injury initially to the acromioclavicular ligaments, then to the coracoclavicular ligaments and deltotrapezial fascia, leading to subluxation or dislocation of the acromioclavicular joint. In an indirect injury, a fall onto an outstretched arm leads to superior displacement of the humerus into the acromion causing injury primarily to the acromioclavicular ligaments as the coracoclavicular ligaments are relaxed.[48]

In grade I and II injuries, the coracoclavicular ligaments remain intact and are typically treated nonoperatively. Most authors advocate surgical treatment for grade IV, V, and VI injuries as residual symptoms (chronic pain, stiffness, decreased range of motion, decreased abduction strength) are common after nonoperative treatment of these more severe injuries.[18,39,47] Treatment of grade III injuries

[‖]References 1, 11, 13, 16, 21, 39, 42, 43, 54.

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remains controversial. Surgery has been advocated acutely in overhead laborers or throwing athletes, or in those who are symptomatic after nonoperative treatment.[¶]

The optimal treatment protocol remains controversial.[#] Surgical treatment centers on restoring vertical stability to the acromioclavicular joint by repairing or reconstructing the injured coracoclavicular ligaments. In repair of the coracoclavicular ligaments, various techniques such as K-wires, plates, screws, sutures, tapes, or suture anchors hold the acromioclavicular joint in a reduced position while the coracoclavicular ligaments heal.** These techniques rely on the assumption that the ligaments will not only heal but will heal with the same biomechanical properties as the native ligaments. Instead of relying on the native ligaments to heal, other authors have described various techniques of reconstructing the coracoclavicular ligaments with a local tissue source.[††] However, many authors have questioned the strength of these reconstructions and recommend augmention with other fixation devices.[14,27,30,39,48,53,67] More recently, several authors have described techniques using tendon grafts to reconstruct the coracoclavicular ligaments.[16,24,34,38]

Despite the numerous techniques, no one method has emerged in the literature as the gold standard. Several authors have conducted biomechanical studies in an attempt to determine the best repair.[16,19,29,33,45] Lee et al[38] demonstrated semitendinosus reconstructions to have superior tensile strength compared with many commonly used methods of augmentation and showed biomechanical properties similar to native coracoclavicular ligaments. However, these studies focused on a single pull to tensile failure. The performance of these grafts when subjected to repetitive loading remains unanswered. The objective of this study is to compare the performance of 3 different coracoclavicular ligament reconstructions subjected to cyclical physiologic loads in a human cadaveric model.

MATERIALS AND METHODS

Five fresh-frozen human whole cadaveric shoulders (4 male, 1 female) whose ages ranged from 42 to 58 years (average, 52) were thoroughly thawed and dissected. Four left shoulders and 1 right shoulder were used. Only the coracoacromial ligament, the clavicle, and the scapula were preserved. The acromioclavicular and coracoclavicular ligaments were sectioned in each specimen with sharp dissection. Specimens were kept moist with normal saline throughout the experiment.

The clavicle and scapula were connected to a materials testing machine (MTS Systems Corporation, Eden Prairie, Minnesota) via a customized fixation system and potting technique used in an earlier article from our institution.[38] The clavicle was secured to a 4.5-mm dynamic compression plate (Synthes, Paoli, Pennsylvania) with nuts, bolts, and washers through 2 drill holes. The MTS clamp was then secured to the middle of the plate using another set of bolts, nuts, and washers. The scapula was secured to the MTS machine with four 5.0-mm Schanz screws (Synthes): 2 into the scapular spine and 2 into the glenoid subchondral bone. Polymethyl methacrylate was then used to coat each of the Schanz screws to ensure that no movement occurred at the screw-bone interface. The Schanz screws were connected via standard external fixation connecting bars (Synthes), and the MTS clamp was secured onto the connecting bar (Figure 1). This setup provided rigid fixation of the clavicle and scapula to the MTS machine and prevented all other displacements except for the direct superior displacement of the clavicle on the scapula.

All 3 reconstructions were performed on the same cadavers in the following order: coracoacromial ligament transfer with augmentation, coracoacromial ligament transfer without augmentation, and a semitendinosus allograft without augmentation. The coracoacromial ligament transfer was performed as described by Weaver and Dunn.[66] The coracoacromial ligament was released from its insertion on the undersurface of the acromion and transferred to the intramedullary canal of the clavicle. A Bunnell-type weave with a No. 2 Ethibond (Ethicon Inc, Johnson & Johnson, Somerville, New Jersey) was used to secure the coracoacromial ligament to the clavicle through two 1.6-mm drill holes in the superior cortex.

Augmentation of the coracoacromial ligament transfer was performed with a No. 5 Ethibond suture. A 4.0-mm drill hole was made in the anterior third of the clavicle at the level of native coracoclavicular ligament insertion. The suture was then passed through the drill hole, around the base of the coracoid, and tied to itself with the acromioclavicular joint in a reduced position (Figure 2). After the augmented coracoacromial ligament transfer was tested, the coracoacromial ligament transfer without augmentation was performed by placing another No. 2 Ethibond suture into the nonstressed portion of the coracoacromial ligament.

Five semitendinosus hamstring grafts were harvested from 5 separate fresh-frozen human cadaveric legs (5 males) whose ages ranged from 45 to 62 years. All tendon grafts were kept moist in saline at room temperature and were pretensioned for 5 minutes to minimize stress relaxation. The tendon grafts were looped around the coracoid, and the medial end was placed from inferior to superior through the 4.0-mm drill hole in the anterior third of the clavicle near the native insertion of the coracoclavicular ligaments. (Figure 3). The free ends of the graft were then secured on the lateral side of the coracoid by tying the tendon ends in a double surgical knot and by using supplemental side-to-side No. 0 Ethibond suture (Ethicon Inc) on the knot (Figure 4). Again, the acromioclavicular joint was held reduced while the knot was secured and reinforced.

The reconstructions were cyclically loaded at 2 different ranges of forces until failure. The first loading cycle ranged from 40 N to 80 N for 2500 cycles. If the graft maintained reduction of the acromioclavicular joint at these loads, the graft was then subjected to the second loading cycle, with loads ranging from 40 N to 210 N for 2500 cycles. For each

¶References 3, 6, 17, 20, 25, 32, 37, 51, 52, 59.
#References 2, 3, 17, 25, 31, 37, 41, 49, 50, 59, 62, 64.
**References 4, 7, 8, 11, 12, 26, 28, 40, 44, 58, 60.
††References 5, 9, 10, 23, 35, 36, 46, 55, 56, 63, 65, 66.

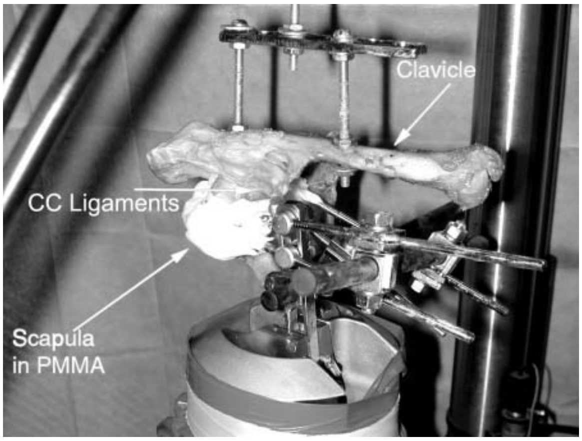

Figure 1. Set-up of clavicle and scapula secured to MTS machine.

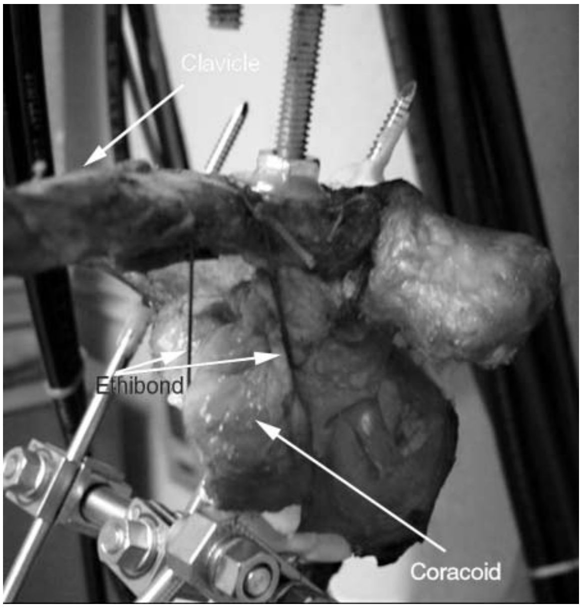

Figure 2. Coracoacromial ligament transfer with No. 5 Ethibond augmentation.

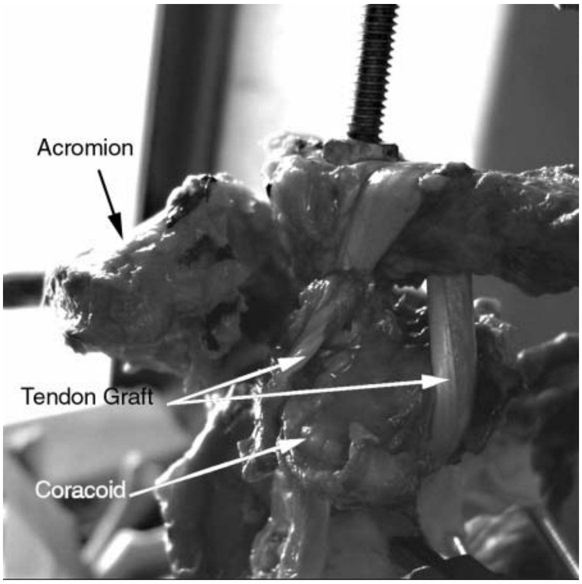

Figure 3. Semitendinosus tendon graft reconstruction.

of these 2 testing cycles, the MTS was programmed to finish each cycle in 1 second. Finally, if the reconstruction survived the second loading cycle, the reconstruction was loaded to failure at a ramp rate of 25 mm/min.

The 40 N to 80 N range was selected to represent load seen by the coracoclavicular ligaments due to the weight of the arm. In a preliminary study (S.J. Lee et al, unpublished data, 2004), an in vivo tensiometer was used to measure forces in the coracoclavicular ligament in 6 patients with arm hanging at the side in a beach-chair position. The highest loads were seen in extension, with a high of 80 N in one patient. The load with the arm hanging due to gravity was markedly lower with a high of 40 N in one patient. The second loading cycle was based on the use of the No. 5 Ethibond (Ethicon Inc) suture for augmentation of the coracoacromial transfer. In the study by Lee et al,[38] the tensile load to failure for this commonly used suture was 280 N. We wanted to evaluate whether this suture could withstand 75% of its reported maximal tensile load applied in a cyclical fashion. Thus, our second range used was 40 N to 210 N. Finally, 2500 cycles was selected based on 5000 steps (2500 strides) per day for an average sedentary or postoperative patient assuming that the arm swings into extension in normal gait.[61]

Failure was defined by the loss of reduction of the acromioclavicular joint by measuring the acromion with calipers (Scienceware Venier Direct Reading Calipers model H13415-0000; Bel-Art Products, Pequannock, New Jersey). Partial failure was defined as 50% displacement of the clavicle relative to the acromion. Complete failure was defined as 100% displacement of the clavicle relative to the acromion—or complete loss of reduction. The number of cycles at which partial and complete failure occurred was recorded for each loading cycle. Differences between the 3 techniques were assessed by comparing the number of cycles to partial (50% displacement of the clavicle) and complete (100% displacement) failure using the Mann-Whitney test. An alpha level of .05 was assumed to be statistically significant.

RESULTS

Coracoacromial Ligament Transfer Without Augmentation

All coracoacromial ligament transfers without augmentation failed during the 40 N to 80 N–loading cycle. Partial

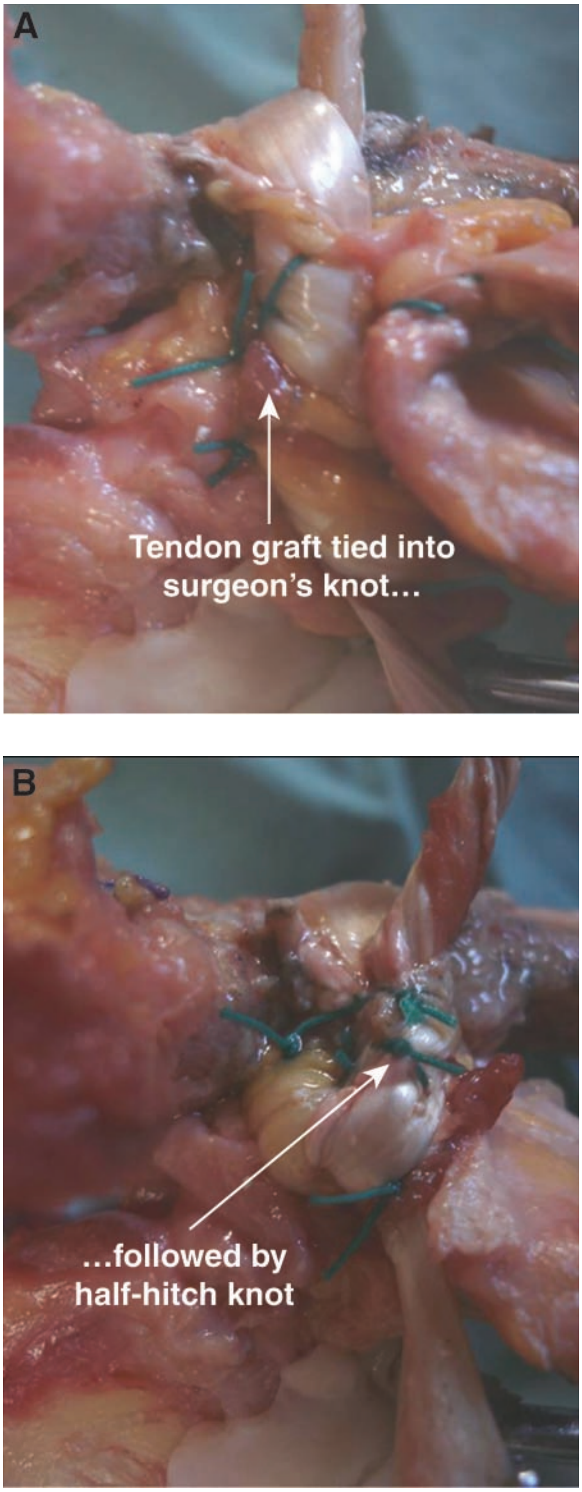

Figure 4. A, tendon graft tied in surgeons knot. B, knot held by sutures.

failure occurred at 4 ± 1 cycles (range, 2-5), and complete failure occurred at 16 ± 15 cycles (range, 6-40). Mode of failure appeared to be from suture pull through the coracoacromial ligament.

TABLE 1
Cycles to Failure, 40-80 N[a]

	With Augment	Without Augment	Semi-tendinosus	*P* Value
50%	DNF	4 ± 1	DNF	.008
100%	DNF	16 ± 15	DNF	.008

[a]DNF, did not fail.

TABLE 2
Cycles to Failure, 40-210 N[a]

	With Augment	Semitendinosus	*P* Value
50%	8 ± 5	DNF	<.01
100%	207 ± 399	DNF	<.01

[a]DNF, did not fail.

Coracoacromial Ligament Transfer With Augmentation

None of the coracoacromial ligament transfers that were augmented with No. 5 Ethibond suture (Ethicon Inc) achieved partial or complete failure during the 40 N to 80 N–loading cycle. However, during the 40 N to 210 N–loading cycle, all the reconstructions failed. Partial failure occurred at 8 ± 5 cycles (range, 4-12) into the second loading cycle, and complete failure occurred at 207 ± 399 cycles (range, 10-920). Mode of failure appeared to be plastic deformation of the No. 5 Ethibond augmentation suture combined with minor suture pull through the coracoacromial ligament.

Semitendinosus

None of semitendinosus reconstructions had partial or complete failure at either the 40 N to 80 N–loading cycle or the 40 N to 210 N–loading cycle. All reconstructions were thus loaded to tensile failure. Mean tensile failure occurred at 523 N ± 28 N. In all cases, the mode of failure was bony (1 failure through the drill hole, 3 failures at the interface of the hardware to clavicle, 1 coracoid fracture).

Comparison

At loads simulating the weight of the arm during normal walking for one day (40-80 N), the coracoacromial transfer with augmentation and the semitendinosus reconstructions all survived. However, the coracoacromial ligament transfer without augmentation failed. These differences were statistically significant (P = .008). At higher loads (40-210 N), the coracoacromial ligament transfer with augmentation had partial failure at 8 ± 5 cycles and complete failure at 207 ± 399 cycles. The semitendinosus reconstruction did not fail (P < .01) (Tables 1 and 2).

DISCUSSION

More than 60 different surgical procedures have been described for the treatment of acromioclavicular joint injury. These surgical treatments can be separated into 2 basic groups. In the first group, the acromioclavicular joint is held reduced while the coracoclavicular ligaments heal. Various types of fixation have been described, including K-wires, plates, screws, sutures, tapes, and suture anchors, with varying degrees of clinical success.[‡‡] However, many of these fixation devices have been associated with complications.[§§] The long-term success of these procedures for acute injuries relies on the assumption that the torn soft tissues will heal with the same biomechanical characteristics as the preinjury state. For chronic injuries, the likelihood of the torn, native coracoclavicular injuries to heal is significantly diminished. As a result, many authors believe it is more appropriate to reconstruct the coracoclavicular ligaments using various methods for chronic and even acute injuries.[‖‖] The most popular method of reconstruction is the coracoacromial ligament transfer from the acromion to the clavicle, as described by Weaver and Dunn.[10,35,46,66]

However, many studies have shown that the tensile strength of this reconstruction is significantly weaker than the native coracoclavicular ligaments.[19,29,38] As a result, authors have described performing coracoacromial ligament transfers augmented with another fixation device to increase the tensile strength of the construct.[14,27,30,53,67] However, given the weakness of the coracoacromial ligament transfer, the ultimate success of these reconstructions still in part relies on the ability of the native ligaments to heal. Recently, tendon reconstructions of the coracoacromial ligaments have been described with the hope of offering a purely biologic reconstruction of the native ligaments that has biomechanical characteristics comparable to the native ligaments.[16,34,38]

Several biomechanical studies have been performed to evaluate the tensile-loading characteristics of the native ligaments as well as various repairs and reconstructions. Jari et al[33] showed that coracoclavicular slings and coracoacromial ligament transfers did not reproduce the stability provided by the native ligaments, while the coracoclavicular screw fixation screw created a construct that was too rigid and led to increased stresses across the acromioclavicular joint. Motamedi et al[45] showed that the commonly used braided polydioxanone suture (PDS) (Ethicon Inc) is as strong but not as stiff as the native coracoclavicular ligaments, leaving concern that the repair will stretch out and not maintain acromioclavicular joint reduction. Other studies have shown that repairs using PDS may not hold the acromioclavicular joint over time. Harris et al[29] similarly reported that coracoclavicular slings and suture anchors provide similar strength to the native ligaments but have significantly greater deformation before failure than the native ligaments, again leading to loss of reduction. Harris also showed the lack of strength of the coracoacromial ligament transfer and recommended such transfers be augmented with another form of fixation.[29] Lee et al[38] reported that semitendinosus reconstructions had a similar strength to the native ligaments and were stronger than many commonly used methods of augmentation.

However, the ideal reconstruction needs to provide enough strength as well as stiffness to maintain acromioclavicular joint reduction in a shoulder that is subjected to repetitive loads. Deshmukh et al[19] compared the performance of Weaver-Dunn reconstructions with and without augmentation to the native ligaments in a cyclic setting. The authors determined that the augmented Weaver-Dunn reconstructions offered superior tensile strength and had less superior laxity (278-369 N and 6.5-9.0 mm) than the nonaugmented Weaver-Dunn reconstructions (177 ± 9 N and 13.6 ± 4 mm). However, none of the augmented reconstructions matched the ability of the native ligaments in resisting superior displacement.[19]

Costic et al[15,16] compared the ability of the native ligaments and reconstructions using the semitendinosus to withstand cyclical loads. The authors found that the reconstructions performed just as well as the native ligaments in maintaining acromioclavicular joint reduction. However, the authors also showed that the stiffness and ultimate load of the native coracoclavicular ligament complex (60.8 ± 12.2 N/mm and 560 ± 206 N) were significantly greater than reconstructed complex (23.4 ± 5.2 N/mm and 406 ± 40 N). Importantly, the authors documented a 40% decrease in bending stiffness of the clavicle itself after a simulated injury, which may have limited the biomechanical properties of the reconstructed complex.[15,16] To date, no study exists comparing the ability of different coracoclavicular reconstructions to hold the acromioclavicular joint reduced in a cyclically loaded environment.

In our study, we evaluated 3 different reconstructions at cyclical loads. In a preliminary study (S.J. Lee et al, unpublished data, 2004), we determined that the native ligaments see a stress of 40 N to 80 N due to the weight of the arm at varying arm positions. Therefore, we loaded each of the 3 reconstructions at 40 N to 80 N to mimic physiologic conditions during gait. Both the coracoacromial ligament transfer augmented with No. 5 Ethibond (Ethicon Inc) and the semitendinosus reconstructions survived. However, the coracoacromial ligament transfer without augmentation failed at 16 ± 15 cycles ($P < .008$).

Other biomechanical studies have examined the strength of isolated transfer of the coracoacromial ligament. One study showed that the tensile properties of the ligament decrease from 312 N to 145 N after transfer. Other studies support this number.[19,29,38] However, in our study, when cyclically loaded, the coracoacromial ligament transfer failed at much smaller loads, suggesting that repetitive loading caused rapid failure of the reconstruction.

In our second trial, the reconstructions were loaded at 40 to 210 N. The augmented coracoacromial transfer failed at 207 ± 399 cycles, whereas the semitendinosus reconstruction did not fail ($P < .01$). Other studies have shown that the No. 5 Ethibond suture will survive a single tensile pull at these loads.[38] However, when cyclically loaded, this augmentation technique did not survive. However, the semitendinosus

[‡‡]References 2, 3, 7, 25, 27, 28, 30, 41, 44, 49.
[§§]References 3, 7, 12, 25, 30, 37, 40, 57, 60.
[‖‖]References 5, 9, 10, 25, 35, 36, 46, 55, 56, 63, 65, 66.

reconstruction withstood these forces, suggesting superior performance to the coracoacromial transfer with augmentation in a cyclically loaded environment.

Finally, all tendon reconstructions were loaded to failure. The average load to failure was 523 ± 28 N. In the study by Lee et al,[38] the pullout tensile strength of the tendon reconstructions was 610 ± 160 N. Thus, the cyclically loaded environment decreased the ultimate tensile strength by 16% after 5000 cycles. Costic et al[16] showed a tensile failure of 406 ± 60 N for the tendon reconstructions after loading the reconstruction for 100 cycles at 20 to 60 N and 100 cycles at 20 to 90 N. However, they also demonstrated a 40% decrease in bending stiffness of the clavicle after a simulated dislocation, which they hypothesized accounted for the decrease in magnitude of tensile failure. In our experiment, the bones were not subjected to a simulated dislocation, which may account for our higher reported tensile strengths.

The use of semitendinosus reconstructions of the coracoclavicular ligaments has several potential advantages. First and foremost, it is a strong repair. Prior studies show that the semitendinosus tendon graft reconstructions have pullout strengths comparable to the native ligaments.[16,38] Furthermore, if both the native ligaments and reconstruction healed in the acute injuries, the overall strength could potentially be additive, offering a coracoclavicular ligament complex that is stronger than the original. In the current study, we showed this reconstruction to hold up to stresses 2 to 3 times that of the weight of the arm stressed under cyclically loaded conditions. Finally, the potential for more aggressive rehabilitation programs exist, allowing earlier return to play. However, such protocols need to be evaluated in a more critical fashion.

Second, it offers a biologic reconstruction for the injured ligaments and the success of the surgery does not depend on the ability of the native ligaments to heal. A biologic tendon reconstruction may be particularly appropriate in the setting of chronic dislocations. It seems reasonable that if the ligaments are not repaired acutely, the ligaments may retract and have less healing potential. Some authors have documented equal results in chronic versus acute injury using reconstruction with coracoacromial ligament transfer.[22] However, Weinstein et al[67] found only a 77% success rate in chronic dislocations versus a 96% success rate for acute dislocations (<3 weeks) despite the use of coracoacromial ligament transfer with augmentation. These data imply that in the chronic setting, native ligaments are less likely to heal, and even a biologic reconstruction with coracoaromial ligament transfer does not produce equal results to the acute setting. It may be that this increased failure rate is due to inadequacy of the coracoacromial reconstruction. Use of a tendon reconstruction may therefore be more appropriate in chronic injuries to the acromioclavicular joint.

The procedure also has several potential disadvantages. If an autograft is selected, donor site morbidity can occur, and a potential graft source for other injuries is expended. If an allograft is selected, disease transmission and infection can become issues.

The strength of this study is that it is the only biomechanical study that compares different methods of coracoclavicular reconstructions in a cyclically loaded setting. Costic et al[16] showed that tendon reconstructions held reduction of the acromioclavicular joint as well as the native ligaments. Our study demonstrates that this reconstruction outperforms 2 commonly used reconstructions in a cyclically loaded setting. Our study also demonstrates that cyclical loading changes the ultimate strength of the grafts used, and grafts should be used that have a large safety factor.

The study has several limitations. First, it is cadaveric, so any dynamic stability provided to the acromioclavicular joint or possible additional forces caused by muscle contraction could not be evaluated. Second, the ligaments were simply cut with sharp dissection, and no traumatic injury occurred. It is unknown what effect a traumatic injury has on the biomechanics of the bony structures but, in the study by Costic et al,[16] a 40% change in the biomechanical properties of the bony structures occurred when the mechanism of injury was simulated. Third, only vertical unidirectional loads were assessed. The performance of these grafts subjected to multidirectional forces remains unknown. Fourth, changes in mechanical properties of the tendon over time remain unknown. The effect of revascularization on its biomechanical properties is unknown. Fifth, cyclical loads were only simulated for 1 full day. The tensile properties decreased 16% for the grafts. It remains unknown what happens during longer loading intervals. Sixth, only one method of augmentation was tested. Countless other methods, including fiber wire, suture anchors, tapes, and braided suture, have been described. However, the main purpose was to establish the strength of a purely biologic reconstruction in a cyclically loaded environment, not to find the strongest tensile construct. Finally, our method of estimating the load seen during gait is based purely on passive measurements, not taking into account possible additional forces due to muscle contraction.

The testing of the cadaveric specimens was repeated on the same shoulders for the coracoacromial ligament transfer alone and with augmentation. Because most surgeons perform this procedure with augmentation, the augmented group was performed first in each specimen to give us the most clinically relevant data. Much of the perceived failure occurred through the Ethibond augmentation suture, although some failure also occurred with suture pullthrough the coracoacromial ligament. When the next trial of coracoacromial ligament transfer without augmentation was performed, the suture was placed into a different portion of the ligament that appeared to be minimally affected by the previous testing.

CONCLUSION

Coracoclavicular ligament reconstruction with a semitendinosus graft offers a biologic method of reconstruction with cyclic-loading characteristics that are superior to currently used techniques. Its strength has been previously shown to be comparable to native ligaments.[38] Also, it does not require use of the coracoacromial ligaments, allowing it to maintain its function as a humeral head stabilizer. Ultimately, it does not rely on the native ligaments to heal for success. It may allow the elimination of postoperative slings and promote earlier, more aggressive rehabilitation and an earlier return to play. However, the effect of time on its biologic and biomechanical properties is largely unknown. Further basic science and clinical studies are needed to assess its role in the treatment of acromioclavicular joint injury.

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