Methods to reconstruct the coracoclavicular ligaments anatomically have been described. No clear advantage of 1 technique has been elucidated. The authors’ hypothesis was that the biomechanical properties of a modified knot fixation technique would be similar to the anatomical double-bundle technique. Sixteen matched cadaveric shoulders were used for this study, and 1 additional shoulder was used in the knot fixation group only. Shoulders were randomly assigned to the anatomical double-bundle coracoclavicular ligament reconstruction technique (n = 8) or a knot fixation technique (n = 9). The intact coracoclavicular ligaments were tested to failure with superior displacement at a rate of 2 mm/s. Reconstruction was performed using a semitendinosus tendon allograft, and load to failure was repeated for each construct. Ultimate failure load, stiffness, and failure mode were compared using a paired t test (P < .05). No significant difference existed in load to failure between native and reconstructed ligaments or between reconstruction techniques. Stiffness decreased significantly after reconstruction in the double-bundle group (from 32.5 to 22.5 N/mm; P = .035) and in the modified knot fixation group (from 35.5 to 21.9 N/mm; P = .043). No significant difference existed in stiffness between the 2 reconstruction groups. A significant difference (P = .003) existed between failure modes between the 2 reconstruction techniques. Although less stiff than the native ligament, either technique used to reconstruct the coracoclavicular ligament can be performed to yield a load to failure similar to the intact ligament. The majority of failures in the double-bundle group were by means of the graft slipping at the screw-tendon interface at 1 of the clavicular drill holes. The modified knot fixation technique failed the majority of the time by graft elongation.
Injury to the acromioclavicular joint may account for as many as 40% of all shoulder injuries. Dislocations of the acromioclavicular joint comprise 12% of all dislocations of the shoulder girdle and 8% of all dislocations. These injuries are 8 times more common in men than in women, with the highest prevalence in those younger than 35 years. The static stabilizers of the acromioclavicular joint consist of the acromioclavicular ligaments, coracoclavicular ligaments, and coracoacromial ligament. The acromioclavicular ligaments are the primary restraint of the distal clavicle to anteroposterior translation, with the superior ligament having greater contribution than the inferior ligament. The coracoclavicular ligaments are the primary restraint to superoinferior translation, where anatomically the trapezoid ligament is anterior and lateral to the conoid ligament.

Multiple surgical techniques have been described for the treatment of complete acromioclavicular joint dislocations. These include primary repair of the ligaments, hardware spanning the joint, ligament or muscle transfers, coracoclavicular ligament augmentation with synthetic suture or tape, and coracoclavicular ligament reconstruction with autograft or allograft. No gold standard treatment has been established. However, a trend exists toward fixation that recreates anatomic placement of the coracoclavicular ligament, with the idea that this technique may more closely mimic the native state and decrease recurrent instability.

The strength and stiffness of the repair at time zero is 1 aspect to consider when determining which type of repair to choose. The purpose of the current study was to compare the biomechanical properties of the anatomical double-bundle coracoclavicular ligament reconstruction to a knot fixation technique using matched semitendinosus tendon allografts through anatomically placed drill holes in the clavicle. These techniques were chosen to compare only the fixation and not the tendon placement.

Materials and Methods

An a priori power analysis using peak load as the primary outcome established a minimum sample size of 8 per group with $\alpha = 0.05$ and 0.8 power. Sixteen matched fresh frozen cadaveric shoulders (4 female, 4 male) were used for this study, and 1 additional shoulder (female) was used in the knot fixation group only. The matched pair to the additional shoulder sustained a fracture to the coracoid during initial testing described below and could not be repaired. The additional shoulder was only used to compare the intact to the repaired. Average age of the specimens was 61.6 years (range, 49-80 years) in the knot fixation group and 64.8 years (range, 49-80 years) in the double-bundle group.

Specimens were thawed approximately 24 to 36 hours prior to testing. Prior to testing, soft tissue was dissected free from the scapula and clavicle, leaving the coracoclavicular ligaments intact. The scapula was secured in a rectangular aluminum pot using polyester resin material (Bondo; 3M, St Paul, Minnesota) and rigidly fixed to the table of a materials testing machine (Model 8500; Instron, Norwood, Massachusetts). During initial practice trials, rigidly fixing the clavicle and testing load to failure created a high occurrence of clavicle fracture, which did not allow accurate testing of the procedure. Therefore, a 15-mm piece of webbing was looped around the clavicle between the coracoclavicular ligament drill hole and rigidly attached to the crosshead of the materials testing machine. The material used had a stiffness of 255 N/mm, minimizing any effect of the material on the values reported.

The specimens were loaded to failure after the acromioclavicular ligament was manually resected. The specimens were preconditioned for 10 cycles at 25 N in the superoinferior plane to eliminate creep. This was followed by load-to-failure testing in the superior direction at 2 mm/s. Failure was defined as 2 cm of displacement, which is approximately the amount of displacement of a grade 3 acromioclavicular separation.

Ultimate load and displacement were recorded using software provided by the manufacturer of the materials testing machine. Stiffness was calculated using the linear portion of the load displacement curve. One specimen sustained a coracoid fracture during this phase of testing and was eliminated from the study because it could not be repaired.

One shoulder in each matched pair was subsequently randomly assigned to an anatomical coracoclavicular ligament reconstruction using either (1) a modified version of the anatomical double-bundle coracoclavicular ligament reconstruction technique described by Mazzocca et al (n=8) or (2) a modified version of the knot fixation technique described by Lee et al (n=9). Identical bone tunnels were made to directly compare only the fixation techniques. Paired semitendinosus allografts were obtained from 5 male and 3 female donors, and 1 from each pair was used for one of the techniques in paired shoulders. One additional allograft was used in the knot fixation group from a male donor. One allograft was randomly assigned to 1 of the 2 techniques. Grafts were 6 mm × 22 cm. Average age of the graft specimens was 43 years (range, 19-65 years) in group 1 and 43.8 years in group 2 (range, 19-65 years).

Modified Anatomical Double-bundle Coracoclavicular Ligament Reconstruction

A semitendinosus allograft was prepared and secured with #2 FiberWire (Arthrex, Inc, Naples, Florida). Clavicular bone tunnels were then drilled in anatomic positions. For the conoid ligament, a 6-mm transosseous tunnel was made 45 mm medial to the distal end of the clavicle in the posterior one-half. For the trapezoid ligament, a 6-mm transosseous tunnel was placed in the central axis of the clavicle, 15 mm lateral to the center of the conoid tunnel. The graft was then looped around the coracoid base in a sling technique. The graft ends were brought through the clavicular drill holes. The acromioclavicular joint was then brought into the clavicle through a subcoracoid approach, with the coracoid performing the role of the conoid ligament. The clavicle was then rigidly fixed to the table of the materials testing machine (Model 8500; Instron, Norwood, Massachusetts) using a 15-mm piece of webbing looped around the clavicle and rigidly attached to the crosshead of the materials testing machine. The material used had a stiffness of 255 N/mm, minimizing any effect of the material on the values reported.

The specimens were loaded to failure after the acromioclavicular ligament was manually resected. The specimens were preconditioned for 10 cycles at 25 N in the superoinferior plane to eliminate creep. This was followed by load-to-failure testing in the superior direction at 2 mm/s. Failure was defined as 2 cm of displacement, which is approximately the amount of displacement of a grade 3 acromioclavicular separation.
was overreduced inferiorly by 2 mm, and 5.5×15-mm bioabsorbable interference screws (Arthrex, Inc) were used for graft fixation. The graft was cut flush with the clavicle after screw fixation (Figure 1).

**Modified Knot Fixation**

A semitendinosus allograft was fashioned in the same manner as the previous technique. Drill holes were placed in the clavicle in the same anatomic positions, representing the conoid and trapezoid ligament insertions as previously stated. The free ends of the graft were then brought through the drill holes inferiorly. The acromioclavicular was overreduced by 2 mm, and the tendon graft was secured on the lateral side of the coracoid by tying the ends into a double surgical knot and supplementing with side-to-side sutures on the knot using #2 FiberWire (Figure 2).

**Bone Mineral Density**

Bone mineral density was measured for each specimen with a micro-computed tomography (µCT) system (VivaCT 40; Scanco Medical AG, Brüttisellen, Switzerland). A sample was taken from the humeral head and the glenoid and scanned using a voltage of 70 kVp and a current of 114 uA at 10 µm resolution. A cylindrical volume of interest was selected, and the bone mineral density was determined using software from the manufacturer.

**Statistical Analysis**

The specimens were preconditioned and load to failure was then repeated for each reconstructed specimen as described above. Failure modes were noted and compared using the Fisher exact test ($P<.05$). Ultimate failure load, stiffness, and failure mode were recorded for each specimen and compared using a paired $t$ test ($P<.05$). Failure was defined at 2 cm of superior displacement of the clavicle, which approximates a grade 3 acromioclavicular separation, as used in a previous study.¹⁰

**RESULTS**

A significant difference ($P=.003$) existed between failure modes between the 2 coracoclavicular ligament reconstruction techniques tested. The majority (7 of 8) of the repairs in the double-bundle group failed at the screw-tendon interface when the tendon slipped through a clavicular drill hole (Figure 3). In 1 specimen, the graft elongated 2 cm. The majority of repairs (8 of 9) in the modified knot fixation group failed because the allograft elongated more than 2 cm, which was considered clinical failure. In 1 specimen, the clavicle fractured through the anatomic clavicular drill holes.

The peak load to failure for the intact specimens was 386.3 N (standard error of the mean [SEM], 55.7 N) and 422.5 N (SEM, 84.2 N) for the anatomical double-bundle and modified knot fixation groups, respectively. The peak load to failure was 326.9 N (SEM, 40.6 N) and 347.5 N (SEM, 26.4 N) for each reconstruction technique, respectively. These differences were not significant between native and reconstructed ligaments ($P=.36$ and .41, respectively) (Figure 4). No significant difference was found between reconstruction techniques ($P=.93$).

The stiffness decreased significantly after reconstruction from 32.5 N/mm (SEM, 4.2 N/mm) to 22.5 N/mm (SEM, 1.7 N/mm) in the double-bundle group ($P=.035$) and from 35.5 N/mm (SEM, 5.7 N/mm) to 21.9 N/mm (SEM, 1.9 N/mm) in the modified knot fixation group ($P=.043$) (Figure 5). No significant difference existed in stiffness between the 2 reconstruction groups ($P=.71$).

Average bone mineral density in the knot fixation group was 642 mg Ha/cm$^3$ in the humeral head (SEM, 6.1 mg Ha/cm$^3$) and 793 mg Ha/cm$^3$ in the glenoid (SEM, 13.6 mg Ha/cm$^3$). Average bone mineral density in the anatomical double-bundle
group was 641 mg Ha/cm³ in the humeral head (SEM, 5.5 mg Ha/cm³) and 794 mg Ha/cm³ in the glenoid (SEM, 14.3 mg Ha/cm³). These values were not significantly different ($P > .05$).

**DISCUSSION**

More than 65 procedures have been described to treat complete acromioclavicular dislocations. The coracoacromial ligament used as a graft for transfer (ie, Weaver-Dunn procedure) has been found to account for only 20% of the peak load of the intact coracoclavicular ligament. Although this is a well-accepted procedure, the lack of strength has led to high rates of recurrence and incomplete reduction. Previous biomechanical studies have shown that a free tendon graft placed anatomically to recreate the conoid and trapezoid ligaments performs similar to the intact coracoclavicular ligament. This reconstruction technique has been found to more closely approximate the native coracoclavicular ligament compared with the Weaver-Dunn repair. Recent clinical studies have suggested that anatomic reconstruction results in good short-term results.

Anatomic position of the coracoclavicular ligament has been determined by osteological studies. Mean length from the end of the clavicle and acromioclavicular joint to the most medial insertion of the coracoclavicular ligament is 46.3 mm. The distance between the trapezoid ligament laterally and conoid ligament medially is 21.4 mm. Recently, studies have used these measurements to put forth reconstruction techniques that recreate the coracoclavicular ligament in its anatomical positions.

The current study compared the biomechanical properties of 2 of the previously published anatomic coracoclavicular ligament reconstruction techniques using semitendinosus allograft.

The anatomical double-bundle coracoclavicular ligament reconstruction technique described by Mazzocca et al was compared with the native, intact state. In their study, no significant difference was found between mean anterior, posterior, and superior translations under a 70-N load and displacement after cyclic loading. This technique also was found to have significantly less anterior and posterior translation under load than the Weaver-Dunn procedure, which was also tested. In addition, mean ultimate load after reconstruction was 396.4 N. This value was similar to the current finding of 326.9 N using a modified version of the technique. A sling technique of looping the graft under the coracoid was chosen over the original method to avoid iatrogenic fracture of the coracoid. The drill hole could create a stress riser from drilling and docking.
the graft into the base of the coracoid.\textsuperscript{13} Placing the graft beneath the coracoid adds another surgical step but avoids the extra surgical steps necessary to fix the graft to the coracoid, including drilling, graft placement, and screw fixation. No failures by coracoid fracture occurred after reconstruction in the current study.

The biomechanical properties of a knot fixation technique described by Lee et al\textsuperscript{10} were compared with several techniques. Lee et al\textsuperscript{10} chose this knot fixation method based on their preliminary studies showing that it had the highest load to failure and was the only technique that predictably failed at the midsubstance of the tendon graft and not at the fixation site. In the study, compared with the native ligament, the semitendinosus graft was found to be statistically similar in load to failure but was significantly less stiff and had greater elongation at failure.\textsuperscript{10} The current study had similar findings when comparing a modified version of the knot fixation technique with the intact specimen. The reconstruction was significantly less stiff but had similar peak load.

The current authors made 2 modifications to the knot-tying technique described by Lee et al\textsuperscript{10}. First, instead of creating a single clavicular drill hole to loop the graft through, 2 anatomically placed drill holes recreating the conoid and trapezoid were used. This was believed to more closely represent the native coracoclavicular ligament and more readily compare the 2 fixation techniques. In addition, the free ends of the graft were secured on the clavicle using a modified version of the knot fixation group. This study reinforces previous studies that demonstrated excellent repair strength of a knot fixation technique while avoiding the need for additional hardware and a failure site.\textsuperscript{10}

Augmentation with synthetic material, such as absorbable or nonabsorbable sutures or tapes, can be considered. However, an associated risk of cutout exists at the clavicular drill holes or coracoid from the sawing motion of the material, especially if it is nonabsorbable. Fracture between the clavicular drill holes was seen as mode of failure in 1 specimen, before the defined failure of 2 cm of superior displacement occurred.

A range of size existed in shoulder specimens used in this study. It is possible that the locations and distances of the anatomic coracoclavicular ligament drill holes should be scaled based on specimen size. The larger specimens could have drill holes farther apart and farther from the distal end of the clavicle, and the smaller specimen drill holes could also be modified.

This study has several limitations. As a cadaveric study, the dynamic stability provided by the deltoid and trapezius were not examined. Also, because the intact specimens were loaded to failure, it is unknown whether this simulated trauma had any effect on the bony mechanics, such as deformation. However, all specimens were treated similarly, and, because all failures were attributed to graft elongation or drill hole or interface failure, it is unlikely that this had an effect. In addition, the study did not investigate cyclic loading.

This study compared 2 anatomic coracoclavicular ligament reconstructions and minimized as many variables as possible. Matched cadaver shoulders were randomized to 1 of 2 reconstruction techniques using matched semitendinosus allografts. Using matched grafts as well as matched shoulder specimens should remove some variation seen in cadaveric testing.

\section*{Conclusion}
Both the modified anatomical double-bundle coracoclavicular ligament reconstruction technique and the modified knot fixation technique resulted in constructs with similar peak loads but lower stiffness compared with the intact, native coracoclavicular ligament. No significant difference was found between the 2 techniques with regard to peak load or stiffness; however, the failure modes differed significantly. The modifications made to the previously published techniques have potential benefits. The anatomically positioned clavicular drill holes recreating the conoid and trapezoid ligaments may more closely mimic the intact state. Also, the sling technique of passing the graft around the coracoid reduces stress risers secondary to drilling and fixation. This study also reinforces the excellent fixation strength of knot fixation of graft while avoiding the need for additional hardware and a failure site.

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