

Mapping of the Inferior Glenohumeral Ligament for Suture Pullout Strength

A Biomechanical Analysis

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Background: Suture pullout during rehabilitation may result in loss of tension in the inferior glenohumeral ligament (IGHL) and contribute to recurrent instability after capsular plication, performed with or without labral repair. To date, the suture pullout strength in the IGHL is not well-documented. This may contribute to recurrent instability.

Purpose/Hypothesis: A cadaveric biomechanical study was designed to investigate the suture pullout strength of sutures in the IGHL. We hypothesized that there would be no significant variability of suture pullout strength between specimens and zones. Additionally, we sought to determine the impact of early mobilization on sutures in the IGHL at time zero. We hypothesized that capsular plication sutures would fail under low load.

Study Design: Descriptive laboratory study.

Methods: Seven fresh-frozen cadaveric shoulders were dissected to isolate the IGHL complex, which was then divided into 18 zones. Sutures in these zones were attached to a linear actuator, and the resistance to suture pullout was recorded. A suture pullout strength map of the IGHL was constructed. These loads were used to calculate the load applied at the hand that would initiate suture pullout in the IGHL.

Results: Mean suture pullout strength for all specimens was 61.6 ± 26.1 N. The maximum load found to cause suture pullout through tissue was found to be low, regardless of zone of the IGHL. Calculations suggest that an external rotation force applied to the hand of only 9.6 N may be sufficient to tear capsular sutures at time zero.

Conclusion: This study did not provide clear evidence of desirable locations for fixation in the IGHL. However, given the low magnitude of failure loads, the results suggest the timetable for initiation of range-of-motion exercises should be reconsidered to prevent suture pullout through the IGHL.

Clinical Relevance: From this biomechanical study, the magnitude of force required to cause suture pullout through the IGHL is met or surpassed by normal postoperative early range-of-motion protocols.

Keywords: biomechanics; IGHL; inferior glenohumeral ligament; instability; rehabilitation; shoulder; suture pullout

The glenohumeral joint is the most mobile joint in the human body, which also has the highest dislocation rate.^{7,10} Owing to poor bony congruency, it has a reliance on soft tissue stabilizers. The inferior glenohumeral ligament (IGHL) is a major static stabilizer of the glenohumeral joint.²⁷ It originates from the glenoid and labrum as a hammock-like thickening of the capsule that inserts onto the proximal humeral neck inferior to the lesser humeral tuberosity.⁶ There are 3 distinct sections described: an anterior band; a posterior band; and an interposed axillary pouch.

Depending on the rotation and position of the shoulder, the tension on various parts of the IGHL differs; however, it is known that the IGHL is involved in anterior, posterior, and multidirectional instability.^{11,14,28} Biomechanical studies have demonstrated selective capsular plication of the IGHL, and inferior capsular tissues have been demonstrated to have a restrictive effect on internal and external rotation as well as on abduction.¹⁶ Failure of the IGHL labral complex can occur at the glenoid origin (40%) (eg, Bankart lesion), a midsubstance tear (35%), and the point of insertion on the humerus (25%) (eg, humeral avulsion glenoid labrum lesion).^{1,4,28}

Arthroscopic reconstruction for shoulder instability involves repairing the torn soft tissue capsulolabral complex with or without capsular plication.²² In some specific

The Orthopaedic Journal of Sports Medicine, 9(1), 2325967120969640
DOI: 10.1177/2325967120969640
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instability conditions such as multidirectional instability, capsular plication is the primary surgical treatment when nonoperative management has failed.²⁴ While arthroscopic techniques have improved in recent years, recurrent instability after arthroscopic shoulder stabilization ranges from 3.4% to 33.3%, with a mean rate of 13.1% when pooling 12 high-quality trials.⁸ A multitude of factors influence failure of reconstruction, including age, ligamentous laxity, contact or collision environment, structural bony damage (particularly glenoid bone loss), time to surgery, surgical technique, and implant design.³ Despite the existence of consensus protocols such as the American Society of Shoulder and Elbow Therapists Consensus Rehabilitation Guideline,^{9,15} there is wide variation in postoperative rehabilitation protocols after arthroscopic shoulder stabilization. This includes accelerated range of motion (ROM) techniques compared with extended immobilization.⁹ Whether this affects the integrity of the repair is not known. Given this variability in rehabilitation, early ROM exercises may result in tearing of the surgical reconstruction, particularly as forces applied to the hand or elbow may be magnified at the humeral capsule.

While there are a number of studies in the literature investigating pullout strength of suture in tendons,^{29,34} to our knowledge, no study has specifically investigated the pullout strength of a suture in the IGHL. First, we aimed to create a map of the IGHL with reference to suture pullout strength in different zones, which might inform surgeons of the ideal position for suture placement to prevent suture pullout after Bankart repair and capsular plication. We hypothesized that there would be no significant variability of suture pullout strength between specimens and zones of the IGHL. Second, we sought to determine the impact of early mobilization on potential integrity of the capsular plication sutures in the IGHL at time zero. We hypothesized that capsular plication sutures would fail under low load.

METHODS

Specimens

Four female and 3 male shoulders with a mean age of 64 years (range, 41-75 years) were used in this study. Cadavers were donated as part of the university anatomy program. Ethics approval was granted for cadaveric research. Specimens were evaluated by the same fellowship-trained shoulder and elbow surgeon (S.R.), and any specimens exhibiting any degradation of the shoulder capsule, including

previous capsuloligamentous injury and osteoarthritis, were excluded from the study. In each specimen, the humerus was dissected and all soft tissue removed except for the IGHL. The humeral shaft was cut approximately 15 cm from the most proximal point of the humeral head. The specimen was potted in a polyvinyl chloride (PVC) pipe using polymethyl methacrylate. A length of wire was tied around the PVC pipe to create a “hanger.” The IGHL was also released from the glenoid, and the glenoid side of the IGHL was reinforced with a modified Krackow stitch and tied up to the hanger with uniform tension. This allowed for quicker placement of sutures between tests and for images of the failure to be captured with a high-definition camera (CB-200GE, JAI Ltd) (Figure 1). The potted IGHL was secured to the electromechanical testing system (E10000; Instron Corp) base via a vise with 3 rotational degrees of freedom. The specimens were oriented such that the IGHL was being pulled orthogonal to the long axis of the humeral shaft.

Suture Placement

A total of 18 sites were tested in each IGHL (Figure 2A). The sites were kept as consistent as possible among specimens. The 18 test sites were divided into 4 rows. The space between successive rows was 5 mm. Five sites were tested on the first and third rows and 4 test sites were tested on the second and fourth rows to allow for staggering of the test sites between adjacent rows. This was done to minimize damage to adjacent test sites. The distance between adjacent sites on each row was calculated based on the width of the tissue in the height of the first row. All sutures were placed by the same fellowship-trained shoulder and elbow surgeon so that suture placement would remain as consistent as possible between specimens. The No. 2 Orthocord (DePuy Synthes) was utilized because of evidence indicating less cheese-wiring effect.²⁰

Biomechanical Testing

A simple stitch was passed through each test site from the inner surface to the outer surface without any tissue plication and the free ends secured to a capstan-style suture gripper attached to the linear actuator of the Instron testing machine crosshead via a 1-kN load cell (Figure 1). Each site was tested in a systematic manner for all specimens, starting at the glenoid side (site 1) and finishing at the humeral side (site 18). No knot was tied to remove any source of error from variable tensioning of the

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Final revision submitted June 9, 2020; accepted June 24, 2020.

One or more of the authors has declared the following potential conflict of interest or source of funding: S.R. has received research support from Mathys Orthopaedics. D.B. has received research support from Smith & Nephew; consulting fees and speaking fees from Mathys Orthopaedics, Rotation Medical, Smith & Nephew, Wright Medical, and Zimmer Biomet; and royalties from Allegra Orthopaedics; and has stock/stock options in Allegra Orthopaedics. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approval for this study was obtained from Macquarie University (reference No. 5201300835).

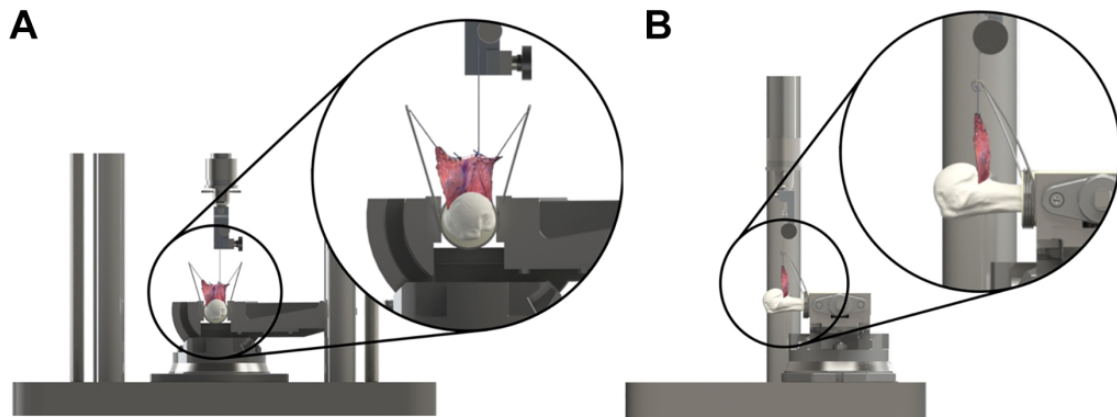


Figure 1. Schematic of the test setup from the (A) front and (B) side. Insets show base and vise detailing how the wire hanger is wrapped around the polyvinyl chloride pot.

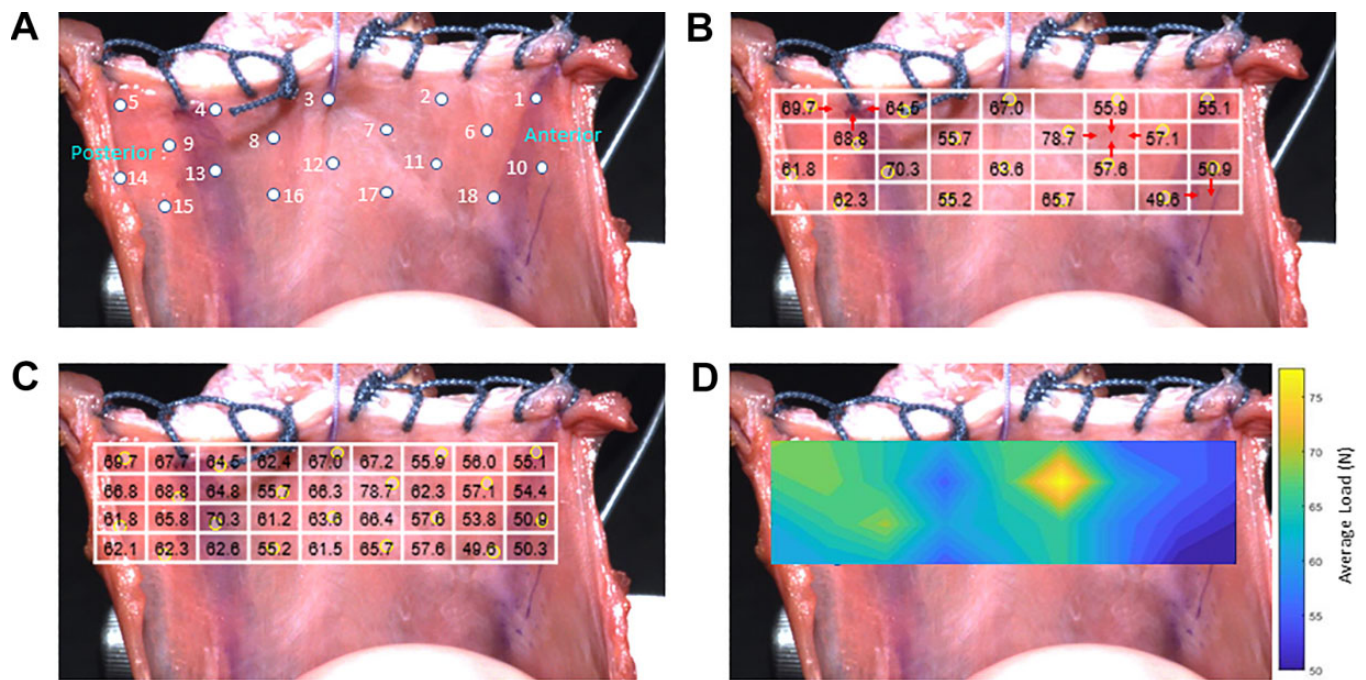


Figure 2. Generation of IGHL Suture Pullout Strength Map showing (A) test site numbering based on proximity to glenoid border and anteroposterior position, (B) creation of a partially filled 4 × 9 grid based on mean results of tests including red indicators for (C) a completed 4 × 9 grid and (D) creation of a heat map.

knot. A displacement rate of 1 mm/s was applied, consistent with previous literature.³⁴ Failure was defined as deviation in the linearity of the live force/displacement curve and/or visible tearing of the ligament-suture interface as observed via video.¹⁸ The test was stopped immediately at the point of failure to preserve the tissue quality for the remaining test cycles. We utilized a force actuator, video analysis, and visual observation to truncate the experiment as soon as any capsular damage was noted.

The mean suture pullout loads were mapped in a grid (Figure 2B). The pullout strength of untested zones was

calculated from a mean of the adjacent 4 zones (Figure 2C). Using Matlab (MathWorks), a color-coded heat map was then generated from these values (Figure 2D).

Statistical Analysis

Means and standard deviations of forces were calculated for each test site across all specimens. The significance levels between the different sites was computed using a 1-way analysis of variance. All analyses were undertaken in SPSS Version 25.

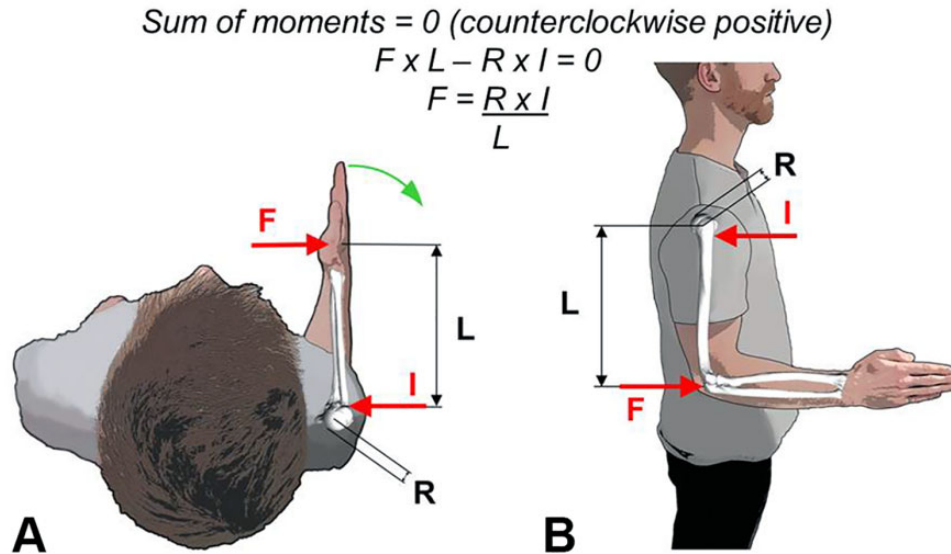


Figure 3. Biomechanical model with schematic. (A) External rotation model. (B) Humeral stretch model. *R*, radius of humeral head; *I*, failure load of the IGHL; *L*, length of (A) forearm or (B) humerus (similar to other studies^{17,19}); *F*, load at the hand in (A) external rotation or (B) humeral stretch causing failure at the IGHL. IGHL, inferior glenohumeral ligament.

Calculation of Forces at the Capsule

A simplified biomechanics model was used to approximate the maximum loads that could be applied to the hand/elbow during standard passive rehabilitation activities (eg, external rotation with the force at the hand). For all calculations, the humeral head was assumed to be spherical, and friction and support from surrounding soft tissue (including the rotator cuff and labrum) were assumed to be negligible. The length of the forearm and humerus were averaged based on the anthropometric measurements recorded by US Army,¹⁷ and the mean radius of the humeral head was based on calculations by Ianotti et al.¹⁹ In addition, the worst-case loading is assumed, in which the load is initially applied to a single suture.

For external rotation with force through the hand, the elbow was assumed fixed at 90°, with the forearm neutral. This was chosen to best simulate the position of the limb in postoperative rehabilitation protocols. Torsion was created around the long axis of the humerus by applying a load at the hand regardless of the position of abduction (Figure 3A). We also analyzed the potential load on the IGHL from a force applied at the elbow (Figure 3B). However, these values were similar to a force applied at the hand given a similar length of the radius and humerus.^{17,19} Therefore, we reported only results related to forces applied to the hand in external rotation in this paper.

RESULTS

IGHL Suture Pullout

The mean failure loads and ranges are presented in Table 1. The mean (±SD) pullout strength of all tests for all

TABLE 1
Suture Pullout Failure Force by Test Site

Site	Failure Load, N ^a
1	69.7 ± 20.7 (40-102)
2	64.5 ± 25.6 (43-118)
3	67.0 ± 18.7 (38-96)
4	65.0 ± 22.1 (31-93)
5	55.1 ± 21.8 (20-90)
6	68.8 ± 35.9 (28-118)
7	55.7 ± 29.2 (32-109)
8	78.7 ± 51.9 (35-172)
9	57.1 ± 12.4 (37-75)
10	61.8 ± 26.9 (27-111)
11	70.3 ± 19.9 (40-102)
12	63.6 ± 25.5 (20-100)
13	57.6 ± 29.3 (15-110)
14	50.9 ± 20.6 (31-83)
15	62.3 ± 24.5 (22-85)
16	55.2 ± 14.8 (36-73)
17	65.7 ± 32.1 (28-110)
18	49.6 ± 27.7 (13-93)

^aData are reported as mean ± SD (range).

specimens was 61.6 ± 26.1 N. The highest mean load was 78.7 ± 51.9N at site 8 and the lowest was 49.6 ± 27.7 N at site 18 (Figure 1B). The ranges shown in Table 1 reveal great variability in suture pullout strength between individual shoulder samples (overall range, 13.0-172.3 N).

Suture Pullout Strength Map

A mean suture pullout strength map of the IGHL was constructed from the above mean failure load data (Figure 2). Suture pullout loads at each of the testing sites

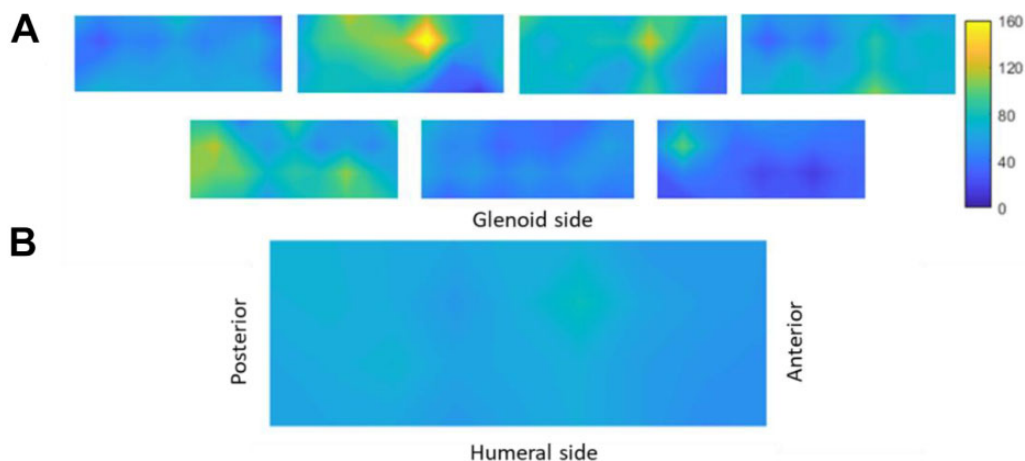


Figure 4. Color maps for (A) individual specimens and (B) mean results.

were placed on a 4 × 9 point grid (Figure 2, A and B). The untested zones within this grid were calculated as a mean of the adjacent tested zones (Figure 2, B and C). This was converted into a continuous color map of the mean suture pullout strength of the IGHL (Figure 2D).

Individual pullout strength maps were also created to visually represent the data (Figure 4A). These maps were all plotted on the same color scale for easy comparison. The high variability in pullout strength between specimens and within some specimens is evident in these figures. Replotting the mean pullout strength on this same color scale clearly highlights the homogeneity of the mean results presented above (Figure 4B). This supports our primary hypothesis that there would be very little variation between zones of the IGHL.

Calculation of Forces at the Capsule

Our calculations (Table 2) suggest that the mean external rotation force at the hand to cause suture pullout was 3.4 N (range, 0.7-9.6 N) for male and 3.7 N (range, 1.2-7.2 N) for female specimens. Given the absolute highest load to failure of sutures for an individual IGHL specimen was 172.3 N in males, this corresponds to only a 9.6 N (980 gf) load at the hand.

DISCUSSION

This study is the first to investigate the individual suture pullout strength of sutures in the IGHL in a cadaveric model. Our data revealed a high degree of variability in the IGHL tissue, both between specimens and within individual specimens. The mean heat map suggests a trend toward homogeneous strength distribution, although we were not able to draw this conclusion from our data. More importantly, the overall magnitude of pullout strength for sutures in the IGHL was found to be relatively low, with a mean of 61.6 N. Utilizing calculations described earlier,^{17,19} this translates to a mean external rotation load of 3.7 N at the hand (approximately 380 gf). The highest

TABLE 2
Calculated Suture Pullout (Mean and Absolute) With Force

External Rotation Load to Failure	Male	Female
Load to failure at IGHL, N		
Minimum	13	20
Maximum	172	118
Mean	62	61
Load to failure at hand, N		
Minimum	0.7	1.2
Maximum	9.6	7.2
Mean	3.4	3.7
Mean forearm length (mm)	360	329
Minimum humeral head radius (mm)	20	20
Applied torque, N·m		
Minimum	0.34	0.52
Maximum	4.47	3.07
Mean	1.61	1.59

Mean forearm length derived from Gordon et al¹⁷; minimum humeral head radius from Iannotti et al.¹⁹ IGHL, inferior glenohumeral ligament.

value for pullout strength of sutures was 172 N, which translates to a force of approximately 9.6 N or 980 gf at the hand. These are exceedingly small loads that could be encountered in postoperative rehabilitation programs.

Extensive work has been done on pullout strength of sutures through tendons; for example, in rotator cuff repair, suture pullout strength was recorded at 191 N,³⁴ and in pectoralis major repair, suture pullout strength of 383 N was reported.²⁹ However, evidence regarding the suture pullout strength through ligaments has been scarce. Much of the work in ligaments has focused upon either the failure of the whole ligament structure, an entire capsulolabral specimen, or a repaired (simulated) Bankart lesion. In contrast, our study concentrated on the strength of a single point of the IGHL at a suture-tissue interface, which, to our knowledge, has not been studied.

Wytrykowski et al³⁵ demonstrated maximum load to failure for the anterolateral ligament in the knee as mean 141

N, with 161.1 N for the iliotibial band. Boardman et al² measured the coracohumeral ligament load to failure at 359.8 N and the superior glenohumeral ligament to be 101.9 N. Likewise, the whole native IGHL has been shown to have a mean load to failure in the range of 491 to 874 N.^{21,23,25} Different parts of the IGHL have also been demonstrated to have different biomechanical properties, with the anterior band of the IGHL having been shown to have a higher strain at failure than the superior band or posterior pouch.¹ Failure of the IGHL has been demonstrated to occur predominantly at the glenoid insertion, followed by midsubstance and the humeral side.^{1,31} While these studies are important for context of the native tissue in injury, they do not give clinicians information about suture pullout strength after repair.

Load to failure and failure mode after repair of the capsulolabral complex have been studied previously, although these studies have always been in the context of the entire capsulolabral complex rather than the IGHL selectively. Failure has been shown to occur at the bone-anchor interface (103-240 N),^{26,30,33} via suture breakage (224-233 N),^{25,30} or at the suture-tissue interface (261 N).²⁵ The most common method of failure in cadaveric studies has been shown to be via suture pullout through the tissue in 66% (10/15)²⁵ to 84% (16/19)¹⁸ or through pullout of the anchor from bone in 75% (15/20)²⁶ of tested specimens. Our reported mean load to failure of 61.63 N is lower than some reported values for suture pullout through tissue in the literature. Mohammed et al²⁵ tested the biomechanical pullout strength of 3 simulated Bankart lesion reconstruction techniques in 20 human cadaveric shoulder girdles. They reported the load to failure for interosseous suture Bankart repair at 261.7 N. All specimens failed via suture pullout through the soft tissues. However, these load to failure values are not directly comparable. Mohammed et al utilized 3 interosseous sutures (No. 2 Ti-Cron; Covidien) and tested pullout failure of the capsulolabral complex as a composite. Conversely, our study tested pullout failure of the IGHL only with a single simple suture (No. 2 Orthocord; J&J Medical) in specific portions of the IGHL. Therefore, the pullout strength was dissipated over 3 anchoring points through the capsulolabral tissue rather than a single suture in the IGHL only, as in our study. Interestingly, a recent cadaveric paper by Bokshan et al⁵ reported peak resistance of the capsulolabral tissues to 1 cm anterior translation of an intact shoulder as 43.4 N, with 52.8 N for a Bankart repair with 4 anchors (including a 6 o'clock anchor with capsular plication), which is similar to the values reported in our study. However, direct comparisons between the 2 studies are difficult as the authors did not report the mode of failure—they utilized several anchors as opposed to 1 suture; and unlike our study, they did include labral tissue as well as rotator cuff musculature in their model.

The low magnitude of force demonstrated in our results for suture pullout through the IGHL has implications for postoperative shoulder stabilization rehabilitation. Our results demonstrate that 380 g of force at the hand in external rotation is the mean force that would cause tearing of the sutures through the capsule, with 960 gf being the maximum pullout force recorded. These loads are exceedingly

low and easily encountered in early ROM protocols. The same is true for calculated torque loads, whereby previous studies by Zumstein et al³⁶ have demonstrated that in the absence of other forces, the tension on the IGHL is 40 times the external rotation applied force at the hand. They utilized a similar force-balancing biomechanical model; however, they calculated external rotation of an extended arm rather than with the elbow at 90°.³⁶ Therefore, we suggest that in the early stages of recovery, external rotation exercises not be used. This is an important suggestion given the wide variation in the timing of passive ROM exercises in the literature. In a review of 30 postoperative protocols for arthroscopic Bankart repair, 19 (63.3%) protocols recommended immediate postoperative passive supine external rotation while only 9 (30%) recommended immobilization for a mean of 2.8 ± 1.6 weeks.⁹

There is a delicate balance in postoperative rehabilitation between protection of the repair and prevention of permanent stiffness.¹³ Gerber et al¹⁶ demonstrated that a 1-cm anterior plication restricted external rotation by 20.6° to 38.6° at 0° of abduction. This finding was mirrored by Wang et al,³² who also reported significant loss of external rotation and maximum elevation after anteriorly tightened shoulders compared with controls. In light of this and our study results, early return to full motion may occur as a consequence of tearing of the suture through the IGHL capsular repair. Rehabilitation movements may need to be limited at time zero given the low pullout strength. When exercises are introduced, clinicians and therapists should be mindful of the time frame of healing of plication to avoid failure of the repair.

This study is subject to several limitations. In the interest of not damaging the ligament for subsequent tests, the test was stopped at the earliest sign of failure. However, it is possible that the tissue could withstand more suture pullout load than this before catastrophic failure occurs. As well as the limited number of specimens, which affected power, the mean age of the donor specimens in our study (66 years) is higher than the mean age of shoulder stabilization patients (35 years¹²), leading to known age-related changes in tissue quality.²¹ Lee et al²¹ demonstrated significantly superior structural properties of the anterior band of the IGHL in a younger group (mean age, 38.5 years) compared with an older group (mean age, 74.8 years). However, this is a limitation that is shared with all cadaveric studies in the literature, with mean ages in biomechanical shoulder instability studies in the range of 55 to 77 years.^{18,25,26} As an *in vitro* biomechanical study in cadaveric tissue, our findings demonstrate the suture pullout strength of capsular plication of the IGHL at time zero only. The biomechanical model utilized for calculation of forces at the capsule is a simplified model based upon balancing load vectors. This approach to calculation of forces at the IGHL has been reported previously in the literature.³⁶ It does not include the complex interplay between soft tissue and dynamic stabilizers present in an *in vivo* shoulder (eg, labrum and rotator cuff musculature), and represents a “worst-case scenario,” particularly as multiple sutures may be applied in capsular advancements. However, given that our study aimed to record the pullout strength in the IGHL specifically as a major static stabilizer, this was a necessary limitation.

CONCLUSION

From this biomechanical study of IGHL pullout strength, the variability in failure loads across the test sites and between specimens makes it difficult to make definitive statements regarding desirable locations for tissue fixation. However, the fact that the maximum pullout loads are low and that these loads equate to a load of a maximum of only 9.6 N at the hand in external rotation suggests that clinicians should reconsider the timetable for loading the surgical construct in postoperative rehabilitation protocols. We call for further in vivo studies to promote investigate this concept.

ACKNOWLEDGMENT

The authors acknowledge Robert Potra and David Axford from the MQ Health Translational Shoulder Program for their assistance with the medical illustrations.

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