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# Mapping glenohumeral laxity: effect of capsule tension and abduction in cadaveric shoulders

**Andrew P. Kraszewski, PhD[a,*], Stephanie W. Mayer, MD[b], Andreas Kontaxis, PhD[a], Howard J. Hillstrom, PhD[a], Ali Sheikhzadeh, PhD[c], Russell P. Warren, MD[d]**

[a]*Department of Rehabilitation, Hospital for Special Surgery, New York, NY, USA*
[b]*Department of Orthopedic Surgery, University of Colorado, Children's Hospital Colorado, Aurora, CO, USA*
[c]*Occupational & Industrial Orthopaedic Center, NYU Langone Medical Center, New York, NY, USA*
[d]*Sports Medicine & Shoulder Service, Hospital for Special Surgery, New York, NY, USA*

**Background:** Shoulder capsular plication aims to restore the passive stabilization of the glenohumeral capsule; however, high reported recurrence rates warrant concern. Improving our understanding of the clinical laxity assessment across 2 dimensions, capsular integrity and shoulder position, can help toward the standardization of clinical tools. Our objectives were to test and describe glenohumeral laxity across 5 capsular tension levels and 4 humeral position levels and describe tension-position interplay.
**Methods:** We tested 14 dissected cadavers for glenohumeral laxity in 5 directions: anterior, posterior, and inferior translation, and internal and external axial rotation. Laxity was recorded across capsule tension (baseline, stretched, 5 mm, 10 mm, and 15 mm of plication) and position (0°, 20°, 40°, 60° of scapular abduction). Repeated-measures analysis of variance with post hoc contrasts tested the effect of tension, position, and composite tension × position on laxity.
**Results:** Capsule tension, position, and composite interplay had a statistically significant, although unequal, effect on laxity in each direction. Laxity was consistently overconstrained in 15-mm plication and was overall greatest in 20° and lowest in 60°. Restoration occurred most in 10 mm, but this depended on the position. The composite effect was significant for external and internal rotation and inferior laxity, but laxity at the middle range (20° or 40°) was different than at the end range (0° or 60°) for all directions.
**Conclusions:** On average, laxity was restored to baseline tension after 10-mm plication, but this determination varied depending on shoulder position. Middle-range laxity behaved differently than end-range laxity across plication tensions. This information is useful in understanding the unstable shoulder as well as for standardizing clinical laxity assessment.
**Level of evidence:** Basic Science Study; Biomechanics


**Keywords:** Multidirectional instability; plication; clinical laxity test; glenohumeral capsule; translational laxity; rotational laxity; restoration; differential engagement

The glenohumeral joint is the primary articulation in the shoulder. A properly controlled and stable joint allows for normal function required in daily life[4] through balanced forces from active and passive structures surrounding the shoulder.[28] However, an inherent lack of bony restraint puts the

*Reprint requests: Andrew P. Kraszewski, PhD, Leon Root, MD Motion Analysis Laboratory, 510 E 73rd St, New York, NY 10021, USA.
E-mail address: kraszewskia@hss.edu (A.P. Kraszewski).

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glenohumeral joint at risk for aberrant translation, and the passive tissues play a key role in constraining excessive motion. The basic function of the glenohumeral capsule is to passively limit motion in rotation and translation near end-range positions.[1,3] Capsular tightening limits shoulder range of motion (ROM) and protects against hyper-rotation, subluxation, and other injury. However, the extent of the native capsule's restraint on ROM depends on joint position. The capsule's role during functional activities is crucial as a passive stabilizer at the end ROM when active agonist-antagonist stabilization is not effective but does not typically contribute to stability in mid-ROM tasks.[3,23] Individuals whose activity chronically challenges the extremes of available shoulder ROM, and thus the check-reign capabilities of the capsule, put demanding strain on these tissues. Hyperlaxity threatens normal stabilization and control of the shoulder, sometimes leading to discomfort and pain. Competitive young overhead athletes may acquire hyperlaxity over time or have congenital factors that increase the risk of developing shoulder pathology.

A common yet difficult shoulder pathology to manage is excessive symptomatic laxity in more than 1 direction, generally labeled multidirectional instability (MDI). It was first described by surgeons Neer and Foster as instability in multiple directions.[13] The clinical signs of a nontraumatic unstable shoulder can be very subtle, and the literature suggests that no one clinical laxity test has good diagnostic value.[9,24] Clinical laxity can be marked when dislocation occurs or more subtle with mild pain as the chief complaint, secondary to muscles one overuses in an attempt to control the joint. When conservative nonsurgical treatment is ineffective, surgical treatment may be indicated, commonly a capsular plication or other capsulorrhaphy procedure. Arthroscopic plication attempts to restore passive capsular stabilizing properties, but with a prognosis that is debated.[7,10,15]

Capsular plication is a common surgical intervention for MDI, and arthroscopy has been increasingly used to treat various degrees of this pathology. But, we have limited understanding how surgical alteration of capsular tissue affects the loading environment of the glenohumeral joint. Also, how surgery can be optimized intraoperatively to appropriately restore the tension properties to an intact condition remains unknown. Current knowledge relates a narrow range of clinical shoulder tests and objective biomechanical measurements, which limits our understanding of plication efficacy intraoperatively.

Therefore, the purpose of this study was to investigate and describe the interplay of capsule tension and shoulder position on passive glenohumeral capsular laxity. The research objectives were to report capsular laxity at different levels of capsule tension (baseline, stretched, and 5-mm, 10-mm, and 15-mm plication) and report capsule tension behavior across different glenohumeral positions (0°, 20°, 40°, and 60° scapular abduction). We hypothesized that laxity would differ significantly with the level of capsule tension, the level of shoulder position, and both compositely. We also hypothesized that laxity in plicated (5 mm, 10 mm, 15 mm) tension levels would be significantly different between middle-range positions (20° or 40°) and end-range positions (0° or 60°).

## Materials and methods

This was a cross-sectional experimental study of shoulder laxity in dissected cadaveric shoulders.

### Cadaver preparation

We procured 14 fresh-frozen shoulder (scapula and humerus) models from an anatomic donation organization (Anatomy Gifts Registry; Hanover, MD, USA). The deceased donors (9 men and 5 women) were an average age of 56 ± 11 (range, 33 to 66) years. While frozen, all specimens were scanned with computed tomography and evaluated for any signs of osteoarthritis. Each specimen was kept at −35°F and then thawed for 24 hours to room temperature before experimental testing. Then, all specimens were tested for ROM by the study orthopaedic surgeon.

All periarticular tissues were dissected by a single experienced orthopedic surgeon. Care was taken not to violate the capsule by leaving the rotator cuff tendinous insertion intact. All capsules were vented at the rotator interval and then sutured using 2-0 Vicryl (Ethicon Inc., Bridgewater, NJ, USA). Retroreflective motion tracking marker clusters were rigidly attached to the humerus and scapula. Humerus and scapula bony landmarks were manually identified and registered with a markered wand. A circumduction trial was used to calculate the effective glenohumeral joint center of rotation.

The bones were cut and rigidly set in aluminum potting fixtures: the humerus was resected midshaft, and the proximal aspect was set in a cylindrical frame; the scapular inferior angle and superior border were resected, and the scapula was set in a square frame. Plaster of paris was poured into each potting frame around the bone and allowed to harden. The humeral and scapular fixtures were attached to a glenohumeral laxity testing device with multiple degrees of freedom, designed to test glenohumeral translation and axial rotation in multiple positions (Fig. 1). Cluster marker trajectories were recorded with a calibrated motion analysis system (Motion Analysis Corp., Santa Rosa, CA, USA) accurate to ±0.2 mm and ±0.3°. An attached multiaxis load cell (MC3-6-1000; AMTI, Watertown, MA, USA) measured applied torque.

### Capsule laxity testing

Each shoulder underwent glenohumeral translational and rotational laxity testing in 4 fixed levels of scaption (abduction in the scapular plane), referred to as "position": 0°, 20°, 40°, and 60°. Accuracy was confirmed with real-time 3-dimensional (3D) kinematic feedback. For all tests, a constant 22-N force was applied to the humerus and aligned to compress into the glenoid face.

#### Translational tests

Translational laxity tests were done in neutral fixed flexion and axial rotation; a 44-N load was applied cyclically 5 times along anterior, posterior, and inferior directions, selected randomly. The load was applied manually to the scapula potting frame with a calibrated spring scale. Each load cycle started with the humeral head centered

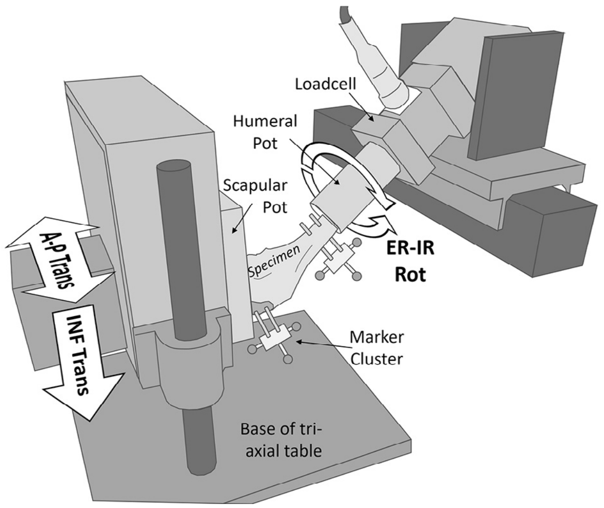


**Figure 1** Schematic of the laxity testing device. To the left, anterior-posterior (*A-P*) translation and inferior (*INF*) translational loads were applied to the scapular fixture. To the right, the humeral fixture applied axial rotational (*Rot*) torque, measured by the in-series loadcell. Other elements of the fixture allowed fine adjustment of glenohumeral position. *ER-IR*, external rotation-internal rotation.

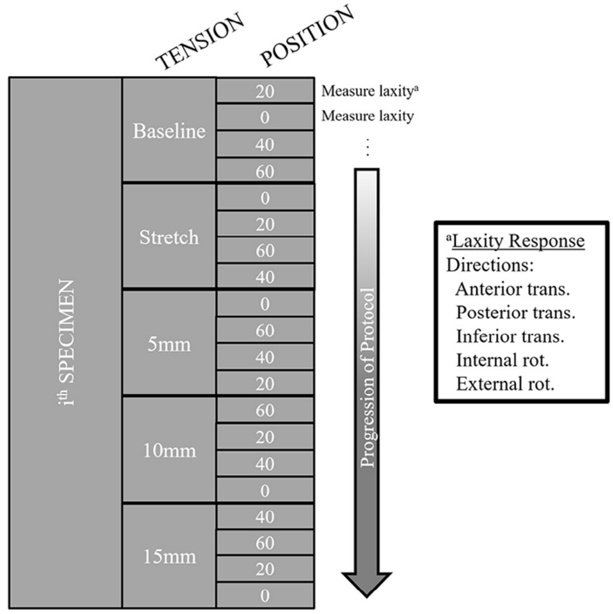


**Figure 2** Diagram of study design and testing protocol. Glenohumeral capsule laxity measurement was recorded at each position. The position and laxity direction order were randomized; the order of positions that appear here serve as an example.

in the joint and then was manually returned to center after the 44-N load was reached.

### Rotational tests

Axial rotational laxity tests were done in fixed scapular abduction, fixed flexion, and with translational degrees of freedom unconstrained; the joint was cycled 5 times in internal (IR) and external (ER) axial rotation directions, selected randomly. The starting rotation angle was neutral and proceeded at 5.0°/s using the Bionix robotic input (MTS Systems, Eden Prairie, MN, USA) until 2.0 N-m axial torque was reached, and then returned to start at the same rate.

## Capsule tensions

All specimens underwent an identical experimental testing protocol. Figure 2 provides a representation of the study design and protocol. Laxity was repeatedly measured across 5 capsule tension levels: baseline, stretched, 5-mm plication, 10-mm plication, and 15-mm plication. Immediately before baseline testing, preconditioning was done to minimize time-dependent behavior of the capsular tissue. The joint was fixed in 30° of scapular abduction and cycled in internal and external axial rotation from neutral 10 times at 5.0°/s until 1.0 N-m torque was reached.[22] Baseline served as the control for each specimen. A stretched tension protocol was implemented for each specimen by applying a constant 5.0 N-m torque in both IR and ER for 30 minutes[2] with the joint fixed in 40° scapular abduction.[22]

Each specimen then underwent sequential 5-mm, 10-mm, and 15-mm plication. Plication repairs were performed externally with the shoulder in approximately 50° of scaption and neutral axial rotation according to the surgeon's preference. Plication sutures were placed additively in the anterior (3:00), posterior (9:00), and inferior (6:00) capsule regions (Fig. 3, *A*). In each region, 3 parallel bites or imbrications (B1, B2, B3) were taken starting 10 mm from the rim and proceeded laterally with a 5-mm space between bites. The sutures were oriented North-South, and their magnitude and spacing was measured with a 1-mm resolution metric ruler (Fig. 3, *B*). An experienced orthopedic surgeon performed all repairs using Ethibond-Extra (Ethicon Inc.) suture with tied double half-hitch knots. For each plication magnitude level, all bites in all regions were additively plicated. Before a new level was plicated, all sutures were cut and remeasured so that the new sutures were centered on the old suture holes (Fig. 3, *B*).

## Signal processing and data extraction

Marker trajectory and loadcell data were processed in Visual3D software (C-Motion, Germantown, MD, USA). Data signals were smoothed with a low-pass Butterworth filter using a 3.0-Hz cutoff frequency. Bony landmark locations were taken from the computed tomography image and used to create specimen-specific scapula and humerus anatomic segment definitions.[26] These were applied to the cluster data to calculate glenohumeral kinematics. Kinematics were expressed with respect to the scapular anatomic frame axes, offset to the glenoid center of rotation. Anterior, posterior, and inferior translational laxity were defined as the maximum excursion of the humeral head center along the anterior (+*x*), posterior (–*x*) and inferior (–*y*) directions, respectively. ER and IR laxity was defined as the maximum IR and ER rotation of the humerus with respect to the scapula. Laxity values from the last 3 cycles of each test were averaged for analysis.

## Statistical analysis

The dependent laxity variables of the statistical model were anterior, posterior, and inferior translation (mm) and ER and IR (°)

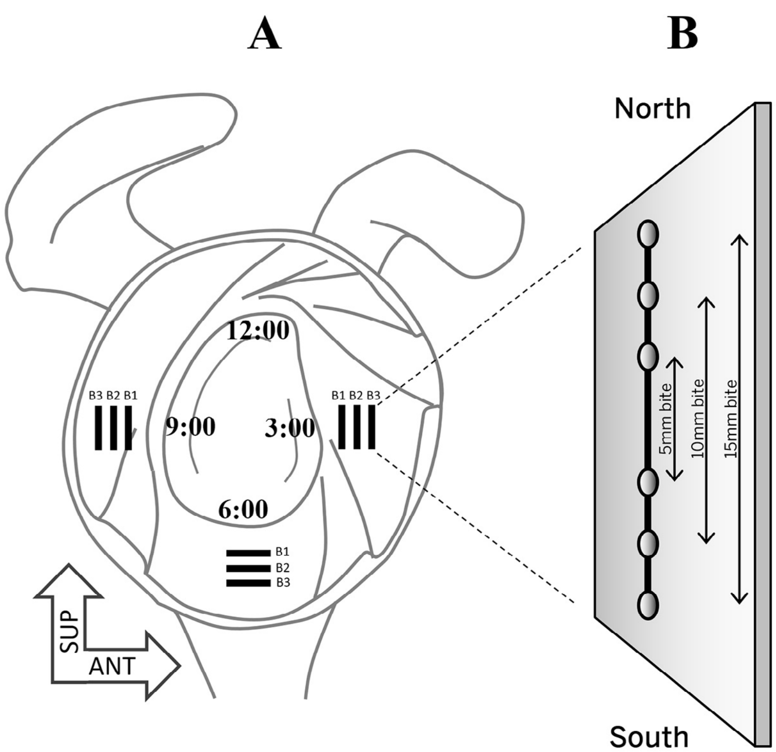


**Figure 3** (**A**) Illustration shows plication suture placement and orientation depicting a right scapula with internal capsule cross-section and glenoid clock face location reference where each row of 3 suture bites (*B1*, *B2*, *B3*) were centered, represented by *thick black lines*. Suturing was done from outside the capsule. *SUP*, superior; *ANT*, anterior. (**B**) Illustration shows suture hole spacing detail of a single bite (*B3*) and successive plication magnitudes (5 mm, 10 mm, and 15 mm), with holes aligned in a North-South/superior-inferior fashion. Sutures placed at 6:00 were aligned anterior-posterior.

rounded to integer precision. The independent categoric variables were capsule tension (baseline, stretched, 5 mm, 10 mm, and 15 mm) and position (0°, 20°, 40°, and 60°) as well as the composite variable, tension × position. Analyses were performed using SPSS 22 software (IBM, Armonk, NY, USA) and Real Statistics Resource Pack 5.2 software.[30]

Laxity is descriptively reported using mean values and standard errors to the nearest integer value. Normalized differences in laxity are reported as percentages with mean values. The research objectives were addressed with repeated-measures analysis of variance (RM-ANOVA) models that separately evaluated the RM-ANOVA model in each direction. A factor's effect on laxity was assumed to be statistically significant at $P < .05$, and in case of violation of normality, the model was adjusted with the Greenhouse-Geisser epsilon.

Post hoc comparisons were performed within each factor as contrast models that compared laxity differences between specific factor levels. Contrasts within capsule tension compared laxity in each level against the baseline, contrasts within position compared laxity to 0°, and the composite contrasts compared laxity in middle range (20° or 40°) with laxity in the end range (0° or 60°) across plication levels (5 mm, 10 mm, and 15 mm) only. Each contrast was considered statistically significant at $P < .05$. The Bonferroni correction was not applied to $P$ values in the main statistical model or contrasts. Determination of a restorative plication level was if a contrast of a given capsule tension level was not significantly different from the baseline.

## Results

Overall glenohumeral laxity behavior is shown in Figure 4 as a 3D surface or landscape that encompasses the entire experiment. Laxity from combined translational and rotational directions is represented vertically, with capsule tension and position represented horizontally. The surface contours are projected onto left and right vertical planes to isolate the main contribution of each experimental condition stratified by the other condition. Across tension laxity generally increased from baseline to stretched, followed by a decrease with plication from 5 mm through 15 mm. Overall, laxity was highest in stretched and lowest in 15-mm plication tensions and was highest in 20° and 40° and lowest in 0° and 60° positions. Notably, laxity in 5-mm plication was marginally higher than baseline values.

Direction-specific laxity is shown in Figure 5 by row, and capsule tension, position, and composite tension × position factors are shown by column. Capsule tension laxity was pooled from all positions, and position laxity was pooled from all tensions. The $P$ values below each graph represent the statistical main effect of each factor for each corresponding direction. Significant contrast bars are shown above each graph, except for the composite column graphs.

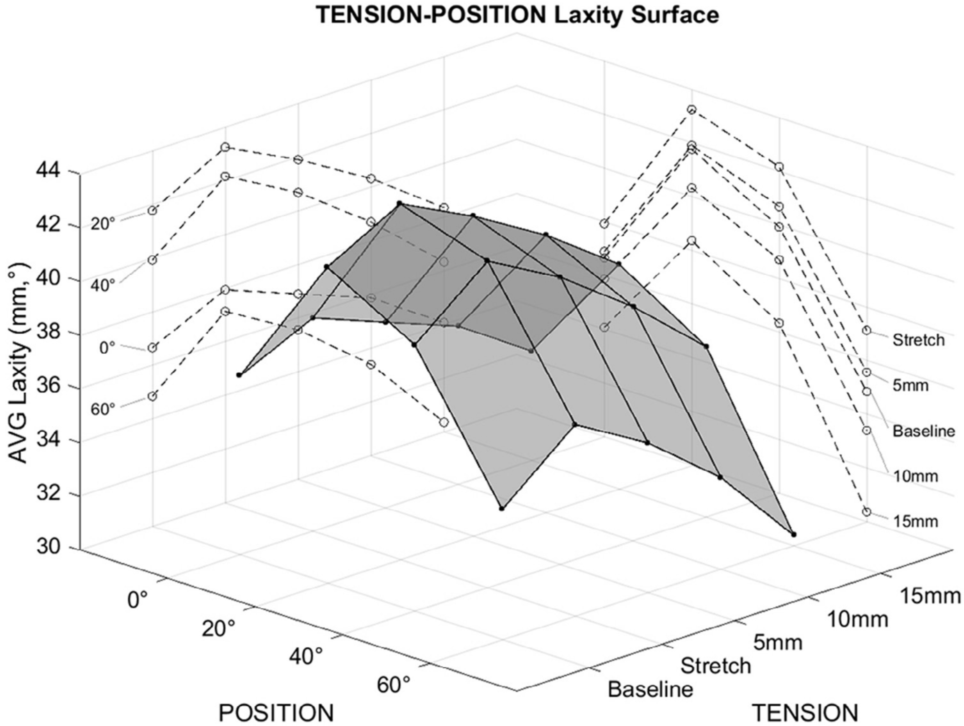


**Figure 4** Overall glenohumeral laxity. The 3-dimensional surface summarizes the effects of capsule tension and position (horizontal dimensions) on combined translation and rotation laxity (vertical dimension). The vertices are laxity values, and the spaces between were filled to create a semitransparent surface. The *dashed lines* with *open circles* on the left and right vertical planes are projections of the surface contours, which stratifies the position and tension groups, respectively.

Capsule tension had a significant effect on laxity in each direction except for anterior laxity ($P = .124$). Anterior laxity behavior also did not follow the capsule tension trend by increasing from baseline through 5-mm plication then decreasing through 15-mm plication. All other directions increased from baseline to laxity and then decreased to 15 mm. The relative changes in stretched laxity compared with baseline were as follows: IR increased most (10%, 4° ± 1°), followed by ER (4%, 3° ± 1°), posterior (4%, 1 ± 0 mm), inferior (3%, 1 ± 0 mm), and anterior (1%, 0 ± 0 mm). Laxity decreased in all directions from 5-mm to 15-mm plication. The relative changes in 15 mm laxity compared with 5 mm were as follows: inferior decreased most (−15%, −3 ± 1 mm), followed by posterior (−15%, −3 ± 1 mm), anterior (−9%, −2 ± 1 mm), ER (−9%, −8 ± 2°), and IR (−9%, −5 ± 1°). Contrasts revealed plicated capsule tension was restored (not significantly different than baseline) at 5 mm, 10 mm, and 15 mm for anterior; 5 mm for posterior; 5 mm and 10 mm for inferior; 10 mm for IR; and 5 mm for ER.

Position had a significant effect on laxity in all directions. Exception to the overall position trend was inferior laxity, which consistently decreased with abduction, and ER laxity which consistently increased with abduction. For anterior, posterior, and IR directions, the most laxity was observed was in 20° and the least laxity was observed in 60°; for inferior, the most laxity was in 0° and least was in 60°, and the opposite was seen in ER. The largest relative change in laxity compared with 0° occurred at the 60° position for inferior (−50%, −17 ± 2 mm), posterior (−44%, −8 ± 1 mm), and ER (29%, 21° ± 3°) directions. This occurred at the 20° position for anterior (13%, 3 ± 1 mm) and IR (16%, 7° ± 1°) directions. Laxity in all directions except inferior was significantly different between 0° and 20°.

The overall composite tension × position effect was significant for ER laxity ($P = .029$), IR laxity ($P = .016$), and inferior laxity ($P = .040$). The composite effect on anterior and posterior laxity was not significant. Depending on position, laxity generally increased and decreased at different rates across tension levels. In addition to Figure 5, Figure 6 is useful for visualizing these changes. For example, laxity increased less in 0° from baseline to stretched IR than the other positions. After stretched, laxity in 20° and 40° decreased at a rate faster than 0° and slower than 60°. Composite contrasts were significant for all directions.

Detail of composite laxity behavior across plication tensions is seen in Figure 6. Here, laxity values were adjusted to baseline and stratified into positions to enhance position-dependent laxity patterns. On average, inferior laxity in 0° did not overtighten the joint

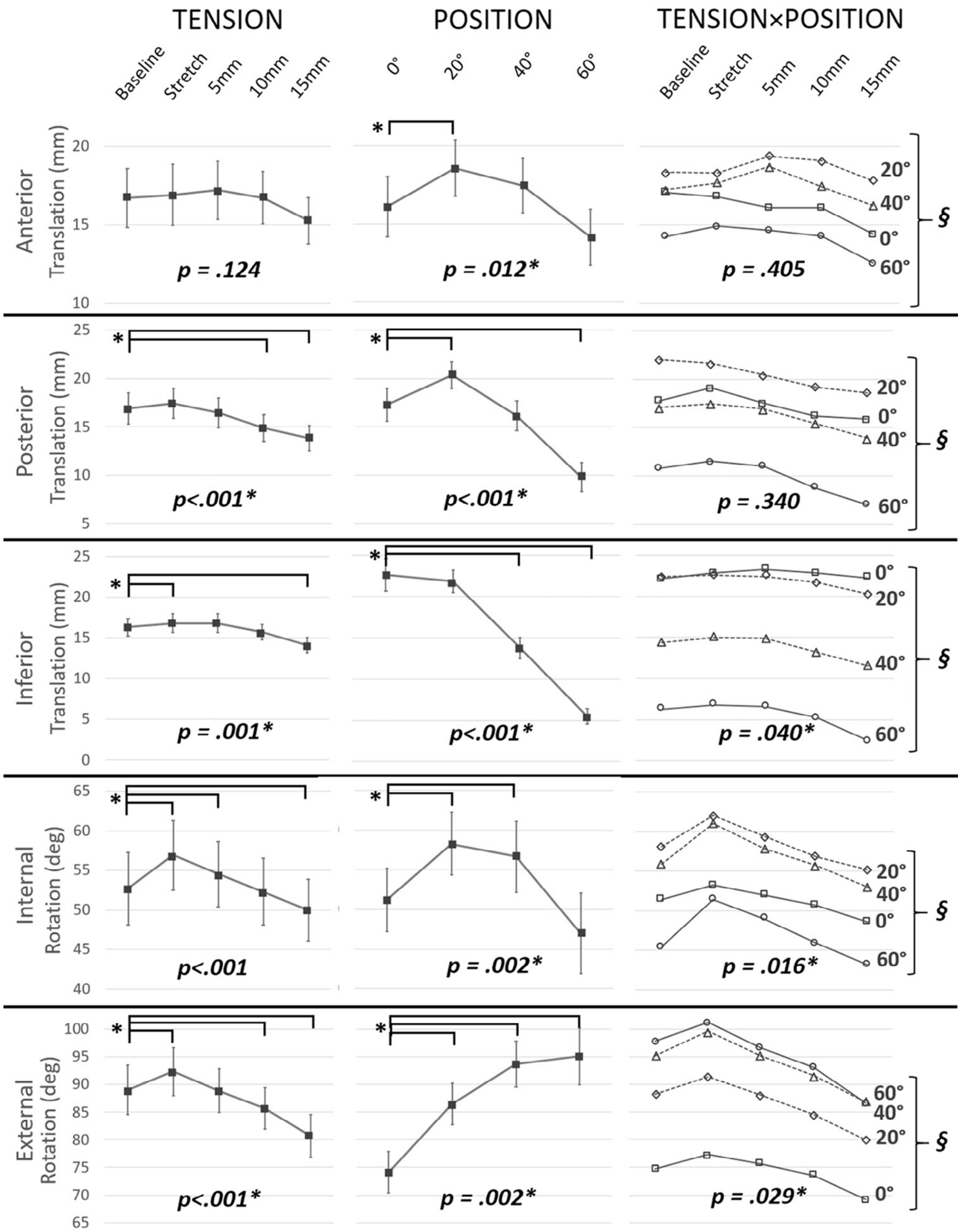


**Figure 5** Estimated marginal means and ±1.0 standard error bars of glenohumeral capsule laxity across factor levels (horizontal) and directions (vertical). Capsule tension, position, and composite tension × position levels are listed in the columns and each direction is listed in the row. Capsule tension values encompass laxity across all positions, and position values encompass laxity across all capsule tensions. The *P* values of each factors' main effect and corresponding direction are given below each graph. The *brackets* and * indicate a significant contrast difference ($P < .05$) between tension and position levels. §$P < .05$ for composite contrast. The *errors bars* are not shown for the composite graphs. For each direction, the vertical axis scale lines are the same from left to right for all graphs in that row. Within the composite graphs, the *dotted lines* are the middle-range (20° or 40°), and the *solid lines* are the end-range (0° or 60°) positions.

compared with 20°, 40°, and 60°. Similarly, ER laxity in 0° showed less decrease over plication than the other positions. Within the composite contrasts, significant differences in laxity were found between middle-range (20° or 40°) and end-range positions (0° or 60°) for anterior ($P = .002$), posterior ($P < .001$), inferior ($P < .001$), ER ($P = .037$), and IR ($P = .002$) directions. This is strong evidence to suggest laxity behavior was mediated by the tension-position interplay differently between the middle range and end range.

## Discussion

This study investigated biomechanical laxity of the glenohumeral capsule in 5 directions across multiple capsular

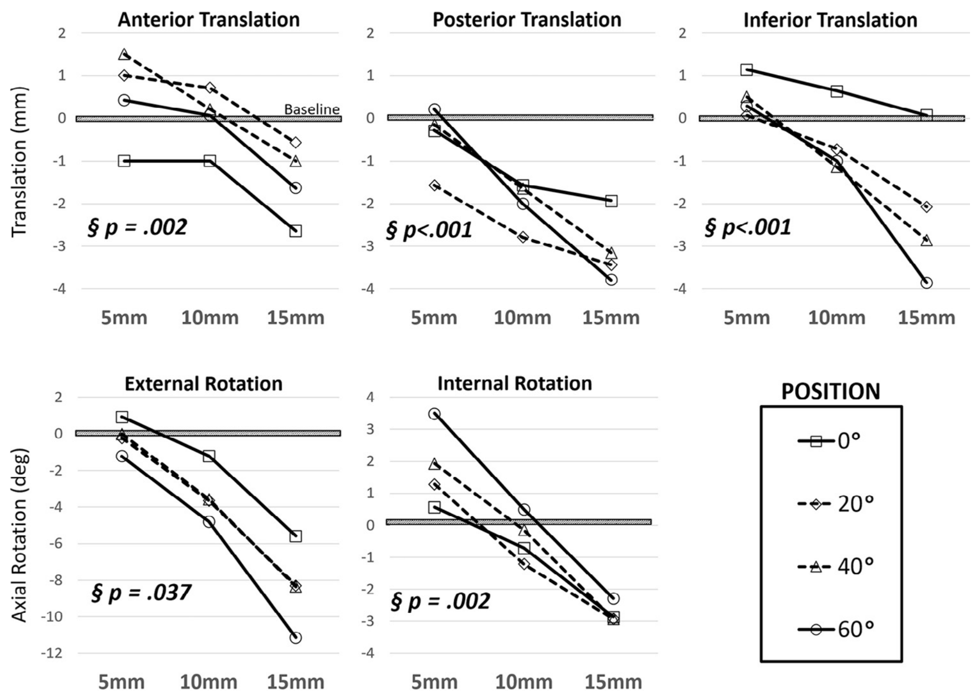


**Figure 6** Composite laxity effect across plication levels, stratified by position. Plotted are the mean laxity values offset by baseline to better compare laxity changes between positions. §$P < .05$ (significant difference) in composite laxity, between middle-range (20° or 40°) and end-range (0° or 60°) position subgroups for external and internal rotation, with *P* values given. The *dotted lines* show the middle-range position (20° or 40°) and the *solid lines* show the end-range position (0° or 60°).

tensions and scapular abduction positions. We found glenohumeral capsular laxity in a cadaveric model varied as a composite effect with capsule tension and position as well as with each independently. MDI is a challenging pathology to manage,[25] and variation of capsular plication among orthopedic practice is recognized as a challenge that complicates management of atraumatic shoulder pathology.[1,7,10,29] Complexity of glenohumeral laxity eludes accurate classification and thus universal standardization, but this problem can be partially addressed through improved clinical laxity tests already familiar to the clinician. To achieve this, we believe a better understanding of the relationship of tension and position is necessary.

The effects of injury and capsule plication on glenohumeral joint mechanics and stability have been reported in many in vitro biomechanical studies.[2,5,6,8,12,14,17-22,27] Overall, prior investigations have reported the translational and rotational mechanical responses of the stretched and surgically repaired capsule; however, gaps in knowledge remain. First, the positions tested were limited by not investigating the middle range of abduction; second, the spectrum of repairs did not adequately probe both an underconstrained or overconstrained capsule tension; and third, whether a composite effect of tension and position exists is not known, and if so, should be considered and for what directions it is important.

Passive shoulder laxity is mediated primarily by the capsule, which constrains joint motion through a "differential engagement" mechanism. Differential capsule engagement occurs due to (1) varying capsule ligament stiffness and slack length properties within an individual, (2) varying capsule ligament stiffness and slack length properties between individuals, and (3) tension-position codependence. We believe this complex relationship is implied throughout the literature but has not been explored experimentally. A lack of uniformity in experimental methodology makes directly comparing results difficult and may explain discrepancies with our work and the literature. A summary of translation and rotational laxity from this work and the literature, across capsule tension levels in the 0° and 60° position, is in Figure 7.

A unique aspect of this study was the measurement of capsular laxity in 5 directions across every combination of 5 tension levels and 4 position levels: a total of 100 different combinations. We have attempted to improve our knowledge of laxity at various capsular tensions and positions and have shown new relationships over a larger range of experimental conditions. Other studies have reported laxity measurements in up to 5 directions, most commonly anterior translation, posterior translation, ER, and IR, and tested at up to 2 positions, most commonly 0° and 60°.[2,14,16,17,20]

The stretched condition in this work was intended to simulate atraumatic MDI. After stretching, we found significant increases in inferior, ER, and IR laxity compared with baseline, but anterior and posterior laxity increases were not significantly different. Changes in laxity ranged up to 0.5 mm translationally and 4.2° rotationally. Similar studies have reported increases after stretching that agree with our work.[2,14,20] Presently, the precise loading pattern, dosage, percentage

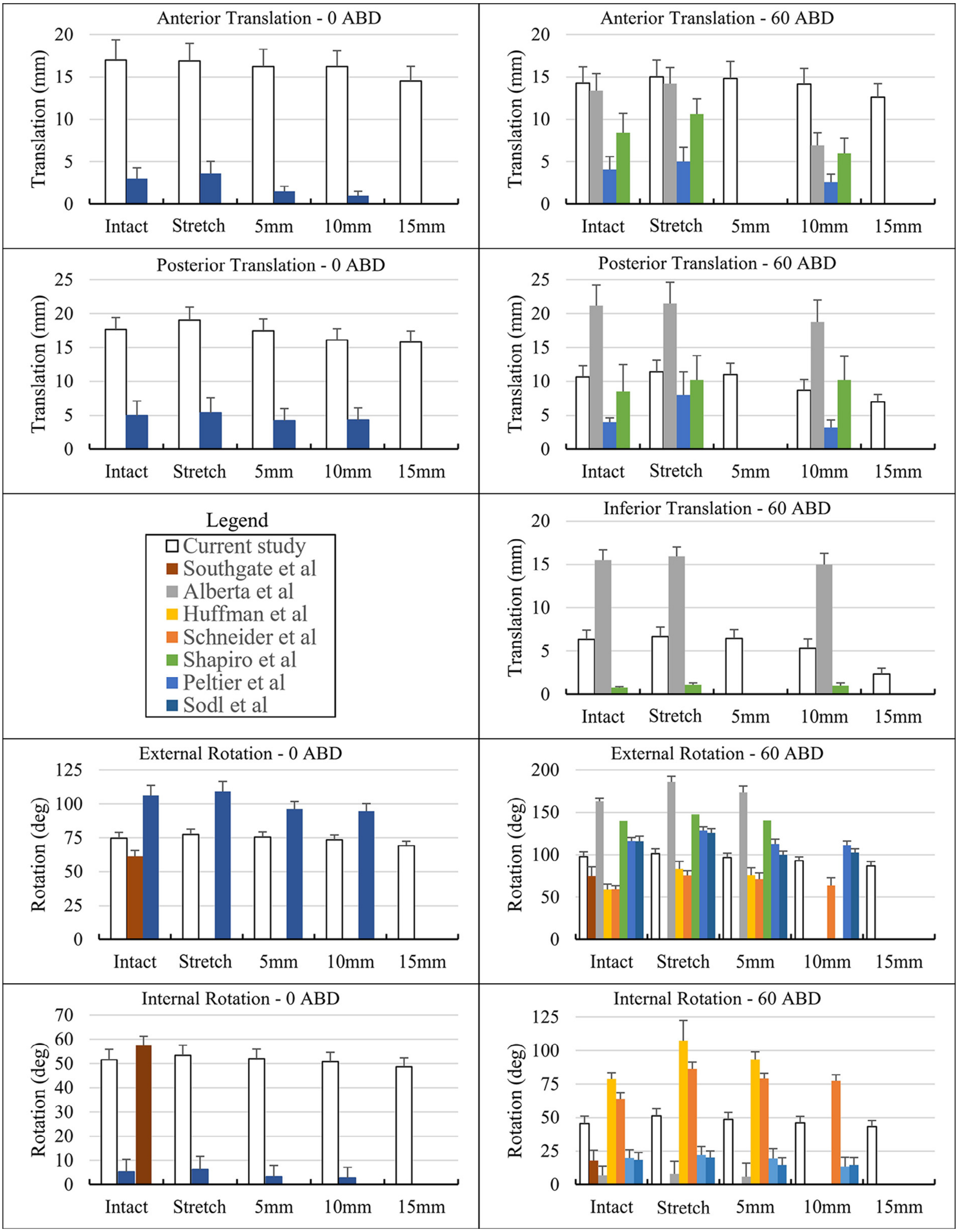


**Figure 7** Comparison of glenohumeral laxity across the relevant literature. Mean values are shown +1.0 standard error for each direction in 0° and 60° positions. Directions are in separate rows and 0° is in the left column. The *unshaded bars* show data from this work. *ABD*, abduction. (To view this figure in color, the reader is referred to the web version of this article.)

increase, or directions of laxity to characterize MDI in a cadaveric model are not known and require additional research.

Surgical plication intends to restore the capsular tissues, but precisely describing from the available research what constitutes capsule restoration to a preinjury state and the surgical parameters required to achieve this is difficult. In lieu of an accepted definition, we assumed a basic definition of restoration to be average laxity values not statistically different from baseline (control). We also assumed underconstrained and overconstrained laxity to be average laxity values significantly greater and smaller than baseline, respectively. Our experiment simulated 3 plication tensions of incremental magnitude to create a basic spectrum of restorative laxity—from too loose to too tight. The magnitudes were chosen based on available literature where 5-mm and 10-mm plication magnitudes are most commonly studied[2,14,16-18,20] and reported up to 15-mm plication.[6] Still, a comparison of our experimental protocol with the literature must be interpreted with differences in methodology between all studies in mind.

We found laxity after 5-mm plication was not significantly different from baseline except for the IR direction, which was greater by 1.8° ± 0.8°. Also, posterior and ER laxity were on average equal to or decreased below baseline. In 1 other study, Schneider et al[17] reported IR and anterior translation were significantly greater than intact after a 5-mm inferior capsular shift, and ER was greater on average but not significant. We found mixed agreement with our 5-mm plication results and the literature, which may be due to differences in methodology. Interestingly, average anterior laxity increased from stretched to 5 mm, which is counterintuitive, but this trend was also found in several other studies.[14,16,18,20] Even so, our data suggested on average a 5-mm plication could be considered a conservative (underconstraining) tension for laxity restoration in cadaveric models.

After a 10-mm plication, we found posterior and ER laxity were significantly less than baseline, suggesting 10 mm may overconstrain these directions. On average, anterior laxity was greater than baseline, and inferior and IR laxity were less where changes ranged from 0.1 mm to −1.9 mm and −0.4° to −3.2°. Other studies have reported varied results across translation and rotational laxity as to significant decreases at 10 mm from control.[14,16-18,20] We found mixed agreement with our findings and the literature about the restorative capacity of a 10-mm plication. Our work suggested 10-mm plication restored capsular laxity in most directions. Furthermore, we found 10-mm plication overconstrained rotational laxity more often than translational laxity. This finding is important because surgeons must not overconstrain glenohumeral rotation, especially ER in the overhead athlete.

In the 15-mm plication condition, we found laxity significantly decreased below baseline for posterior, inferior, ER, and IR laxity, but not anterior laxity; changes ranged from −1.4 mm to −3.0 mm and from −2.7° to −8.2° below baseline. Other than our work, no other comparable study has reported using a 15-mm magnitude plication. Only Fitzpatrick et al[6] reported capsule imbrication of 15 mm, but it was done only posteriorly and on select cadaveric specimens. Based on our results, we show a 15-mm plication will overconstrain cadaveric glenohumeral motion at time 0, but how this condition would evolve over the course of rehabilitation and return to activity and whether overconstrained laxity regresses to preinjury status is not known.

Our findings highlight that the capsule has a different engagement mechanism throughout scapular abduction, and humeral elevation is thus a key factor in laxity. We found laxity in all directions was affected by changes in position, and most changes were significantly different from 0° abduction. A study by Southgate et al[22] was the only other study of rotational laxity in a middle-range position that reported elevation significantly affected rotation. Their findings were in good agreement with our work, but no surgical repair conditions were tested. To our knowledge, our reported translational glenohumeral laxity in middle range has no basis for comparison in the literature. Our results quantify the sensitivity of glenohumeral laxity to scapular abduction and provide new information in the middle range of abduction.

The reported composite effect of capsule tension and position highlighted the complexity of passive shoulder laxity, which underscores the multidimensional nature of clinical laxity testing. A main finding was that laxity decreased differently across plication levels as a result of codependence on position. This means that predicting capsule tension is influenced by both the plication tension and position chosen, which also implies clinical laxity assessment may differ because of it. This phenomenon was statistically significant for rotational laxity and inferior laxity. The other directions showed no evidence of an overall composite effect, which was masked due to generally higher data variability in the composite translation data. However, these results described an omnibus (RM-ANOVA) composite effect, which was nonspecific to any tension and position levels. In contrast, the composite contrast analyses revealed a significant effect in all directions. This is strong evidence that the tension-position interplay is specific to surgical plication and between middle-range and end-range abduction. Composite laxity knowledge, when applied, may mediate the interpretation of clinical laxity tests, such as tension restoration, related to surgery. Such a determination is complicated and, arguably, never certain. Still, shoulder position is a source of variability that may lead to different conclusions, such as whether laxity is above, equal to, or below a restorative level, or how much tightening was achieved. Our findings, although limited to a small cohort, indicate that investigations into the enhancement of clinical laxity tests need to carefully consider capsule tension and also the position tested.

We also suggest caution in the use of statistical composite effects in practice, because they must be considered carefully. From one perspective, laxity in a direction that is composite-sensitive may have the potential to better distinguish among capsule tension-position combinations. From another perspective, avoiding such a direction may be wise because of the additional complexity it would bring to clinical practice. Nonetheless, the design, use, and interpretation of clinical laxity tests may be confounded if composite effects are present and not accounted for.

This work has several limitations that must be considered when interpreting the results. First, the average age of the models was 56 years, for which there is less clinical laxity in the general population.

Second, the information obtained in this study was through dissection of cadaveric models; thus, they do not represent an in vivo scenario. The effect of removing pericapsular tissues on laxity has not been sufficiently studied, but it is reasonable to expect our laxity values overestimate in vivo glenohumeral laxity. Also, freezing and thawing would influence soft tissue properties, but its extent is not well understood.

Third, the small sample size makes the results difficult to generalize to larger and more diverse groups.

Fourth, our experiment simulated an MDI pathology, and therefore, the conclusions may not extend to other capsulolabral pathologies that include both traumatic and atraumatic lesions. Our work specifically targeted the capsular tissue, but in vivo pathoanatomy is more complex and, for example, commonly includes labral detachment.[15] Also, whether the observed change in laxity created in stretched tension was clinically meaningful is unknown. This may lessen the extent surgeons can usefully interpret changes, because ascertaining relevance in the context of a cadaveric study is difficult. Still, our results showed increases in laxity in line with other cadaveric studies that had a laxed experimental condition,[2,14,17,19,20] which is detailed in Figure 7.

Fifth, undue incremental stretching could have accrued with repeated loading and been exacerbated by plication resuturing. This effect was not quantified or controlled for during testing or in our analysis.

Sixth, suture orientation and placement may not reflect widespread practice. The sutures in this were oriented "North-South," but "East-West" sutures are also common in orthopedic practice. Plication suture alignment, for example, parallel to the capsule's localized principal strain or in line with the capsule fibers,[19] might possibly have a different effect on laxity. Yet, no study to date has directly compared biomechanical consequences of multiple suture orientations. Alternatives to this study's imbrication technique include anchoring to the labrum because of its more robust tissue, and glenoid bone anchors, which are used when labral quality is poor. The posterior and inferior plication technique is not common in practice due to the need for a separate open posterior approach and proximity to the axillary nerve and possible entrapment into the plication respectively[11]; however, arthroscopic techniques for plication do commonly encompass these areas.

Last, the study may not translate directly to clinical practice, but the data strongly suggest an interplay between glenohumeral laxity, arm position, and capsule condition that is present in all or most shoulders in the context of atraumatic shoulder instability repair.

## Conclusions

Glenohumeral laxity in the dissected cadaveric shoulder was affected by capsule tension and position unequally across directions. We found that a 5-mm plication had a marginal effect on laxity but did not limit motion, whereas a 10-mm plication overconstrained laxity in posterior translation and external rotation, and a 15-mm plication overconstrained laxity in all directions. The composite effect, however, had observable consequences on glenohumeral laxity and redefined the restorative plication tension in some cases. This information suggests that decisions based on a clinical laxity assessment depend on the amount of abduction. Laxity tests done in middle-range abduction may have the potential to enhance diagnostic accuracy and standardization both in and out of a surgical setting, but research in this area is underdeveloped. Our analysis showed evidence that laxity in IR, ER, and inferior translation was susceptible to interplay of tension and position.

The practical takeaway from this study should be conservative; still, we believe this knowledge will be necessary in developing a standardized approach to clinical shoulder assessment. As such, future work should examine capsular tension-position codependence on laxity in more realistic shoulder models and in conjunction with other pathologies. Future studies should also investigate how to optimize clinical tests that maximize diagnostic accuracy by investigating other planes of motion, while collecting additional clinical metrics. Our findings provide valuable insight and a clinically relevant resource of glenohumeral laxity across a multitude of conditions. In addition, the methodology presented here can be adapted to extend our understanding of joint mechanics with other capsulorrhaphy procedures.

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