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Correction

A correction has been published for this article. The contents of the correction have been appended to the original article in this reprint.

The Effect of Supraspinatus Tears on Glenohumeral Translations in Passive Pitching Motion

Andreas M. Mueller,*† MD, Claudio Rosso,*† MD, MSc, Vahid Entezari,* MD, MSc, Brett McKenzie,* BSc, Andrew Hasebroock,* BSc, Ugo Della Croce,‡ PhD, Ara Nazarian,*§ PhD, Arun J. Ramappa,|| MD, and Joseph P. DeAngelis,|| MD
Investigation performed at the Center for Advanced Orthopaedic Studies, Beth Israel Deaconess Medical Center and Harvard Medical School, Boston, Massachusetts, USA

Background: Supraspinatus tears are common in pitchers. However, the effect of these tears on glenohumeral (GH) mechanics is incompletely understood.

Purpose/Hypothesis: To describe the effect of supraspinatus tears and repairs on GH kinematics during an abbreviated throwing motion using the intact shoulder girdle. The hypothesis was that supraspinatus tears would lead to an increase of GH translation in the coronal plane and supraspinatus repairs would restore GH kinematics.

Study Design: Controlled laboratory study.

Methods: Six shoulders from 3 fresh-frozen cadavers were tested in a novel 7 degrees of freedom robotic testing system. Torsos were mounted and the wrist was pinned to an actuator mounted on an upper frame. After the deltoid was removed, the shoulders were studied during an abbreviated throwing motion (ATM) from maximum external rotation to the midcoronal plane to establish a baseline. The ATM was repeated after creation of a 1-cm supraspinatus tear, after creation of a 3-cm supraspinatus tear, and after repair with a transosseous equivalent (TOE) technique. Retroreflective bone markers and high-speed infrared cameras were used to measure GH kinematics and calculate the center of rotation of the GH joint (COR_{GH}) instantaneously.

Results: The 1- and 3-cm supraspinatus tears did not significantly alter GH translation. The TOE repair shifted the COR_{GH} posteriorly, as evidenced by a significant decrease in the overall GH translation in all 3 planes (P = .003, .019, and .026, for x-y, y-z, and x-z planes, respectively).

Conclusion: In contrast to a TOE repair of the supraspinatus tendon, isolated supraspinatus tears did not perturb GH kinematics in this cadaveric model of the throwing shoulder.

Clinical Relevance: In throwing athletes, treatment of rotator cuff tears should be addressed with caution to avoid an unintended alteration in GH kinematics due to overtightening of the tendon.

Keywords: supraspinatus tear; glenohumeral joint; translation; shoulder biomechanics; pitching

Supraspinatus tearing is common in professional pitchers and may pose a substantial threat to their career longevity.[31,44] These tears may result from internal impingement as the posterior-superior rotator cuff impacts the glenoid and the superior labrum during the throwing motion.[25] During the deceleration part of a throwing motion, the posterior capsule of the glenohumeral (GH) joint is exposed to high strain.[19] This may result in an adaptive hypertrophy and contraction of the posterior capsule. This change in the tissue compliance shifts the humeral head's point of contact with the glenoid toward the posterior-superior quadrant and, in turn, increases the strain on the articular surface of the supraspinatus tendon.[12,17] This effect is compounded by the tremendous tensile stresses experienced during deceleration. This process of internal impingement can lead to a partial supraspinatus tear, which may progress to a full-thickness tear.[31]

The effect of an isolated supraspinatus tear on GH kinematics remains unclear: Numerous studies have demonstrated the role of the supraspinatus as a dynamic stabilizer of the GH joint.[3,6,7,32,47] Nonetheless, many authors propose the transverse force couple theory: Cocontraction of the infraspinatus and the subscapularis in the midrange of motion is believed to be sufficiently strong to prevent excessive GH translation, particularly in the superior direction.[9] Therefore, some studies investigating simple elevation motion patterns did not demonstrate any alterations of GH kinematics in supraspinatus-

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deficient shoulders compared with shoulders with an intact rotator cuff.[24,43,46,50] Yet recent electromyographic (EMG) results suggest that the dynamic effect of the transverse force couple may be reduced during extreme ranges of internal and external rotations as experienced in pitching[¶]: Boettcher et al[8] and Dark et al[13] observed EMG activity of the subscapularis exclusively in internal rotation, while EMG activity of the infraspinatus was only observed in external rotation. There was no concomitant EMG activity of the subscapularis and infraspinatus as proposed by the transverse force couple theory.

However, with the reduced dynamic effect of the transverse force couple, the rotator cuff may still provide a passive restraint against abnormal GH translations.[10,15,37,40,49,52] Previous studies investigating simple elevation motion patterns suggested that the supraspinatus may also passively resist superior and inferior GH translation.[52,39,47] Unfortunately, no biomechanical study has described the passive effect of the supraspinatus during the much more complex pitching motion. In addition, cadaveric investigations that have examined the role of the rotator cuff as a passive restraint have constrained the shoulder by immobilizing the scapula to manipulate the humerus over a limited trajectory.[15,37,40,49] Unrestrained scapulothoracic motion is a prerequisite for normal GH kinematics, and any alteration in the scapula's position significantly disrupts GH motion.[27,36]

To advance our understanding of passive GH kinematics, an automated robotic system was developed to test pitching motion with an unconstrained scapulothoracic joint.[18] Using this passive cadaveric model, we hypothesized that a supraspinatus tear would increase superior-inferior GH translations (ie, in the coronal plane) and that repair of the rotator cuff tear would restore normal GH kinematics.

MATERIALS AND METHODS

Testing Apparatus

A validated robotic system was used for this study.[18] The system consists of a lower frame housing the cadaveric torso and an upper frame to which the upper limb is attached (Figure 1). The torso frame can move along the x-, y-, and z-axes and rotate around the z-axis, while the upper limb frame can move along the x-, y-, and z-axes. All axes are moved by actuators and controlled via a programmable central controller to generate any motion trajectory within the actuators' limits with high reproducibility and accuracy.

Cadaveric Torsos

Three fresh-frozen human cadavers were acquired from Medcure Anatomical Tissue Bank. The cadaveric torsos originated from 3 white males with a mean ± SD age of 55 ± 4 years, height of 190 ± 4 cm, and body mass index of 27.1 ± 1.85 kg/m^2. Testing was performed bilaterally. Torsos were mounted on a rod fixture and held in place with expanding foam. The hand was disarticulated at the distal radioulnar joint, and the arm was secured directly to the hand frame by use of a Schanz pin inserted through the radius and ulna. The skin and the deltoid muscle were removed. Passive retroreflective marker clusters were placed in the humeral shaft, the posterolateral acromion, and the sternum. To protect the cadaveric specimens, testing was performed at a reduced speed (duration of motion, 28.6 seconds). This testing setup was used and validated in previous studies.[36,45]

Simulation of Throwing Motion and Implementation of Supraspinatus Tear and Repair

Shoulders were tested through an arc of motion that began at 120° of external rotation (ER_{120}) and ended as the hand arrived at the midcoronal plane (ER_{90}). Throughout this arc, the arm was abducted to 90°. This motion can be considered as part of a throwing motion from late cocking to the end of deceleration. External rotation was achieved in this passive model by placing a restraint posterior to the abducted humerus. During the investigation, each specimen served as its own internal control, and changes in GH kinematics were recorded as the difference from the baseline (BL) condition to account for hysteresis (dependence of tissue properties on current and previous environmental conditions minus time dependence). All conditions were tested in triplicate, and the average data were analyzed.

Each specimen was tested 3 times from ER_{120} to ER_{90} to establish BL. A full-thickness supraspinatus tear measuring 1 cm anterior to posterior (referred to as ST1) was created at the middle of the supraspinatus insertion (50-yard line), and the specimen was tested again 3 times (Figure 2A). The tear was then extended anterior and posterior until 3 cm of the supraspinatus footprint was detached (referred to as ST3) (Figure 2B). Tears were not extended

[¶]References 8, 9, 13, 14, 23, 24, 29, 46, 48, 50.

[§]Address correspondence to Ara Nazarian, PhD, Center for Advanced Orthopaedic Studies, Beth Israel Deaconess Medical Center and Harvard Medical School, 330 Brookline Avenue, RN115, Boston, MA 02215, USA (e-mail: anazaria@bidmc.harvard.edu).

*Center for Advanced Orthopaedic Studies, Beth Israel Deaconess Medical Center and Harvard Medical School, Boston, Massachusetts, USA.

[†]Orthopaedic Department, University Hospital Basel, Basel, Switzerland.

[‡]Information Engineering Unit, POLCOMING Department, University of Sassari, Sassari, Italy.

[||]Department of Orthopaedic Surgery, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, Massachusetts, USA.

A.J.R. and J.P.D. contributed equally as senior authors to this work.

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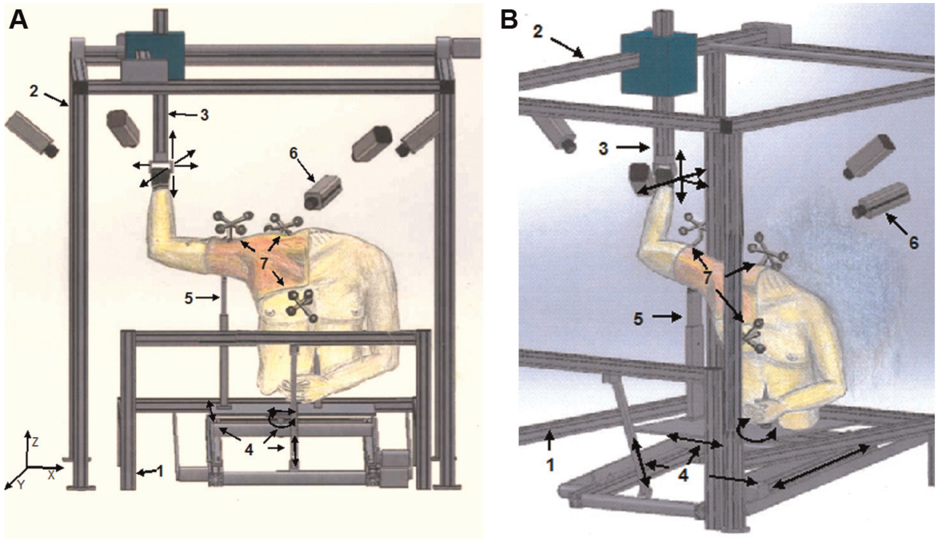

Figure 1. Schematic illustration of the 7 degrees of freedom testing apparatus as seen (A) from the front and (B) from the side. It consists of a lower frame (1) housing the torso and an upper frame (2) controlling the upper extremity. An actuator (3) attached to the cadaver at the level of the wrist moves along the x-, y-, and z-axes. Multiple actuators within the lower frame (4) move the torso along the x-, y-, and z-axes and around the z-axis. Maximum external rotation is achieved with the use of a posterior restraint (5). Five high-speed cameras (6) track the motion of bone-embedded markers (7).

Figure 2. Representative (A) 1-cm and (B) 3-cm tears along with (C) a double-row repair.

into the biceps. After this condition was tested 3 times, a transosseous equivalent (TOE) rotator cuff repair[42] was performed by 2 orthopaedic surgeons with longstanding experience in shoulder surgery (A.J.R. and J.D.A.): Two suture anchors (Bio-Corkscrew FT, 5.5 × 15 mm; Arthrex) were inserted in the greater tuberosity just lateral to the articular surface of the humeral head to create a medial row. From anterior to posterior, the anchors were separated from each other by approximately 1 cm. Each suture anchor contained 2 strands of No. 2 braided Fiberwire. A suture lasso (Arthrex) was used to shuttle each suture limb through the supraspinatus tendon to create a horizontal mattress suture. The sutures were tied. The limbs of each knot were then fixed laterally by use of two 4.5-mm PEEK Pushlock anchors (Arthrex) 1 cm inferior to the lateral edge of the greater tuberosity in line with the medial suture anchors (referred to as supraspinatus repair, SSR) (Figure 2C). After the completion of the repair, each specimen was tested.

Motion Analysis

Five Qualisys Pro Reflex (Qualisys AB) high-speed cameras (120 Hz) fixed to the testing frame were used to collect the motion of the passive retroreflective bone-embedded marker clusters that were drilled into the humeral shaft, the sternum, and the acromion (Figure 1). Before testing, the high-speed cameras were subject to multiaspect calibration. Anatomic scapular, humeral, and thoracic landmarks were calibrated with respect to these technical (bone-embedded) marker clusters by use of a point wand. These anatomic landmarks were previously defined by the International Society of Biomechanics[53] and include the following anatomic structures: The acromioclavicular joint (AC), the posterolateral edge of the acromion (AA), the coracoid process (PC), the inferior angle of the scapula (AI), the root of the spine of the scapula (TS), the inferior angle of the scapula (AI), the spinous process of the seventh cervical vertebra (C7) and eighth thoracic vertebra (T8), the xiphoid process (PX), the suprasternal notch (IJ), and the medial and lateral epicondyles (EM and EL). The calibrated scapular and humeral landmarks were used along with equations outlined by Meskers et al[34] to determine the instant center of rotation of the GH joint (COR_{GH}) within the scapular reference system. In this system, the z-axis is a line connecting the TS and AA points; the x-axis originates from the AA point and is perpendicular to the plane formed by the AI, the AA, and the TS points; and the y-axis is the common line perpendicular to the x- and y-axes. Translations of the GH were considered to be equal to 0 in the BL condition at ER_{120}.

Statistical Analysis

Translations of the GH were recorded continuously throughout the simulated motion from ER_{120} to ER_{90}. For each condition, the average GH translation was plotted over time to calculate the total translation and the area under the curve (AUC) during each motion segment. The absolute GH translations were calculated for BL, ST1, ST3, and SSR at ER_{120}, ER_{110}, ER_{100}, and ER_{90} (Figure 3). Two-way repeated-measures analysis of variance (ANOVA) was performed to compare GH translation for the condition (BL, ST1, ST3, SSR) and the axis (x, y, and z). The AUC was calculated for each condition on each axis by use of the trapezoidal rule to appropriately assess the path-dependent motion (Matlab v 12; Mathworks). The Wilcoxon signed rank test was used to compare the AUCs between the conditions. Total translation was calculated for each condition (BL, ST1, ST3, SSR) between ER_{120} and ER_{90} by use of the distance formula, and a univariate ANOVA was used to compare total translation for each axis during the different conditions.

With 6 specimens from 3 donors included (3 pairs), the statistical power was 80% to detect a difference of greater than 1.0 mm of GH translation between the different conditions (BL, ST1, ST3, SSR) and 85% power to detect mean differences of greater than 1.2 mm of translation using ANOVA with a compound symmetry correlation structure to handle the paired specimens.

Statistical analysis was conducted with SPSS (v 21.0; IBM-SPSS Inc). Two-tailed *P* values less than .05 were considered significant.

RESULTS

The COR_{GH} demonstrated a similar pattern of motion for all of the experimental conditions (BL, ST1, ST3, and SSR) during the simulated motion from ER_{120} to ER_{90}. About the x-axis (anterior-posterior [AP]), COR_{GH} moved anteriorly at the beginning of early acceleration, from ER_{120} to ER_{100}, and then moved posteriorly as the humerus approached ER_{90} (Figure 3, top panel). The AP total translation was 5 mm (net translation, 4 mm). The

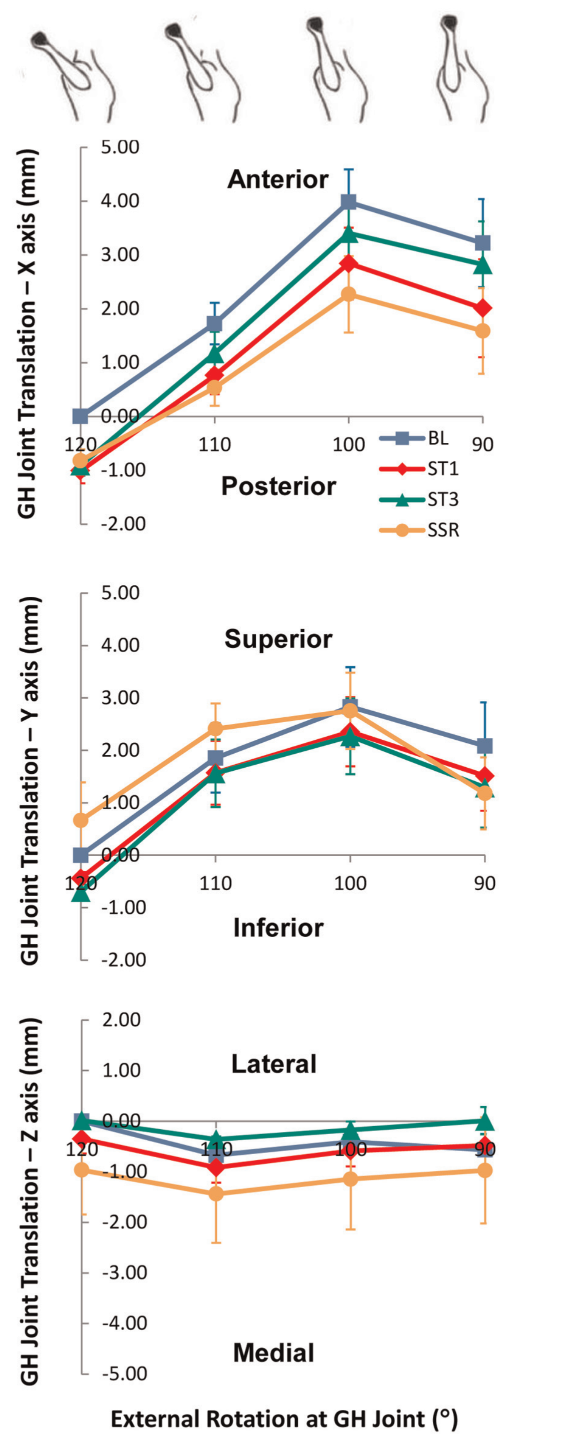

Figure 3. Glenohumeral (GH) joint motion trajectory in the x-, y-, and z-axes for all conditions (BL, baseline; SSR, supraspinatus repair; ST1, 1-cm supraspinatus tear; ST3, 3-cm supraspinatus tear) at all external rotation positions (ER_{120}, ER_{110}, ER_{100}, and ER_{90}).

COR_{GH} behaved similarly about the z-axis (medial-lateral [ML]), moving medially from ER_{120} to ER_{100} and laterally from ER_{100} to ER_{90} (Figure 3, bottom panel). In the z-axis, the COR_{GH} exhibited the smallest translation (total superior-inferior [SI] translation, <2 mm; net translation, <1 mm). In the y-axis (SI), the COR_{GH} moved superiorly from ER120 to ER110 and inferiorly from ER110 to ER90 (Figure 3, middle panel). The total SI translation was 4 mm (net translation, 3 mm).

While the motion in the AP plane (x-axis) demonstrated a common pattern, the magnitude of the translation decreased among experimental conditions ST1, ST3, and SSR. The COR_{GH} had the most motion in the BL condition, followed by ST1, ST3, and SSR conditions. There was a significant difference between BL and SSR at ER_{120}, ER_{110}, ER_{100}, and ER_{90} (P < .04). No significant differences were observed in the SI or ML planes (y- and z-axes, respectively).

The AUC analysis revealed that the rotator cuff repair (SSR) significantly affected the motion trajectory in all 3 axes when compared with the other conditions (P = .041, .044, and .04 for x, y, and z, respectively). The remaining trajectories were not significantly different (P > .05) (Figure 3).

When the COR_{GH} was plotted on 2 axes, an AUC analysis was used to compare each path-dependent movement. The movement of COR_{GH} from ER_{120} to ER_{90} is presented in the coronal plane (Figure 4A), the sagittal plane (Figure 4B), and the axial plane (Figure 4C). When the 4 conditions (BL, ST1, ST3, SSR) were compared in the coronal plane, the 1-cm rotator cuff tear (ST1) resulted in a medial and inferior shift, the 3-cm tear (ST3) translated the COR_{GH} laterally, and the repair (SSR) moved the COR_{GH} farther medially and superiorly.

In the sagittal plane, the 1-cm tear shifted the COR_{GH} posteriorly and inferiorly, the 3-cm tear resulted in a posterior shift of the COR_{GH}, and the repair moved the COR_{GH} posteriorly and superiorly. In the axial plane, the 3-cm tear shifted the motion more laterally, while the repair caused a more medial shift (Figure 4C).

The repair (SSR) had a lower overall translation in all 3 planes when compared with the BL condition (P = .003, .019, and .026 for x-y, y-z, and x-z planes, respectively).

DISCUSSION

This investigation evaluated the effect of a supraspinatus tear on GH kinematics during an abbreviated throwing motion in a cadaveric model. On the basis of previous research,[39,47,52] we hypothesized that a supraspinatus tear would result in increased SI translation of the humeral head and that its repair would restore normal GH kinematics. However, our data revealed that GH translations were not altered with supraspinatus tears during the simulated motion from 120° to 90° of external rotation in this passive cadaveric model. When 1- and 3-cm tears were created in the supraspinatus, no significant differences were observed in the joint's translations. Our study was 80% powered to detect a 1.2-mm difference

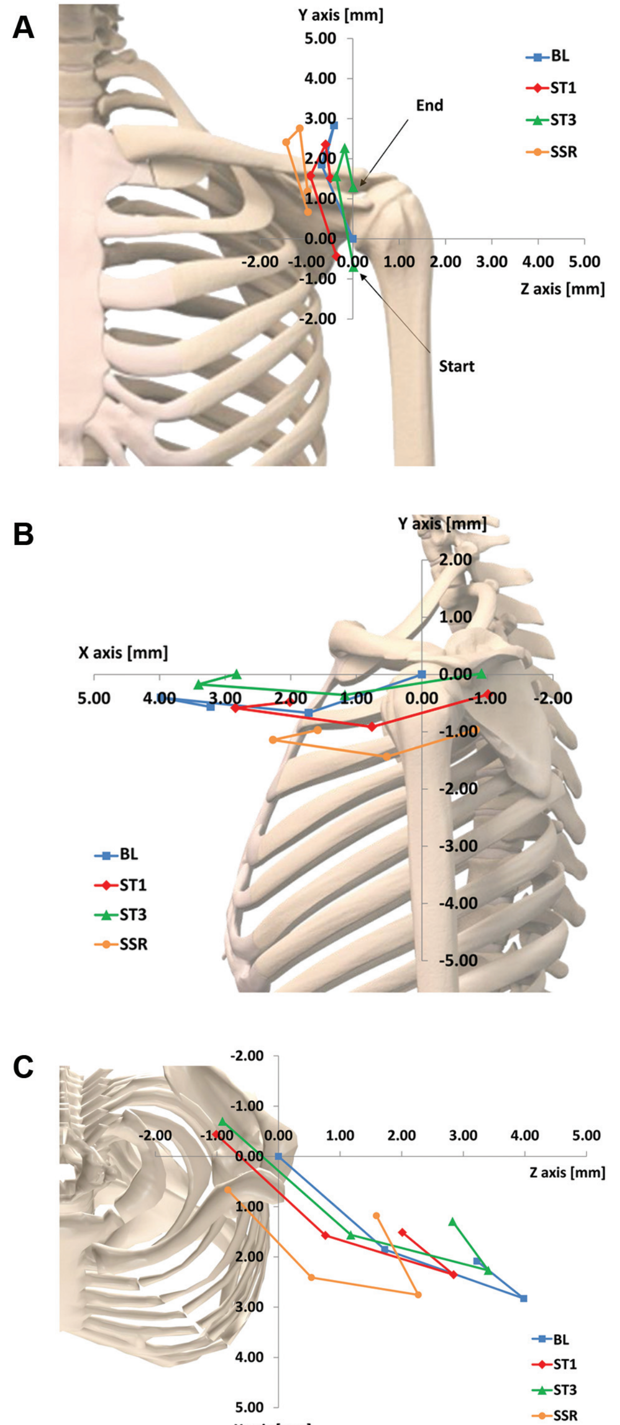

Figure 4. Glenohumeral joint translation in coronal (A), sagittal (B), and axial (C) planes. The start (120° of external rotation, ER_{120}) and end (90° of external rotation, ER_{90}) points of motion are outlined in Figure 4A, with ER_{110} and ER_{100} steps in between. This motion pattern is consistent across all conditions and axes. BL, baseline; SSR, supraspinatus repair; ST1, 1-cm supraspinatus tear; ST3, 3-cm supraspinatus tear.

of GH translations between the different testing conditions (BL, ST1, ST3, SSR). According to a previous magnetic resonance imaging study,[28] 1 mm of GH translation may be detected between patients with symptomatic rotator cuff tears and asymptomatic controls. Therefore, results from our study may be useful to detect clinically relevant differences with an acceptable probability of a β error.

Our findings are consistent with the work of Oh et al.[38] In their investigation using a cadaveric model with simulated muscle loading conditions, they demonstrated that only tears that propagated from the supraspinatus into the infraspinatus tendon led to a significant alteration of GH kinematics. Isolated supraspinatus tears did not significantly affect GH kinematics.[38]

In our study, the supraspinatus tendon was detached from its footprint and was not excised. Therefore, this investigation may model supraspinatus tears with little or no tendon retraction. In this situation, the torn supraspinatus tendon may lose its direct passive effect on the humeral head. However, it may still maintain its role as a subacromial spacer, preventing superior migration of the humeral head as suggested by Werner et al[52]: In this in vivo study, paralysis of the supraspinatus and/or the infraspinatus muscles was not associated with an increase of superior translation at 30° of resisted abduction. Yet the more inferior directed (passive) forces of the pectoralis major, teres major, and latissimus dorsi tendon may also pull the humeral head in a rather inferior position.[22,54] We could not detect a significant increase of inferior translation even with a complete detachment of the supraspinatus tendon. Yet, in our tear configurations, the rotator cable was not completely disrupted. As demonstrated by Burkhart et al,[11] the rotator cable consists of a thickening of rotator cuff fibers running perpendicular and approximately 1.8 mm medial to the supraspinatus tendon insertion and spanning with its humeral attachments from the biceps to the inferior boarder of the infraspinatus. Since the tears created in our study did not extend into the bicipital groove, the most anterior humeral attachments of the rotator cable were left intact. Like a suspension bridge, the remaining rotator cuff cable may have biomechanically compensated for the more laterally located rotator cuff tears and thus counteracted inferiorly directed loads. This hypothesis may be supported by a recent biomechanical investigation showing that the anterior rotator cable is the primary force-transmitting structure at the proximal humerus.[33] Nonetheless, continued loading in vivo could potentially propagate the tear and disrupt the humeral attachments of the rotator cable and thus alter GH kinematics. Such tear propagation may particularly occur in large supraspinatus tears (ie, >60% width).[1]

In contrast to the simulated rotator cuff tear, the TOE rotator cuff repair had a significant effect on shoulder motion. After the repair, the joint kinematics were constrained, resulting in less anterior translation of the COR_{GH} and less overall translation compared with the normal shoulder (baseline). The TOE rotator cuff repair resulted in path-dependent changes in the trajectory when compared with baseline with a significant posterior shift of COR_{GH}. Yu et al[54] and Bey et al[5] also found that supraspinatus repairs did not restore normal GH joint biomechanics, and those investigators observed that double-row repair might overtighten the tendon, leading to abnormal GH kinematics. However, Yu et al and Bey et al observed a more superior shift and not a posterior shift of the COR_{GH} after supraspinatus repair. This might be explained by the different motions that were investigated: In abduction, as investigated by Yu et al and Bey et al, the humeral head translates inferiorly. In external rotation and abduction, as shown in our study and by Massimini et al,[30] the humeral head moves anteriorly and posteriorly rather than inferiorly. During a repair, any overtightening of the supraspinatus tendon may counteract the main axis of translation during a specific motion pattern.

From a clinical standpoint, our results may foster the debate about the ideal management of isolated full-thickness supraspinatus tears in overhead athletes. In this population, these injuries may be much less common than partial tears, but when full-thickness tears occur they pose a significant threat to the athlete's career.[51] Current treatment recommendations propose a TOE repair technique[41] or other double-row techniques.[31] However, the results of such repairs in overhead athletes are still disappointing, with a low rate of return to play (about 8%-40%).[31,51] Pitchers, for example, complain of early fatigue and prolonged recovery times.[31] From our results, one may hypothesize that a "tight" repair like the TOE repair may lead to a permanent perturbation of normal GH kinematics, which are crucial for efficient pitching biomechanics. Future studies could explore whether less tight repairs like the single-row technique may not perturb GH biomechanics and may lead to improved clinical results. Future studies could also test whether nonoperative treatment is an option, as the long-term results of this treatment are not as inferior as previously believed.[20] The negative effect of the repair may also support debridement of partial supraspinatus tears because this approach has been shown to yield good results in pitchers.[2]

This study has several limitations. As a passive cadaveric representation of the throwing motion, this model cannot account for the dynamic muscle forces central to GH stability.[26] Most important, the model does not replicate the stabilizing force provided by the supraspinatus. However, Werner et al[52] did not find any active contribution of the posterior-superior cuff to prevent superior translation of the humeral head. Electromyographic studies[21] in professional pitchers have also shown that the supraspinatus muscle is most active during early and late cocking and is much less active (only 21% of its maximal activity) during the propulsive period of the pitch that was modeled in our study. Nevertheless, these EMG results still suggest some resting tone of the supraspinatus muscle during the motion modeled in our study. This resting tone could increase the stability of the GH joint. Therefore, we cannot completely exclude that a dynamic supraspinatus activity may lead to different results than those observed in this study. Additionally, in our study, GH translations were calculated based on a regression analysis of the instant center of rotation. The precision of this estimation for the

GH center of rotation depends on the reliability of the anatomic landmark calibration. However, there is inherent variability in the calibration of these landmarks, since these landmarks are areas rather than discrete points.[16] This precision may partly explain the interspecimen variability for the amount of GH translations observed in this study. The motion from ER_{120} to ER_{90} was simulated at a much lower speed than an actual throwing motion to prevent any damage to the cadaver and testing setup. As shown by Bergmann et al,[4] lowering the speed of a specific motion may alter GH peak forces and moments, although the directions of GH forces remain constant. To simulate external rotation, a posterior restraint was placed against the abducted humerus, which could also increase absolute anterior GH translations. Moreover, the deltoid was removed before testing. Previous studies[35] suggested that the deltoid may have some bulk effect to reduce GH translations. However, in this study, every specimen served as its internal control; therefore, our analysis did not focus on absolute GH translations but rather changes of GH translations between different testing conditions (BL, ST1, ST3, SSR). Since we also used a highly standardized robotic setup, the observed changes of GH translations could be attributed directly to the created supraspinatus tear or repair.

CONCLUSION

In this kinematic cadaveric study on glenohumeral translations of the throwing shoulder, isolated supraspinatus tears did not significantly alter GH kinematics. However, a TOE repair of the supraspinatus tendon shifted the COR_{GH} posteriorly and resulted in less total motion from 120° to 90° of external rotation. For this reason, in throwing athletes, treatment of rotator cuff tears using a TOE should be addressed with caution to avoid an unintended alteration in GH kinematics due to overtightening of the supraspinatus.

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Corrigendum

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In the above article, an author was inadvertently omitted: Andrea Cereatti, PhD (Department of Information Engineering, Political Sciences and Communication Sciences, University of Sassari, Sassari, Italy). The corrected citation information is as follows:

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