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The Impact of Decreased Scapulothoracic Upward Rotation on Subacromial Proximities

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Abstract

BACKGROUND: Decreased scapulothoracic upward rotation has been theorized to increase an individual's risk for rotator cuff compression by reducing the clearance for the tendons in the subacromial space (ie, subacromial proximities). However, the impact of decreased scapulothoracic upward rotation on subacromial proximities has not been tested during dynamic in vivo shoulder motion.

OBJECTIVE: To determine the impact of decreased scapulothoracic upward rotation on subacromial proximities.

METHODS: Shoulder kinematics were quantified in 40 participants, classified as having high or low scapulothoracic upward rotation, during scapular plane abduction using single-plane fluoroscopy and 2-D/3-D shape-matching. Subacromial proximities were calculated as (1) the normalized minimum distance between the coracoacromial arch and humeral rotator cuff insertion, and (2) the surface area of the humeral rotator cuff insertion in immediate proximity to the coracoacromial arch. The effect of decreased scapulothoracic upward rotation on subacromial proximities was assessed using 2-factor mixed-model analyses of variance. The prevalence of contact between the coracoacromial arch and rotator cuff was also quantified.

RESULTS: Subacromial distances were generally smallest below 70° of humerothoracic elevation. With the arm at the side, the normalized minimum distance for participants in the low scapulothoracic upward rotation group was 34.8% smaller compared to those in the high upward rotation group ($P = .049$). Contact between the coracoacromial arch and rotator cuff tendon occurred in 45% of participants.

CONCLUSION: Decreased scapulothoracic upward rotation shifts the range of risk for subacromial rotator cuff compression to lower angles. However, the low prevalence of contact

suggests that subacromial rotator cuff compression may be less common than traditionally presumed.

Keywords

impingement; kinematics; rotator cuff; shoulder

Shoulder pain is a common condition for which patients often seek treatment.⁸ The traditional approach for diagnosing shoulder pain involves attempting to identify underlying pathoanatomy; however, simply identifying the potential source of pain proves insufficient to fully guide intervention.^{3,28,29,43} For example, improvements in functional outcomes for individuals diagnosed with rotator cuff “impingement” or “tendinopathy” average only 50%.^{4,10,48} While this is substantial positive improvement, current intervention strategies based on pathoanatomic diagnoses may be insufficient to fully restore function and patient quality of life.

Diagnosing musculoskeletal conditions based on movement impairments has been proposed to more directly link pathology with a potential underlying cause, and therefore link diagnosis to treatment.^{28,29,42} Numerous studies have shown that individuals with shoulder pain move differently than asymptomatic individuals,^{7,19,20,25,31,33,47} and specific movement impairments may influence mechanisms of shoulder pain in different ways. For example, it has been hypothesized that decreased scapulothoracic upward rotation increases an individual’s risk for subacromial rotator cuff compression by reducing the clearance for the rotator cuff in the subacromial space.²⁵ However, few studies have investigated the impact of specific movement abnormalities on mechanisms of joint and soft tissue injury.

A study by Karduna et al¹⁶ utilized a cadaveric model to investigate the impact of reducing scapular upward rotation on “subacromial clearance” (defined as a magnitude of glenohumeral translation resulting from a specific force) when the arm was positioned at 90° of humerothoracic elevation and maximal internal rotation. In this position, the authors found that reducing scapular upward rotation increased subacromial clearance. However, other studies suggest that by this humerothoracic elevation angle, the rotator cuff insertions may no longer be in a position to be compressed because they have passed under the lateral acromion.^{2,9,22} Another study, by Seitz et al,⁴⁵ altered scapulothoracic position during a scapular assistance test and found that an increase in scapulothoracic upward rotation and posterior tilt significantly increased bone-to-bone acromiohumeral distance at 45° of humerothoracic elevation. However, this study is limited by static arm positions and the use of a 2-D ultrasonic measure of acromiohumeral distance.

The apparent conflict between the results reported by Karduna et al¹⁶ and Seitz et al⁴⁵ reflects the inherent complexity of studying the effect of scapular kinematics on subacromial distances. Ultimately, subacromial distances are dependent on glenohumeral relationships (ie, kinematics and anatomy); therefore, scapulohumeral rhythm¹⁴ likely confounds the analysis when subacromial distances are studied relative to humerothoracic elevation angles. For example, at the same angle of humerothoracic elevation, an individual in less scapulothoracic upward rotation would require more glenohumeral elevation compared to an individual in more upward rotation. Therefore, the impact of decreased scapulothoracic

upward rotation on subacromial distances likely depends on the angle of humerothoracic elevation at which the movement impairment is observed.

More recently, some researchers have concluded that movement impairments, such as scapular dyskinesis, may not be clinically meaningful because they are often observed in asymptomatic individuals^{35,41,49} and treatment may improve symptoms without concurrent changes in scapular kinematics.³² However, relationships between symptom status and movement abnormalities or tissue pathology are not straightforward, and the long-term implications of movement impairments on tissue health are not known. Further, nearly all studies investigating scapular kinematics do so with surface-based motion sensors, which are prone to measurement error, limiting interpretation of results.^{11,17,26} Ultimately, there remains a critical need to identify whether abnormal shoulder movement, among other factors, contributes to the development of rotator cuff disease and, if so, how, so that we may improve clinical outcomes through more targeted rehabilitation strategies.

The purpose of the current study was to determine the impact of decreased scapulothoracic upward rotation on subacromial proximities during arm elevation in the scapular plane. In this study, the term *subacromial proximities* is used to collectively describe 2 primary outcome measures: (1) the normalized minimum distance between the coracoacromial arch and humeral rotator cuff insertion, and (2) the surface area of the humeral rotator cuff insertion in immediate proximity to the coracoacromial arch (ie, subacromial proximity area). It was hypothesized that, compared to participants classified as having high scapulothoracic upward rotation, participants classified as having low scapulothoracic upward rotation would have significantly decreased normalized minimum distance and increased subacromial proximity area below 60° of humerothoracic elevation. Furthermore, we hypothesized that participants classified as having high scapulothoracic upward rotation would have increased normalized minimum distance and decreased subacromial proximity area above 60° of humerothoracic elevation. In other words, the angle of arm elevation was hypothesized to statistically interact with upward rotation classification groups regarding subacromial proximity measures.

METHODS

Study Participants

Sixty participants were recruited from the community and screened for initial eligibility using research electronic data capture (REDCap) tools.¹² Study inclusion/exclusion criteria are provided in TABLE 1. To ensure a broad distribution of kinematics, 30 participants were symptomatic and 30 had no history of shoulder pain. Symptomatic and asymptomatic cohorts were matched based on age, sex, and the dominance of the side tested. Following inspection of their kinematic data, participants were classified as being in a low scapulothoracic upward rotation (low UR), mid scapulothoracic upward rotation (mid UR), or high scapulothoracic upward rotation (high UR) group after quantifying and ranking their upward rotation at 30° of humerothoracic elevation during the dynamic trial described below. This angle corresponded to the approximate humerothoracic elevation angle at which subacromial proximities are generally smallest.^{9,22,23} The 20 participants with the highest scapulothoracic upward rotation were assigned to the high UR group, while the 20

participants with the lowest scapulothoracic upward rotation were assigned to the low UR group (TABLE 2). Data for the mid UR group were not analyzed. All participants provided written informed consent. The study protocol was approved by the University of Minnesota's Institutional Review Board and All-University Radiation Protection Advisory Committee.

Data Collection

Shoulder kinematic data were acquired using a BV Pulsera mobile C-arm fluoroscopy system (Koninklijke Philips NV, Amsterdam, the Netherlands) (99.5-cm source-to-image distance, 30-cm field of view, 1024×1024 image resolution) synchronized to a 5-camera motion-capture system (Vero cameras and Vicon Tracker software; Oxford Metrics, Yarnton, UK) using MotionMonitor software (Innovative Sports Training, Inc, Chicago, IL). A calibration cube was imaged by both systems to establish a global reference frame. Reflective marker clusters were placed on participants' thorax and humerus, and clinically meaningful coordinate systems were established.⁵¹

To ensure radiation safety, all female participants underwent pregnancy testing immediately prior to fluoroscopic data collection, and all participants wore a lead apron and eye protection. Fluoroscopic images were acquired using high-definition fluoroscopy (continuous X-ray mode) and the system's automatic kilovolt/milliampere function. Participants were positioned with their scapula approximately parallel with and as close as possible to the image intensifier. Fluoroscopic images and Vicon data were acquired simultaneously, with the arm resting at the participant's side and during dynamic scapular plane abduction.

Shoulder magnetic resonance scans were acquired using a 3-T scanner (MAGNETOM Prisma; Siemens AG, Munich, Germany) and shoulder coil array, as previously described.¹ The scan field of view included the entire scapula and proximal humerus.

Data Processing

Three-dimensional bone models of the scapula and proximal humerus were created for each participant from the magnetic resonance scans using Mimics software (Materialise NV, Leuven, Belgium). Scapular anatomical coordinate systems were defined by digitizing landmarks on the 3-D model using published recommendations.²⁷ Modified humeral coordinate systems were used because the medial and lateral epicondyle landmarks could not be visualized in the magnetic resonance field of view.²² Once 3-D models were rendered, all data were blinded such that the knowledge of clinical presentation did not inadvertently bias kinematic descriptions (via shape-matching) or measures of rotator cuff thickness.

Fluoroscopic image calibration and undistortion were performed using XMALab Version 1.3.3.¹⁸ To reduce data processing time, fluoroscopic images were downsampled to every 10° of humerothoracic elevation based on Vicon data. Kinematic tracking was performed via 2-D/3-D shape-matching using JointTrack software (FIGURES 1A and 1B).³⁶ Glenohumeral, scapulothoracic, and humerothoracic kinematics were calculated using x - z' - y'' , y - x' - z'' , and y - x' - y'' rotation sequences, respectively.^{40,51} The data-collection and data-

processing protocols have been validated in our lab, with root-mean-square errors for glenohumeral joint orientation and position of 0.7° to 3.3° and 1.2 to 4.2 mm, respectively.²¹

Two anatomical regions of interest (ROIs) were defined on each participant's 3-D humeral model. First, the humeral rotator cuff insertion ROI was defined by following the margins of the tendon to its insertion on the greater tuberosity in each of the 3 magnetic resonance image views. Second, the articular margin ROI was defined as a 0.7-mm-wide portion of the humeral rotator cuff insertion ROI along its medial-most aspect. This width was defined based on the resolution of the magnetic resonance scan. Each participant's rotator cuff thickness was measured at the articular margin on the magnetic resonance slice corresponding to the anterior-posterior midpoint of the humeral rotator cuff insertion ROI. Additionally, the acromion ROI was defined on each participant's 3-D scapular model. Finally, a plane was fit between the anterior acromion and coracoid process based on anatomical descriptions,⁶ because the coracoacromial ligament could not be visualized on the magnetic resonance images and therefore reconstructed directly.

A custom MATLAB code (The Math-Works, Inc, Natick, MA) was used to animate each participant's 3-D humeral and scapular bone models using their glenohumeral motion data. Subacromial proximities were quantified at each angle of humerothoracic elevation by calculating the 3-D distance between the coracoacromial arch and the humeral rotator cuff insertion ROIs. Minimum distances were then normalized to the participant's rotator cuff thickness and expressed as percentages (FIGURE 1C). For example, a normalized minimum distance of 100% indicated that the minimum distance between the bone structures was equivalent to the measured rotator cuff thickness. From these normalized minimum distances, 5 primary dependent variables were calculated.

First, the smallest normalized minimum distance was determined for each humerothoracic elevation angle based on the pairwise minimum distances between the coracoacromial arch and the articular margin ROI. This was necessary because the thickness of the rotator cuff was only quantified at the articular margin and cannot be assumed to be constant across its surface.

Second, contact (presence/absence) between the rotator cuff tendons and the coracoacromial arch was recorded when the normalized minimum distance was less than 120%. This cutoff was chosen to allow for approximately a 1-mm error in minimum distance due to shape-matching, based on the results of sensitivity analyses (APPENDIX, available at www.jospt.org).

Third, subacromial proximity areas were calculated as the surface area of the humeral rotator cuff insertion in immediate proximity to the coracoacromial arch. The threshold of "immediate proximity" was defined as the participant's rotator cuff tendon thickness (ie, normalized minimum distance of 100% or less, meaning the tendon and acromion were presumed to be in direct contact) (FIGURE 2).

Fourth, the absolute minimum distance was calculated as the smallest normalized minimum distance during the participant's dynamic trial.

Fifth, the position of absolute minimum distance was defined as the humerothoracic elevation angle at which the absolute minimum distance occurred.

In addition to kinematics, scapular and humeral morphology have been hypothesized to impact an individual's risk for subacromial rotator cuff compression.^{13,15,38} Therefore, acromial slope, glenoid inclination, glenoid version, critical shoulder angle, and humeral head radius were quantified on each participant's 3-D bone models as potential covariates.

Statistical Analysis

An a priori power analysis was performed to determine that 20 participants were needed per group to detect a 2-mm group difference in minimum distance using a standard deviation from unpublished data within our lab. An oversampling approach was utilized to increase the range of scapulothoracic upward rotation values and ensure a separation in mean scapulothoracic upward rotation between the low and high groups of at least 10°, which was considered clinically meaningful. A Monte Carlo simulation was performed to determine the amount of oversampling required using kinematic data from previous studies.^{30,34} Sixty total participants (20 participants per group) were necessary to ensure a 10° difference in scapulothoracic upward rotation between the low and high groups.

Demographic data were compared between cohorts (symptomatic, asymptomatic) and groups (low UR, high UR) using 2-sample independent *t* tests, Mann-Whitney *U* tests, or chi-square tests, as appropriate. Data normality was assessed prior to statistical analysis using skewness, kurtosis, and Shapiro-Wilk statistics. The relationships between proximity measures and potential covariates were assessed using Pearson's correlation. However, no variable was moderately or highly correlated ($|r| \geq 0.5$) (TABLE 3); therefore, none were retained as a covariates for the statistical analyses.

Two-factor mixed-model analyses of variance with a Toeplitz covariance structure were utilized to determine the effect of scapulothoracic upward rotation on the normalized minimum distance and subacromial proximity area. The between-subject factor was group (low UR, high UR), and the within-subject factor was the angle of humerothoracic elevation. For the analysis of normalized minimum distance, humerothoracic elevation angles included the arm resting at the side (minimum position) and elevated to 30°, 60°, and 90° during dynamic scapular plane abduction. However, only 30°, 60°, and 90° of humerothoracic elevation were investigated for the analysis of subacromial proximity areas, because no participant had a measurable area of the humeral rotator cuff insertion in immediate proximity when the arm was at the side. The appropriate covariance structure with which to model the within-subject effects was determined according to recommendations.²⁴ The prevalence of contact between the rotator cuff and coracoacromial arch was compared between groups using chi-square tests at the minimum position and at 30°, 60°, and 90° of humerothoracic elevation. Two-sample independent *t* tests were used to compare the magnitude and position of absolute minimum distance between groups. Statistical analysis was performed in SAS Version 9.4 (SAS Institute Inc, Cary, NC) using an a priori type I error rate of 5%.

RESULTS

Demographics

Participant demographic data are provided in TABLE 2. There was no significant difference in the proportion of asymptomatic and symptomatic participants between the high UR and low UR groups ($P = .34$, $\chi^2 = 0.92$, $df = 1$; 50% versus 35%). However, the low UR group had significantly greater mass ($P = .02$, $t = -2.39$, $df = 38$; mean difference, 10.4 kg) and body mass index ($P = .02$, $t = -2.42$, $df = 38$; mean difference, 2.6 kg/m²). Further, symptomatic participants in the low UR group had a significantly higher maximum pain rating within the last week on a numeric pain-rating scale (0–100) compared to symptomatic participants in the high UR group ($P = .04$, $t = -2.15$, $df = 21$; mean difference, 14.5 points).

Kinematics

Consistent with their group classification, the low UR group was descriptively in decreased UR throughout the dynamic trial compared to the high UR group (FIGURE 3). Groups differed by 10.0° in upward rotation at 30° of humerothoracic elevation (the angle at which participants were classified).

Normalized Minimum Distance

Normalized minimum distance was generally smallest in both groups below 70° of humerothoracic elevation. The difference between the high UR and low UR groups in normalized minimum distance was dependent on the angle of humerothoracic elevation (interaction: $P = .049$, $F_{3, 113} = 2.71$) (FIGURE 4). When the arm was at the side, participants in the low UR group had significantly smaller normalized minimum distance ($P = .049$, $t = 1.99$, $df = 113$; mean difference, 34.8%). Nonnormalized minimum distances are presented in the APPENDIX figure.

Subacromial Proximity Areas

There was no difference between the high UR and low UR groups in the magnitude of subacromial proximity area ($P = .14$, $F_{2,76} = 2.00$) (FIGURE 5).

Prevalence of Contact

The prevalence of contact between the rotator cuff tendon and coracoacromial arch across humerothoracic elevation angles is presented in FIGURE 6. The highest prevalence occurred at 60° of humerothoracic elevation, where 32.5% of the rotator cuff tendons of participants were in contact with the coracoacromial arch. There was no significant difference between groups in the proportion of participants experiencing contact at any angle of humerothoracic elevation ($P > .41$). Overall, contact occurred at least once during the dynamic trial in 45% of all participants, without a significant difference between the low UR and high UR groups ($P = .53$, $\chi^2 = 0.40$, $df = 1$; 50% versus 40%).

Absolute Minimum Distance

The absolute minimum distance occurred at an average humerothoracic elevation angle of $51.5^\circ \pm 11.8^\circ$ in the low scapulothoracic UR group and at $60.4^\circ \pm 18.4^\circ$ in the high

scapulothoracic UR group ($P = .07$, $t = -1.82$, $df = 38$) (FIGURE 7). There was no difference between groups in the magnitude of the absolute minimum distance ($P = .41$, $t = 0.83$, $df = 32$; mean difference, 5.4%).

DISCUSSION

During scapular plane abduction, normalized minimum distances were generally smallest between 50° and 70° of humerothoracic elevation. Although this finding is in contrast to the theory that subacromial rotator cuff compression occurs above 80° of humerothoracic elevation,³⁷ it is largely consistent with other 3-D studies.^{2,9,22,23} Therefore, considerable evidence now exists to suggest that subacromial rotator cuff compression occurs at much lower angles in humerothoracic elevation than traditionally believed.^{2,9,22}

Consequently, this brings to question the source of pain during arm raising. Traditionally, subacromial compression has been thought to cause pain near midrange or at end-range humerothoracic elevation. However, this explanation is no longer logical in light of the results of this study and others,^{2,9,22,23} as the rotator cuff is not within immediate proximity to the coracoacromial arch in most people by 90° of humerothoracic elevation. However, it is possible that rotator cuff compression occurring at lower angles may become symptomatic in midranges, when the injured or inflamed rotator cuff needs to produce more force to overcome the larger moment arm. In contrast, symptoms above 90° of humerothoracic elevation may be due to other mechanisms, such as internal impingement, which occurs when the rotator cuff tendon becomes entrapped against the glenoid.⁵⁰ Furthermore, it is possible that other shoulder structures (eg, biceps tendon, bursa) that were not accounted for in the current study were the pain generators in individuals with “impingement syndrome” or “anterior shoulder pain.”

Interestingly, only 45% of participants in this study had contact between the rotator cuff tendon and the coracoacromial arch, without a significant difference between groups. This proportion seems surprisingly small, given the presumption that subacromial compression is a predominant cause of rotator cuff injury and shoulder pain.^{38,39} However, the prevalence is comparable to a previous study that reported contact in only 50% of subject-specific anatomical models during a simulated functional reaching task.²² Taken together, these findings suggest that subacromial compression may not occur as often as presumed and also occurs in currently asymptomatic individuals. However, subacromial compression may still be a factor in a subset of individuals and may be more prevalent during other functional motions. Further research is needed to identify the anatomical and kinematic factors that predispose individuals to this mechanism.

With regard to the effect of scapulothoracic upward rotation on normalized minimum distance, our hypothesis was supported: a reduction in scapulothoracic upward rotation shifts the range of closest proximity to lower angles of humerothoracic elevation. This is evident primarily by the significant group-by-angle interaction for normalized minimum distance. In particular, decreased scapulothoracic upward rotation significantly decreased normalized minimum distance when the arm was at the side, and tended to increase normalized minimum distance at 90° of humerothoracic elevation. Given the mean rotator cuff thickness

of 5.6 mm, the 35% group mean difference when the arm was at the side corresponds to an approximately 2.0-mm group difference in minimum distance, which is believed to be clinically meaningful based on our error of measurement (APPENDIX) and thresholds for meaningfulness in previous studies.⁴⁵

The results relative to the position of absolute minimum distance also support the hypothesis that decreased scapulothoracic upward rotation shifts the range of closest proximity to lower angles of humerothoracic elevation. Specifically, participants in the low UR group tended to be in closest proximity to the coracoacromial arch, 9° lower in the range of motion than those in the high UR group. However, the lack of significant difference in the magnitude of absolute minimum distance suggests that decreased upward rotation did not increase the amount of compression.

A previous study by Karduna et al¹⁶ likely also observed a similar shift in the range of motion in which the smallest subacromial “clearance” occurred. The researchers imposed changes in scapular upward rotation in cadaveric specimens when the arm was positioned at 90° of humerothoracic elevation and found that reducing scapular upward rotation increased subacromial clearance. Although not statistically significant, a similar finding was observed in the current study. Specifically, participants in the low UR group tended to have higher normalized minimum distance at 90° of humerothoracic elevation than those in the high UR group. However, for most individuals, the rotator cuff was no longer in a position of compression risk at 90° of humerothoracic elevation, having already passed medial to the lateral acromion. Therefore, the clinical relevance of this increase in subacromial distances is uncertain. Further, it remains unclear whether rotator cuff compression actually results in pathology in humans. The results of animal studies support the role of extrinsic compression in tendinopathy^{5,44,46}; however, the results of these findings have not been confirmed in humans.

The shift in the range of closest proximity between the low UR and high UR groups can be explained by the inherent dependency of subacromial proximities on glenohumeral relationships and the influence of scapulohumeral rhythm.¹⁴ For a given angle of humerothoracic elevation, a reduction in scapulothoracic upward rotation must be accompanied by an increase in glenohumeral elevation. Therefore, at lower angles of humerothoracic elevation, a decrease in scapulothoracic upward rotation (or increase in glenohumeral elevation) will move the edge of the acromion downward and into closer proximity with the medial aspect of the rotator cuff insertion (FIGURES 8A and 8B). At higher angles of humerothoracic elevation, an increase in scapulothoracic upward rotation will raise the acromial edge upward and back over the medial aspect of the rotator cuff insertion, resulting in closer proximity with this important area of the tendon (FIGURE 8C). However, a decrease in scapulothoracic upward rotation will move the acromial edge downward, but the medial aspect of the rotator cuff insertion is no longer under it and no longer in a position to become compressed (FIGURE 8D).

Clinically, the finding that decreased scapulothoracic upward rotation creates a shift in the range of closest proximities suggests that it may be important to consider the range of motion in which abnormal scapular motion is observed. For example, if decreased

scapulothoracic upward rotation is observed at lower humerothoracic elevation angles coinciding with symptoms, then it may be prudent to consider increasing scapulothoracic upward rotation as part of a treatment plan. However, if decreased scapulothoracic upward rotation is observed at higher humerothoracic elevation angles coinciding with symptoms, then the symptoms may be due to other mechanisms (eg, internal impingement) or alternate pain generators (eg, biceps tendon). Therefore, it may be important to interpret movement impairments within the context of symptom presentation and the elevation angle at which they are observed.

Although individuals with decreased upward rotation tended to have higher subacromial proximity areas during midrange, the high between-subject variability hindered the ability to detect significant group differences. However, the findings also suggest that the trend of increased upward rotation to decrease normalized minimum distance at 90° of humerothoracic elevation may be an artifact of the distance measure's simplicity, as a concurrent increase in subacromial proximity area was not observed. Ultimately, understanding the mechanism of subacromial rotator cuff compression likely requires more comprehensive measures than simple distances.

An important consideration when interpreting the results of this study is that group classification was performed based on scapulothoracic orientation and not symptom presentation. This approach was necessary to directly test the theory related to decreased upward rotation and subacromial proximities. Notably, there was no significant difference in the proportion of symptomatic and asymptomatic participants in the high and low scapulothoracic UR groups (TABLE 2), which raises the question of whether decreased upward rotation may be a meaningful clinical finding. This, however, is a question the present study cannot answer, given its cross-sectional design and inability to account for the presence/absence of rotator cuff pathology or other important factors. For example, whether currently asymptomatic individuals in the low UR group develop rotator cuff pathology over time is unknown, especially considering the relatively young age of the sample. Further, it is not known whether shoulder pain in symptomatic individuals in the high UR group may be due to mechanisms not investigated in this study (eg, overuse/ exposure). Future research aimed at understanding the etiology of rotator cuff pathology would benefit from a multifactorial and ideally longitudinal approach.

This study has several limitations that should be considered. First, single-plane fluoroscopy result in out-of-plane errors that may impact subacromial proximities (APPENDIX).⁵² However, data processing was performed blinded, and there is no reason to suspect that shape-matching errors will systematically differ between groups. Second, the coracoacromial ligament was modeled as a plane because it could not be reliably reconstructed from the magnetic resonance images. However, there was no substantial change in the results or conclusions when subacromial proximities were quantified to the acromion only. Third, the rotator cuff thickness was measured at the articular margin on a single magnetic resonance image slice for each participant. Because it is not reasonable to assume the rotator cuff thickness is constant throughout its structure, we limited the minimum-distance calculations to the articular margin.

Fourth, mean participant age was relatively young (32 years). However, the aim of the study was not to characterize subacromial proximities across the lifespan or directly relate them to symptomatology, but rather to determine the impact of a particular movement impairment on subacromial proximities. Fifth, due to the current lack of a validated classification for defining decreased scapulothoracic upward rotation clinically, group classification was defined based on scapulothoracic upward rotation at 30° of humerothoracic elevation. We chose this angle because it is within the range of motion in which subacromial distances are smallest.^{9,22,23} Future research should determine whether these movement-based subgroups can be reliably and validly identified with clinical measurements (eg, inclinometers). Finally, this study investigated only 1 theorized mechanism of rotator cuff injury (ie, subacromial compression). Therefore, the results should be interpreted within the broader context of the complex and multifactorial nature of rotator cuff pathology and shoulder pain.

CONCLUSION

The results of this study indicate that subacromial distances are smallest between 50° and 70° of humerothoracic elevation, depending on the amount of scapulothoracic upward rotation. Decreased scapulothoracic upward rotation shifts the range of motion in which subacromial distances are smallest to lower angles. Clinically, this knowledge may help inform ergonomic tasks and exercise prescription to avoid prolonged and repeated exposures within the range of closest proximity.

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APPENDIX

SENSITIVITY ANALYSIS TO DETERMINE IMPACT OF 2-D/3-D SHAPE-MATCHING ERRORS ON MINIMUM DISTANCES

During the validation of the 2-D/3-D shape-matching protocol, glenohumeral kinematics were calculated using both biplane radiostereometric analysis (reference standard) and single-plane 2-D/3-D shape-matching (experimental protocol).²¹ Both sets of kinematics were used to calculate minimum distances using the same modeling approach described in this manuscript, thus allowing for an estimate of error in minimum distances due to shape-matching errors. Error was calculated as the difference in minimum distances between the

reference standard and the experimental protocol and described as root-mean-square, bias (average error), and precision (standard deviation of errors). A 1-sample *t* test was performed to determine whether the bias error was significantly different from zero, which would suggest that a systematic error is present. The results of this analysis are as follows: root-mean-square error, 1.6 mm; bias error, 0.6 mm ($P = .07$); precision, 1.4 mm.

FIGURE.

Minimum distance between the coracoacromial arch and articular margin aspect of the humeral rotator cuff insertion for the high and low scapulothoracic upward rotation groups. Data are presented as mean and unpooled standard error.

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KEY POINTS**FINDINGS:**

Decreased scapulothoracic upward rotation shifts the range of closest proximity to lower angles of humerothoracic elevation.

IMPLICATIONS:

Patients presenting with decreased scapulothoracic upward rotation at low angles of humerothoracic elevation coinciding with their shoulder symptoms may benefit from increasing upward rotation.

CAUTION:

The results of this study only reflect unloaded scapular plane abduction; other motions and/or conditions may produce different findings.

FIGURE 1.

Processes of 2-D/3-D shape-matching (A and B, anterior views) and subacromial proximity calculations (C, posterior view). (A) 2-D/3-D shape-matching involves rotating the 3-D models of the humerus and scapula until their projected contours (blue line) become aligned with those on the fluoroscopic image frame. (B) Once matched, the 3-D pose can be extracted and glenohumeral kinematics calculated. (C) The minimum distance between the coracoacromial arch and humeral rotator cuff insertion is calculated and normalized to the rotator cuff thickness for the corresponding glenohumeral position shown in A and B.

FIGURE 2.

Illustration of the subacromial proximity area metric (posterior view) for a representative participant in the low scapulothoracic upward rotation group at 60° of humerothoracic elevation. The subacromial proximity area was calculated by summing the surface area of each triangular mesh face of the humeral rotator cuff insertion (inset) in which the normalized minimum distance was within the participant's rotator cuff tendon thickness (ie, normalized minimum distance of 100% or less, red color mapping).

FIGURE 3.

Scapulothoracic kinematic data for the high and low scapulothoracic UR groups. Data are presented descriptively as mean and unpooled standard error. Abbreviations: DR, downward rotation; ER, external rotation; IR, internal rotation; UR, upward rotation.

FIGURE 4.

Normalized minimum distance between the coracoacromial arch and articular margin aspect of the humeral rotator cuff insertion for the high and low scapulothoracic upward rotation groups. Minimum distances were normalized to the participant's rotator cuff tendon thickness and expressed as a percentage. Data are presented as mean and unpooled standard error. Groups were compared statistically at the minimum, 30°, 60°, and 90° angles of humerothoracic elevation.

FIGURE 5.

Subacromial proximity areas for the high and low scapulothoracic upward rotation groups. Data are presented as mean and unpooled standard error. Groups were compared statistically at the 30°, 60°, and 90° angles of humerothoracic elevation.

FIGURE 6.

Proportion of participants with contact between the rotator cuff tendon and coracoacromial arch. Contact was defined as a normalized minimum distance less than 120%. Groups were compared statistically at the minimum, 30°, 60°, and 90° angles of humerothoracic elevation.

FIGURE 7.

Distributions of the humerothoracic elevation angle at which the absolute minimum distance occurred for the high and low scapulothoracic upward rotation groups. The solid and dashed lines within each box represent the group median and mean, respectively. The boundaries of the box represent the 25th and 75th quartiles. The error bars represent the upper and lower adjacent values (ie, the most extreme data points not considered outliers). Individual outliers are indicated by a “+” symbol.

FIGURE 8.

The effect of scapulothoracic upward rotation on the proximity between the acromial edge and the articular margin aspect of the rotator cuff insertion (red region on humeral head). (A) Increased scapulothoracic upward rotation at a lower angle of humerothoracic elevation will move the acromial edge upward and away from the articular margin aspect of the rotator cuff insertion. (B) Decreased scapulothoracic upward rotation at a lower angle of humerothoracic elevation will move the acromial edge downward and closer to the articular margin aspect of the rotator cuff insertion. (C) Increased scapulothoracic upward rotation at a higher angle of humerothoracic elevation will raise the acromion upward, thereby moving the acromial edge back over the articular margin aspect of the rotator cuff insertion. (D) Decreased scapulothoracic upward rotation at a higher angle of humerothoracic elevation will move the acromial edge downward, but the articular margin aspect of the rotator cuff insertion has already passed under and medial to the lateral acromion.

TABLE 1

Study Inclusion and Exclusion Criteria

Cohort	Inclusion Criteria	Exclusion Criteria
Symptomatic	Age, 21–60 y Current shoulder joint pain of 4 wk in duration Shoulder symptoms provoked during active motion Ability to raise the arm to 120° of humerothoracic elevation	Shoulder symptoms reproduced during cervical spine screening Radiating pain, numbness, or tingling in the upper extremity 25% reduction in glenohumeral internal or external rotation range of motion compared to the contralateral side Symptom onset following trauma Positive apprehension test History of shoulder surgery History or presence of shoulder fracture, dislocation, separation, adhesive capsulitis, or rotator cuff tear on involved side History or presence of scoliosis Inflammatory joint disease Known skin sensitivities or allergies to adhesives Contraindications to magnetic resonance imaging or radiation exposure
Asymptomatic	Age, 21–60 y	History of pain in either shoulder Symptom provocation during clinical exam, except during 1–2 provocation tests* 25% reduction in glenohumeral internal or external rotation range of motion compared to the contralateral side Positive apprehension test Radiating pain, numbness, or tingling in the upper extremity History of shoulder fracture, dislocation, separation, adhesive capsulitis, or rotator cuff tear History or presence of scoliosis Inflammatory joint disease Known skin sensitivities or allergies to adhesives Contraindications to magnetic resonance imaging or radiation exposure

* Provocation tests included Hawkins-Kennedy, Neer, Jobe, and resisted external rotation.

TABLE 2

Participant Demographics by Scapulothoracic Upward Rotation Group^{*}

	High (n = 20)	Low (n = 20)	P Value
Age, y	32.9 ± 7.3	32.0 ± 8.7	.73
Sex (male), %	30	55	.11
Dominance of the side tested (dominant), %	35	50	.34
Height, cm	170.0 ± 9.2	174.5 ± 6.9	.09
Mass, kg	66.7 ± 14.3	77.1 ± 13.2	.02
BMI, kg/m ²	22.9 ± 3.2	25.5 ± 3.6	.02
Group (asymptomatic), %	50	35	.34
Rotator cuff tendon thickness, mm [†]	5.3 ± 1.2	5.6 ± 0.9	.47
Symptom duration, wk ^{‡§}	31.0	40.0	.85
NPRS in past 7 d (0–100) [§]			
Highest	41.0 ± 17.2	55.5 ± 15.0	.04
Lowest	22.5 ± 22.8	9.2 ± 14.4	.10
DASH (0–100) [§]	13.6 ± 10.0	15.8 ± 5.8	.51
Work subscale	7.0 ± 13.1	7.3 ± 14.8	.97
Sport subscale	18.8 ± 15.3	16.4 ± 18.3	.83

Abbreviations: BMI, body mass index; DASH, Disabilities of the Arm, Shoulder and Hand questionnaire; NPRS, numeric pain-rating scale.

^{*} Values are mean ± SD unless otherwise indicated. Groups were classified as having high or low upward rotation based on their scapulothoracic upward rotation magnitude at 30° of humerothoracic elevation. Groups were compared using independent 2-sample t tests, Mann-Whitney U tests, or chi-square tests, as appropriate.[†] Measured on the magnetic resonance images at the articular margin on the image slice corresponding to the anterior/posterior midpoint of the rotator cuff insertion.[‡] Values are median due to nonnormal data.[§] Comparison was only made between symptomatic subjects within each group.

TABLE 3Assessment of Anatomical Morphology Variables as Potential Covariates^{*}

	Humerothoracic Elevation			
	Minimum	30°	60°	90°
Acromial slope, deg	-0.10 (.53)	-0.25 (.12)	-0.29 (.07)	-0.21 (.20)
Glenoid inclination, deg	0.09 (.59)	0.06 (.73)	-0.35 (.03)	-0.31 (.05)
Glenoid version, deg	0.06 (.71)	0.00 (1.0)	-0.04 (.81)	-0.06 (.72)
Critical shoulder angle, deg	-0.37 (.02)	-0.32 (.04)	-0.38 (.02)	-0.35 (.03)
Humeral head radius, mm	-0.16 (.32)	0.04 (.81)	-0.24 (.13)	-0.21 (.19)

* Values are r (P value). No anatomical morphology variable was considered a statistical covariate because |r| did not exceed the a priori threshold of 0.5.