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Associations between range of motion, strength, tear size, patient-reported outcomes, and glenohumeral kinematics in individuals with symptomatic isolated supraspinatus tears

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Background: Clinical failure associated with nonoperative treatment of rotator cuff tears may be due to inadequate characterization of the individual's functional impairments. Clinically, restricted passive range of motion (ROM) (restrictions imply capsular tightness), limitations in muscle strength, and larger rotator cuff tears are hypothesized to be related to altered glenohumeral kinematics. Understanding these relationships, as well as the relationship between glenohumeral kinematics and patient-reported outcomes (PROs) prior to exercise therapy, may help characterize functional impairments in individuals with rotator cuff tears. The objectives of the study were to describe the baseline presentation of individuals with an isolated supraspinatus tear, including passive ROM, rotator cuff muscle strength, tear size, PROs, and glenohumeral kinematics, and to determine associations among these variables.
Methods: One hundred one individuals with symptomatic isolated supraspinatus tears were recruited for the study and underwent assessments of passive glenohumeral ROM, isometric muscle strength, and ultrasonography to assess anterior-posterior tear size. Glenohumeral kinematics during scapular-plane abduction were measured using biplane radiography. Furthermore, PROs including the American Shoulder and Elbow Surgeons (ASES) score and the Western Ontario Rotator Cuff Index (WORC) score were collected.
Results: Individuals presented with decreased ROM, external rotation weakness compared with the uninvolved side, and pain and disability as measured by the ASES and WORC scores. These findings were not associated with glenohumeral kinematics, with the exception of a weak positive association between glenohumeral contact path lengths and WORC scores ($\rho = 0.25$, $P = .03$). Tear size was 11.7 ± 5.7 mm, and maximum anterior translation, superior translation, and contact path length were 3.0% ± 3.8% of glenoid width, 3.5% ± 3.8% of glenoid height, and 38.2% ± 20.7% of glenoid size, respectively.
Conclusion: Individuals with a symptomatic isolated supraspinatus tear presented with decreased ROM, external rotation weakness, and pain and disability as measured by the ASES and WORC scores. However, no abnormal kinematics associated with these limitations were observed. Thus, given that the tear is isolated to the supraspinatus tendon and no capsular restrictions are present, normal function of the glenohumeral joint may be possible during scapular-plane abduction.

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The incidence of rotator cuff tears in the general population is approximately 30%, with the prevalence increasing in individuals aged > 60 years.[58] Nonoperative treatment, rather than surgical repair, is the initial treatment choice for rotator cuff tears and focuses on reducing pain, restoring normal range of motion (ROM), and strengthening the rotator cuff and scapular stabilizing muscles.[19,20,28,29,37,40,54] Although nonoperative treatment is often effective for relieving symptoms, it fails in 15%-68% of cases, necessitating surgical intervention.[22,47] Failure rates associated with nonoperative treatment may be due to varying treatment protocols or inadequate characterization of impaired function in individuals with rotator cuff tears used to determine the specific treatment for individual patients.[5]

Common impairments associated with rotator cuff tears seen clinically include decreased passive ROM and rotator cuff muscle strength.[4,30] Mechanistically, it has been hypothesized that decreased passive glenohumeral internal rotation and abduction ROM (restrictions are considered to imply posterior and inferior capsular tightness) and decreased rotator cuff muscle strength disrupting the coronal- and transverse-plane force couples (subscapularis, infraspinatus, and teres minor) relate to altered glenohumeral translations and less joint stability.[16,30] To improve the success of nonoperative treatment of supraspinatus tears, a better understanding of the aforementioned impairments prior to nonoperative treatment is necessary as they may provide further insight on the individual's impaired function and direct specifics of nonoperative treatment.

Previous studies using cadavers and static in vivo radiographic images assessed glenohumeral translations in the presence of rotator cuff tears and observed superior migration of the humeral head,[23,27,38,39,57] where it is generally believed that superior migration worsens with increasing tear size.[23,46] However, conflicting results reported inferior glenohumeral translations in individuals with rotator cuff tears isolated to the supraspinatus during scapular-plane abduction measured with biplane fluoroscopy.[35] Furthermore, experimentally induced capsular contractures have been shown to increase anterior and superior glenohumeral translations.[16,30] This phenomenon was termed the "capsular constraint mechanism," in which the humeral head translates away from the tightened portion of the capsule.[11,16] In the clinical setting, both superior migration with increasing tear size and the effects of capsular tightness are widely acknowledged in individuals with rotator cuff tears. Although the effects of capsular tightness are well described in cadavers, few data exist regarding the effects of capsular tightness on glenohumeral kinematics in vivo in individuals with isolated supraspinatus tendon tears prior to exercise therapy. Specifically, the demographic and clinical factors (ie, strength, ROM, atrophy, and tendon involvement) relating to patient-reported outcomes (PROs) have been investigated in individuals with symptomatic atraumatic rotator cuff tears prior to initiation of a physical therapy program, but glenohumeral kinematics were not investigated.[15] Furthermore, the relative changes in a combination of variables such as passive and active ROM, strength, PROs, and in vivo glenohumeral kinematics have been described following a physical therapy program.[3,29,34] However, these previous studies only looked at relative changes and did not determine the time-zero relationship between factors such as passive ROM and glenohumeral kinematics.

Furthermore, little is known regarding the effects of tear size on muscle strength. A previous study investigated the association between abduction, internal rotation, and external rotation muscle strength and the presence of a supraspinatus tear and found that decreased abduction and external rotation strength was associated with supraspinatus tears.[33] Mechanistically, larger tears may further disrupt the glenohumeral force couples and influence rotator cuff muscle strength and contact path length. Thus, understanding whether rotator cuff muscle strength decreases and contact path length increases with increasing tear size will elucidate whether some individuals enter exercise therapy with greater impairments. This information will also aid in directing specifics of future exercise therapy programs.

Thus, few data exist regarding the relationships between passive glenohumeral ROM, rotator cuff muscle strength, tear size, and glenohumeral kinematics in a population of individuals with an isolated supraspinatus tear prior to initiation of nonoperative treatment. Additionally, PROs are commonly collected to gain insight on an individual's perceived pain and function. Thus, if individuals experience larger glenohumeral translations and contact path lengths, which indicate worse control of the humeral head, this may relate to worse patient-reported function. Understanding the relationship between glenohumeral kinematics and PROs may elucidate whether changes in glenohumeral function affect an individual's perception of his or her pain and function prior to exercise therapy.

Therefore, the overall objectives of the study were to describe the clinical presentation of individuals with a symptomatic isolated supraspinatus tear and determine whether common clinical measures of function in individuals with rotator cuff tears relate to in vivo

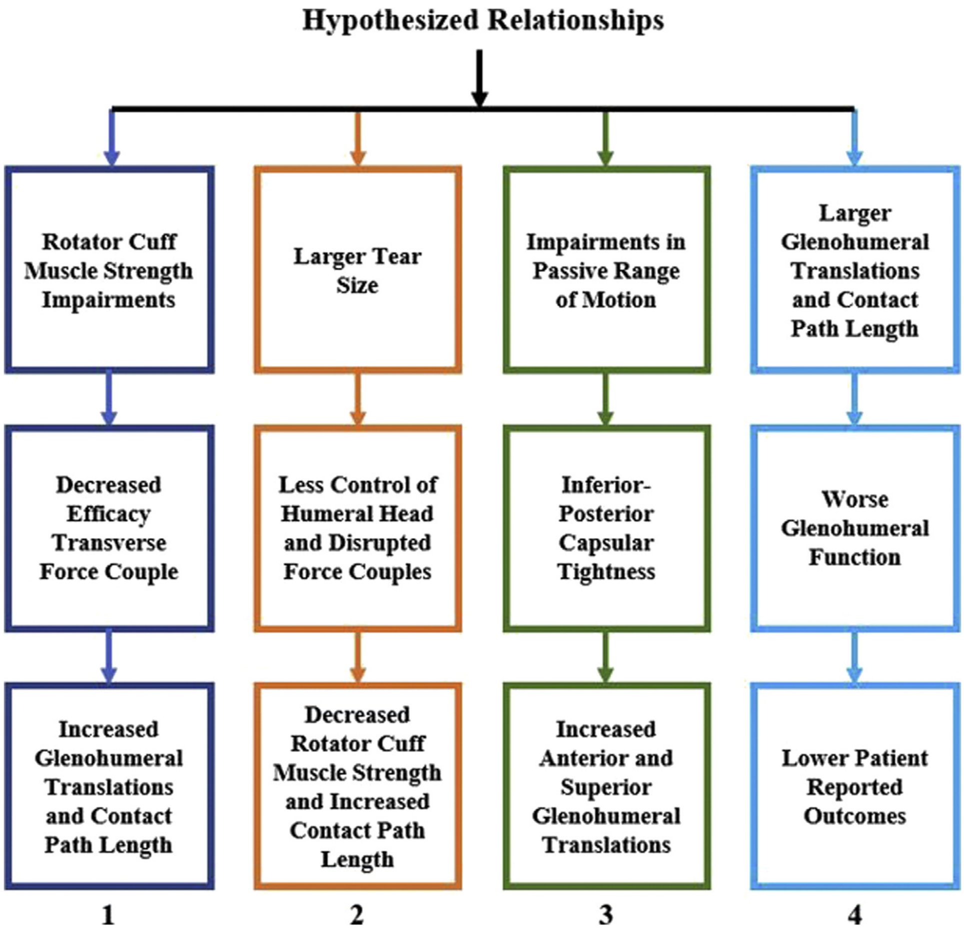

Figure 1 Rationale flowchart for hypothesized relationships.

glenohumeral kinematics. Clinical measures of function used to describe the initial presentation, as well as associations with glenohumeral kinematics, included passive glenohumeral ROM, isometric muscle strength, PROs, and tear size. The specific objectives of this study were as follows: (1) to describe the clinical presentation of individuals with a symptomatic isolated supraspinatus tear; (2) to determine the relationships between passive glenohumeral ROM, isometric rotator cuff muscle strength, tear size, and glenohumeral kinematics; and (3) to determine the relationships between glenohumeral kinematics and PROs (American Shoulder and Elbow Surgeons [ASES] score and Western Ontario Rotator Cuff Index [WORC] score). Achieving these objectives will identify impairments, as well as links between impairments and underlying joint mechanics, in individuals with symptomatic rotator cuff tears isolated to the supraspinatus tendon prior to initiation of nonoperative treatment.

It was hypothesized that (1) internal and external rotation strength would be negatively correlated with maximum superior glenohumeral translations and contact path length, (2) tear size would be negatively associated with internal and external rotation strength and positively associated with glenohumeral contact path length, (3) clinically assessed glenohumeral internal rotation, glenohumeral abduction, and glenohumeral flexion would be negatively correlated with maximum superior and anterior glenohumeral translations, and (4) maximum glenohumeral anterior and superior translations and contact path length would be negatively correlated with PROs (Fig. 1).

Materials and methods

One hundred one individuals (mean age, 60.6 ± 9.7 years; mean body mass index, 28.8 ± 4.9) were recruited to participate in the study and provided institutional review board–approved written informed consent prior to the performance of any research procedure. Individuals were eligible to enter the study if they (1) were older than 40 years; (2) had a body mass index < 40; (3) had a partial- or full-thickness rotator cuff tear isolated to the supraspinatus tendon (confirmed via ultrasound screening of the rotator cuff tendons); and (4) had at least a 110° range of humerothoracic elevation. Individuals were excluded if they had a work-related injury, an asymptomatic rotator cuff tear, severe capsular tightness as evidenced by <30° of internal or external rotation, a duration of shoulder pain > 12 months, or diabetes mellitus.

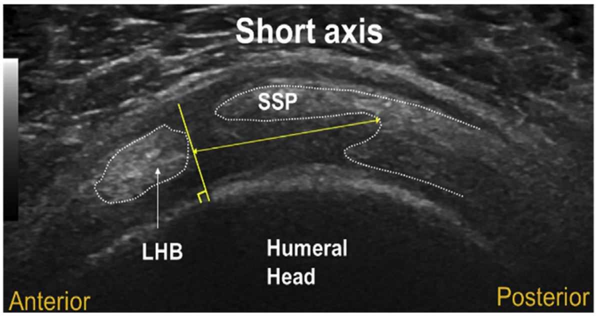

Figure 2 Example of anterior-posterior tear size measurement on short-axis image with tear location of 0.0 mm. The yellow line is drawn tangent to the posterior edge of the long head of the biceps tendon and is the starting location for measurement of tear size. The length of the yellow arrow quantifies the anterior-posterior tear size. Assessments were performed with a 6- 15 MHz linear array transducer (LOGIQE9) by a radiologist in the Department of Musculoskeletal Radiology at the University of Pittsburgh. *LHB*, long head of biceps; *SSP*, supraspinatus.

Passive glenohumeral ROM and isometric strength of the rotator cuff muscles were measured by 1 of 3 certified and experienced physical therapists at the Physical Therapy–Clinical and Translational Research Center, Department of Physical Therapy, University of Pittsburgh. For each individual, passive glenohumeral abduction, flexion, and internal rotation at 90° of humerothoracic abduction were assessed using a goniometer. Individuals were in the supine position for all passive ROM assessments. The amount of glenohumeral abduction and flexion was determined by palpating the lateral border of the scapula while moving the humerus in the coronal and sagittal planes, respectively. When the physical therapist felt the scapula upwardly rotate, the motion was stopped and the measurement was recorded. Internal rotation was measured at 90° of humerothoracic abduction in the coronal plane with the elbow at 90° of flexion. The motion was stopped and the measurement was recorded when the scapula began to tilt anteriorly. These passive ROM measurements were recorded once and were chosen as they assess inferior and posterior capsular tightness, as well as glenohumeral joint function. Previous literature assessing isolated glenohumeral ROM in healthy individuals has demonstrated intraobserver and interobserver repeatability ranging from 0.62 to 0.84 and 0.62 to 0.86, respectively, for various joint positions.[45]

Isometric strength measurements were taken as previously described[13,34] using a handheld dynamometer (Lafayette Manual Muscle Testing System; Lafayette Instrument, Lafayette, IN, USA) in 3 joint positions. Isometric strength measurements included external and internal rotation with the arm at the side (ie, 0° of coronal-plane abduction) and external rotation at 90° of abduction in the coronal plane for the involved and uninvolved sides. The dynamometer was placed distally on the forearm, just proximal to the wrist joint, along the dorsal radius and ulna for measurement of external rotation and on the volar surface for internal rotation. Measurements were taken 3 times in each position and averaged to calculate the final isometric strength. All strength measurements were normalized by dividing the measurement on the involved side by the measurement on the uninvolved side and multiplying by 100% to express strength as a percentage of the uninvolved side. Previous literature has indicated that individuals with chronic pain related to the rotator cuff may have central mechanistic changes potentially affecting bilateral motor control and activation.[6,48,49] However, the physical therapist only collected isometric muscle strength if the individual experienced no pain. If the individual experienced pain at any time, the measurements were stopped and data were not collected. The repeatability for assessing shoulder strength in symptomatic individuals has been shown to be excellent, with intraobserver repeatability of 0.85 (internal rotation) and 0.92 (external rotation) and interobserver repeatability of 0.85 (internal rotation) and 0.82 (external rotation) using a handheld dynamometer.[17]

Study participants completed two PRO measures: the ASES Shoulder Rating Scale[43] and the WORC.[24] The ASES score was considered the primary outcome measure because it is a shoulder-specific outcome measure that has demonstrated evidence of reliability, validity, and responsiveness for individuals with rotator cuff tears.[25,32] The WORC score has also demonstrated reliability, validity, and responsiveness and was collected as it is a rotator cuff–specific outcome measure.[12,25,44] Possible scores for both the ASES and WORC assessments ranged from 0 to 100, where higher scores indicate greater function.

Ultrasound was used to quantify the anterior-posterior (AP) tear size within the supraspinatus tendon. Assessments were performed by a musculoskeletal radiologist using a 6- 15 MHz linear array transducer (LOGIQE9; GE Healthcare, Chicago, IL, USA). Individuals were seated with the glenohumeral joint in extension and the involved-side hand on the iliac wing to expose the supraspinatus tendon.[42,50] The transducer was positioned transversely to the supraspinatus tendon, and a short-axis image was acquired. Tear size was quantified as the AP distance of the tear measured perpendicular to a line tangent to the posterior edge of the long head of the biceps tendon (Fig. 2). For tear size, unpublished data from our laboratory demonstrated a repeatability within 4.0 mm across all observers and showed that repeatability was improved in observers with greater ultrasound experience (June 2020). Studies have also shown high sensitivity and reliability for detection and quantification of rotator cuff tears with accuracy on the order of $\leq$1.0 mm.[26,36,51,53,55]

Glenohumeral kinematics during scapular-plane abduction were measured using a previously described model-based tracking technique with images acquired from a synchronized biplane radiography system at 50 images per second.[9] Individuals underwent a computed tomography scan of the involved shoulder (0.471 × 0.471 × 0.625–mm voxels). Computed tomography images were segmented using Mimics 20 (Materialise, Leuven, Belgium) to create individual-specific bone models of the humerus and scapula. To assess glenohumeral kinematics, individuals were seated with the involved glenohumeral joint at the center of the system and performed scapular-plane abduction. Positioning in the scapular plane was maintained using a laser pointer attached to the ventral surface of the wrist; individuals were asked to keep the laser pointer within an aligned target. Three trials of scapular-plane abduction were performed, lasting 2 seconds per trial. The trial in which maximum glenohumeral elevation was attained was used for all analyses. Biplane radiographs underwent distortion correction, and the imaging system was calibrated following established procedures.[9,13,34] Digitally reconstructed radiographs of the bone models were created from the known geometry of the biplane radiography system. The bone models were then manipulated to match the digitally reconstructed radiographs to the

Table I Demographic characteristics of individuals with symptomatic isolated supraspinatus tears prior to initiation of exercise therapy program

	Data
Age, mean ± SD, yr	60.6 ± 9.7
Male sex, % (n)	49.5 (50)
Race, % (n)	
White	83.17 (84)
Black or African American	12.87 (13)
American Indian or Native American	0.99 (1)
Asian	0.99 (1)
Other	1.98 (2)
Hispanic or Latino ethnicity, % (n)	2.97 (3)
Educational level, % (n)	
High school diploma or less	38.61 (39)
College degree (BS, BA)	38.61 (39)
Postgraduate degree (MD)	22.78 (23)
Employment, % (n)	
Full or part time—regular duty	63.37 (64)
Retired	26.73 (27)
Unemployed	0.99 (1)
Other	8.91 (9)
Type of work, % (n)	
Mostly sedentary	42.57 (43)
Sedentary, substantial walking	10.89 (11)
Moderately active, some lifting	40.60 (41)
Demanding	5.94 (6)
BMI, mean ± SD	28.8 ± 4.9
Duration of shoulder pain, % (n)	
≤1 mo	13.86 (14)
>1-≤3 mo	26.73 (27)
>3-<6 mo	33.67 (34)
≥6 mo	25.74 (26)
Pain development, % (n)	
No injury, gradual onset	57.43 (58)
Injury	42.57 (43)
Activities of daily living	8.91 (9)
Motor vehicle accident	3.96 (4)
Sports	12.87 (13)
Other	16.83 (17)
Smoker, % (n)	
Current	7.92 (8)
Past	25.74 (26)

SD, standard deviation.

corresponding bones on the biplane radiographic images in all 6 *df* for each pair of synchronized images throughout the movement using a validated tracking technique.[9]

The local coordinate system for each humerus was constructed based on the International Society of Biomechanics recommendations with the origin located at the center of the humeral head.[56] However, the scapular coordinate system was modified to create a glenoid-based system to describe humeral motion with respect to the center of the glenoid.[34] In brief, the origin was determined as the midpoint between the most anterior and posterior points on the glenoid rim. Local coordinate system axes were aligned with the most AP and superior-inferior (SI) points on the glenoid rim,[7] with the superior and anterior directions considered positive for all individuals. A Y-X-Y Euler angle rotation sequence was used to quantify translations and rotations with accuracy of ±0.4 mm and ±0.5°, respectively, for dynamic motion.[9] For each data frame, a 3-dimensional distance map was calculated between the humeral head and glenoid surfaces. The centroid of the 3-dimensional distance map was then quantified as the weighted average of the closest 200-mm^2 region between the humeral head and glenoid surfaces; this acted as an estimate of the contact center location during scapular-plane abduction.[1]

Kinematic variables of interest included maximum AP and SI glenohumeral translations and the contact center location[7] during scapular-plane abduction. Because of differences in glenoid geometry between individuals, glenohumeral translations and contact center data were normalized to glenoid AP width and SI height.[7] By use of the normalized glenohumeral contact data, the contact path length was calculated as the change in frame-by-frame position of the contact center, providing a quantification of the distance the humeral head articulated on the glenoid surface during scapular-plane abduction. Because the contact path length incorporates articulation in both the AP and SI directions, normalization based on glenoid AP width and SI height results in a contact path length normalized to glenoid size. A larger contact path length may indicate less joint stability owing to less control of the humeral head on the glenoid surface. For each individual, glenohumeral kinematics (ie, maximum anterior and superior glenohumeral translations) and contact path length were calculated over the final 30° of glenohumeral abduction. Because of variations in the individuals' glenohumeral abduction ROM during data collection, 30° was chosen to evaluate the largest possible range while minimizing data loss and allowing individual-to-individual comparisons.

Descriptive statistics were calculated for all variables. Continuous variables were reported as means ± standard deviations, and categorical variables were reported as frequencies and percentages. An a priori power analysis was performed and indicated that the inclusion of 100 individuals was sufficient to detect an absolute difference of 0.3 between the null-hypothesis correlation of 0.0 and the alternative-hypothesis correlation of 0.3 with a power of 80% ($\alpha = .05$). Normality testing concluded that at least 1 variable in the testing of each proposed relationship was nonparametric. Thus, Spearman correlations were used to determine the relationships between measures of passive glenohumeral ROM, rotator cuff muscle strength, tear size, PROs, and glenohumeral kinematics. Because of the exploratory nature of the study and mechanistic hypotheses proposed, a correction for multiple comparisons was not implemented. Thus, the level of significance was set at $P < .05$ for all analyses.

Results

Complete data were collected for 86.1% of individuals. Individuals' ages ranged from 40.1 to 80.6 years, and male individuals comprised 49.5% of the cohort. The most frequently reported duration of shoulder pain prior to entering the study was >3-<6 months (33.7%), followed by >1-≤3 months (26.7%), ≥6 months (25.7%), and ≤1 month (13.9%). Additional demographic information can be found in Table I.

Table II Kinematics, strength, ROM, and outcome scores

	Data
Glenohumeral kinematics	
Glenohumeral abduction range analyzed, °	57.8 ± 13.2 to 87.8 ± 13.2
Maximum anterior translation, % of glenoid width*	3.0 ± 3.8
Maximum superior translation, % of glenoid height*	3.5 ± 3.8
Contact path length, % of glenoid size*	38.2 ± 20.7
Isometric strength	
ER at 0°*	
Involved, N	79.3 ± 40.8
Noninvolved, N	103.9 ± 41.0
Normalized, %	77.1 ± 30.3
IR at 0°	
Involved, N	110.8 ± 50.6
Noninvolved, N	132.2 ± 54.5
Normalized, %	85.1 ± 23.4
ER at 90°	
Involved, N	76.1 ± 40.6
Noninvolved, N	108.3 ± 45.0
Normalized, %	72.1 ± 32.3
Passive ROM on involved side, °	
Glenohumeral abduction*	113.2 ± 20.7
Glenohumeral IR at 90°	50.3 ± 14.8
Glenohumeral flexion*	115.2 ± 15.6
Patient-reported outcome: total score	
ASES score*	64.4 ± 18.6
WORC score	59.0 ± 21.0

ER, external rotation; *N*, newtons; *IR*, internal rotation; *ROM*, range of motion; *ASES*, American Shoulder and Elbow Surgeons; *WORC*, Western Ontario Rotator Cuff Index.
Data are presented as mean ± standard deviation.
* Data were non-normally distributed.

The ranges of passive glenohumeral internal rotation, abduction, and flexion in the involved shoulder were 50.3° ± 14.8°, 113.2° ± 20.7°, and 115.2° ± 15.6°, respectively. Strength limitations were observed on the involved side for all 3 joint positions. The largest strength limitation was observed in external rotation at 90°, where the involved-side strength was 72.1% ± 32.3% of the uninvolved side. Passive glenohumeral ROM for the involved side and isometric muscle strength as a percentage of the uninvolved side can be found in Table II. The average ASES and WORC scores were 64.4 ± 18.6 (range, 17.5-95.0) and 59.0 ± 21.0 (range, 4.8-97.9), respectively.

Tear size was measured in 93.1% of individuals. Reasons for missing data included poor image acquisition and failure of individuals to report at the time of assessment. Supraspinatus tear size ranged from 0.5 to 28.3 mm, and 65.3% of individuals had a full-thickness tear.

Sixteen individuals did not have ≥30° of available in vivo glenohumeral abduction and were excluded from all kinematic analyses. The range of glenohumeral abduction analyzed for all kinematic outcome measures was from 57.8° ± 13.2° to 87.8° ± 13.2°. Average glenoid width and height used to normalize glenohumeral translation and contact path length were 26.7 ± 3.6 mm and 34.2 ± 3.7 mm, respectively. Furthermore, 84.7% of individuals had maximum anterior translations ≤ 6.0% of glenoid width (ranging from 0% to 15.6% of glenoid width) and 91.8% of individuals had maximum superior translations ≤ 9.0% of glenoid height (ranging from 0.0% to 17.6% of glenoid height). Approximately 65.9% of individuals had contact path lengths < 40.7% of glenoid size and 20.0% of individuals had contact path lengths between 40.7% and 56.7% of glenoid size.

The associations between isometric strength and contact path length, as well as maximum superior glenohumeral translations, were all nonsignificant (Table III). Specifically, there were no significant associations between internal and external rotation strength measured with the arm at 0° or external rotation strength with the arm at 90° of abduction and the contact path length and maximum superior glenohumeral translation (ρ^2 ranged from 0.00 to 0.03, $P > .12$).

There were no significant associations between supraspinatus tear size and contact path length or isometric external or internal rotation strength at 0° of abduction and external rotation strength at 90° of abduction ($P > .46$) (Table IV). No relationships were observed between passive ROM measurements and maximum superior and anterior glenohumeral translations ($P > .27$) (Table V). There were no significant associations between ASES scores or WORC scores and maximum superior and anterior glenohumeral translations ($P > .17$) (Table VI). Furthermore, there was no significant association between contact path lengths and ASES scores, but there was a significant positive association between contact path lengths and WORC scores ($\rho = 0.25$, $P = .03$) (Table VI). Thus, as contact path lengths increased, WORC scores increased.

Discussion

This study described the presentation of individuals with an isolated supraspinatus tendon tear. Overall, the individuals in this study presented with limitations in isometric muscle strength (compared with the uninvolved side); minimal restrictions in passive glenohumeral ROM relative to the normal expected range of glenohumeral abduction, flexion, and internal rotation reported in the literature[45] (and assuming a 2:1 scapulohumeral rhythm); and pain and disability as measured by the ASES and WORC scores. Furthermore, no associations were observed between passive glenohumeral ROM, isometric rotator cuff muscle strength, supraspinatus tear size, and glenohumeral kinematics during scapular-plane abduction. Additionally, no associations were observed between glenohumeral kinematics during scapular-plane abduction and PROs, with the exception of contact path lengths and WORC scores.

Table III Correlation matrix summarizing relationships between isometric rotator cuff muscle strength, contact path length, and superior glenohumeral translations in individuals with symptomatic isolated supraspinatus tear prior to initiation of exercise therapy program

	Contact path length			Maximum superior translation		
	ρ	ρ^2	*P* value	ρ	ρ^2	*P* value
ER strength at 0°	0.04	0.00	.74	−0.01	0.00	.96
IR strength at 0°	−0.03	0.00	.81	−0.17	0.03	.12
ER strength at 90°	−0.05	0.00	.68	0.11	0.01	.34

ER, external rotation; *IR*, internal rotation.

Table IV Correlation matrix summarizing relationships between AP tear size, contact path length, and isometric rotator cuff muscle strength in individuals with symptomatic isolated supraspinatus tear prior to initiation of exercise therapy program

	Contact path length			IR strength at 0°			ER strength at 0°			ER strength at 90°		
	ρ	ρ^2	*P* value	ρ	ρ^2	*P* value	ρ	ρ^2	*P* value	ρ	ρ^2	*P* value
AP tear size	−0.05	0.00	.65	−0.04	0.00	.71	−0.08	0.01	.46	−0.07	0.00	.53

AP, anterior-posterior; *IR*, internal rotation; *ER*, external rotation.

The implications of the findings regarding the initial presentation of individuals with a symptomatic isolated supraspinatus tear are for the development of an exercise therapy program focusing on individualized treatment. The specific exercises performed should be based on the impairments identified during the initial examination, and a set of predefined clinical decision-making criteria should be used to address each impairment and guide progression through the program. For example, the therapist may choose to implement ROM or stretching exercises or joint mobilization when a loss of ROM is present compared with the uninvolved side. Exercises will then be performed at a set dosage until ROM is within normal limits or equal to the uninvolved side. A similar decision-making process would also be used for impairments in muscle strength, where isometric, isotonic, and progressive resistive exercises may be implemented to address the observed weaknesses.

It is interesting to note that all of the hypothesized mechanistic relationships proposed in this study were not supported by the results. Individuals with greater internal and external rotation strength did not demonstrate less superior migration and more joint stability. These findings may indicate that various magnitudes of strength of the subscapularis, infraspinatus, and teres minor can maintain joint stability given that the tear is isolated to the supraspinatus tendon. Numerous studies have described the ability of the transverse force couple to maintain glenohumeral joint stability through the medially and inferiorly directed forces in the presence of isolated supraspinatus tears.[18,41,52] Thus, although it was hypothesized that greater strength of the muscles comprising the transverse force couple would decrease superior glenohumeral translations and increase joint stability, our finding does remain consistent with previous literature regarding the transverse force couple. For comparison, the contact path length has been shown to be 31.6% ± 11.0% of glenoid height (range, 17.2%-58.8%) during coronal-plane abduction in age-matched controls in the range of 20°-70° of glenohumeral elevation. Thus, individuals in the current cohort with isolated supraspinatus tendon tears experienced larger contact path lengths compared with previously reported controls.[3]

The finding that AP tear size was not associated with internal and external rotation strength or contact path length has two implications: First, given a tear isolated to the supraspinatus tendon, the functional strength of the subscapularis, infraspinatus, and teres minor is not affected by the magnitude of the tear size. Second, given a tear isolated to the supraspinatus tendon, larger tears do not result in less glenohumeral joint stability. Two previous studies using cadavers demonstrated no significant alterations in glenohumeral translations with 1-, 3-, or 5-cm supraspinatus tears (given that the infraspinatus tendon is intact),[52] as well as no significant changes in glenohumeral joint reaction force magnitudes during active scapular-plane abduction in isolated incomplete or complete tears of the supraspinatus tendon.[41] In combination, these two findings indicate that individuals with rotator cuff tears isolated to the supraspinatus tendon do not exhibit restrictions in strength or less joint stability based on the size of the isolated supraspinatus tear.

Greater ranges of passive glenohumeral internal rotation, abduction, and flexion were not related to maximum anterior and superior glenohumeral translations during scapular-plane abduction in vivo. This finding suggests that varying amounts of available passive glenohumeral ROM in the presence of a rotator cuff tear isolated to the

Table V Correlation matrix summarizing relationships between passive ROM and maximum superior and anterior glenohumeral translations in individuals with symptomatic isolated supraspinatus tear prior to initiation of exercise therapy program

	Maximum superior translation			Maximum anterior translation		
	ρ	$ρ^2$	*P* value	ρ	$ρ^2$	*P* value
Passive ROM with IR at 90°	−0.12	0.01	.27	0.08	0.01	.45
Passive ROM with GH ABD	0.07	0.01	.52	−0.12	0.01	.30
Passive ROM with GH flexion	−0.09	0.01	.44	−0.04	0.00	.74

IR, internal rotation; *ROM*, range of motion; *GH*, glenohumeral; *ABD*, abduction.

Table VI Correlation matrix summarizing relationships between maximum superior and anterior glenohumeral translations, contact path length, and patient-reported outcomes in individuals with symptomatic isolated supraspinatus tear prior to initiation of exercise therapy program

	ASES score			WORC score		
	ρ	$ρ^2$	*P* value	ρ	$ρ^2$	*P* value
Maximum superior translation	−0.03	0.00	.79	0.15	0.02	.18
Maximum anterior translation	0.17	0.03	.17	0.07	0.00	.55
Contact path length	0.16	0.02	.21	0.25	0.06	.03*

ASES, American Shoulder and Elbow Surgeons; *WORC*, Western Ontario Rotator Cuff Index.
* Statically significant ($P < .05$).

supraspinatus tendon do not affect maximum glenohumeral translations during scapular-plane abduction. Given that the tear is isolated to the supraspinatus tendon and no capsular restrictions are present, as indicated by >30° of internal and external rotation ROM, normal function of the glenohumeral joint is possible. These results differ from the findings of previous studies in cadavers that demonstrated increased anterior and superior glenohumeral translations following posterior capsular plication to limit ROM.[16] The results of this study likely differ from the findings of cadaveric models mimicking posterior-inferior capsular tightness because of their inability to account for activation of the rotator cuff muscles, as well as the exclusion of individuals with <30° of internal and external rotation ROM.

The hypothesized relationships between maximum anterior and superior glenohumeral translations and PROs were also not supported. This finding suggests that PROs were not influenced by glenohumeral translations in individuals with isolated supraspinatus tears (coronal- and transverse-plane couples intact) and >30° of internal and external rotation ROM. Previous studies assessing in vivo glenohumeral translations in healthy control subjects have reported average SI translations between 0.04 ± 1.3 mm and –0.02 ± 1.4 mm and anterior translations between 1.2 ± 2.0 mm and 0.4 ± 2.0 mm from 90° to 120° of humerothoracic abduction.[14] Assuming a 2:1 scapulohumeral rhythm, humerothoracic abduction in this study ranged from 86.7° ± 19.8° to 131.7° ± 19.8° with maximum superior translation of 3.5% ± 3.8% of glenoid height (1.2 ± 1.3 mm) and maximum anterior translation of 3.0% ± 3.8% of glenoid width (0.8 ± 1.0 mm). In contrast to the ASES score, the WORC score was found to positively relate to contact path length, which may indicate that the WORC score does not properly reflect glenohumeral joint stability, as it would be expected that higher scores would relate to more stable joints. However, the observed relationship was weak, and the variation in WORC scores explained by contact path lengths was only 6.0% (Table VI). Therefore, the observed relationship is likely not clinically significant and may have occurred due to chance given the multiple correlations evaluated in the study. Thus, from a biomechanical perspective, individuals with isolated supraspinatus tears, such as those included in this study, do not present with clinically significant differences in glenohumeral kinematics that would likely affect PROs.

Regarding PROs, a previous study investigated the effects of a 12-week exercise therapy program on glenohumeral kinematics (during coronal-plane abduction), isometric muscle strength, and PROs in 5 individuals with symptomatic full-thickness supraspinatus tears.[34] The average WORC and ASES scores prior to exercise therapy were lower by 16.1 and 13.7 points, respectively, compared with the scores in our study. An additional study investigating the effectiveness of physical therapy in treating atraumatic full-thickness rotator cuff tears in 452 individuals reported average WORC and ASES scores that were 11.8 and 10.0 points lower than the WORC and ASES scores in our study, respectively.[29] However, only 70% of individuals had tears isolated to the supraspinatus tendon.

Differences observed in PROs prior to exercise therapy between studies demonstrate the importance of understanding factors relating to PRO scores. Varying PRO scores have been related to active ROM (flexion, abduction, and rotation) and muscle strength in individuals with different shoulder pathologies.[2,31] Furthermore, the effects of exercise therapy and rotator cuff repair were in agreement with the findings of our study showing that glenohumeral kinematics were not related to PROs and subjective self-reported outcomes may be more influenced by pain relief and psychosocial factors such as patient expectations or mental health status.[8,10] Thus, future work should investigate the individual contribution of varying factors to PROs in individuals with isolated supraspinatus tendon tears prior to exercise therapy.

A limitation of this study is the inclusion of partial- and full-thickness tears in all analyses. In future studies, partial- and full-thickness tears will be investigated as separate groups to determine the effects of tear thickness on glenohumeral kinematics and PROs as it has been shown that full-thickness tears are associated with worse PROs.[21] Additional limitations of the study were the inclusion of a single movement to assess in vivo glenohumeral kinematics and the performance of analyses only over the end ROM. However, given the primary role of the supraspinatus for glenohumeral abduction and clinical importance of the end ROM, assessing glenohumeral kinematics in this manner was most reasonable. To better understand the effects of isolated supraspinatus tears, more provocative movements should be investigated. Future work will investigate glenohumeral kinematics during additional movements, as well as determine the biomechanical and clinical factors that predict the success or failure of a 12-week structured exercise therapy program.

Conclusion

This study demonstrates that individuals with isolated supraspinatus tears present with minor limitations in shoulder motion and rotator cuff muscle strength. Furthermore, these limitations were not associated with altered glenohumeral kinematics or PROs prior to an exercise therapy program. Thus, from a biomechanical perspective, individuals with isolated supraspinatus tears (coronal- and transverse-plane force couples intact) and no capsular restrictions as indicated by $>30°$ of internal and external rotation ROM do not exhibit changes in glenohumeral kinematics.

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