Clin Orthop Relat Res (2022) 480:2217-2228
DOI 10.1097/CORR.0000000000002253

Clinical Orthopaedics
and Related Research®
A Publication of The Association of Bone and Joint Surgeons®

Clinical Research

No Strength Differences Despite Greater Posterior Rotator Cuff Intramuscular Fat in Patients With Eccentric Glenohumeral Osteoarthritis

Margaret S. Coats-Thomas BS[1,2,3], Emma M. Baillargeon DPT, PhD[4], Daniel Ludvig PhD[1,2], Guido Marra MD[5], Eric J. Perreault PhD[1,2,6], Amee L. Seitz DPT, PhD[3,7]

Received: 1 January 2022 / Accepted: 4 May 2022 / Published online: 2 June 2022

Abstract

Background When nonoperative measures do not alleviate the symptoms of glenohumeral osteoarthritis (OA), patients with advanced OA primarily are treated with anatomic total shoulder arthroplasty (TSA). It is unknown why TSAs performed in patients with eccentric (asymmetric glenoid wear) compared with concentric (symmetric glenoid wear) deformities exhibit higher failure rates, despite surgical advances. Persistent disruption of the posterior-to-anterior rotator cuff (RC) force couple resulting from posterior RC intramuscular degeneration in patients with eccentric deformities could

---

The institution of one or more of the authors (MSCT) has received, during the study period, funding from the Department of Physical Therapy and Human Movement Sciences at Northwestern University and the Department of Orthopaedic Surgery at Northwestern University.
One of the authors (MSCT) certifies receipt of research funding from the National Institutes of Arthritis and Musculoskeletal and Skin Diseases (NIAMS, F31AR077426) and the American Society of Biomechanics. One of the authors certifies (EJP) receipt of research support funding from Northwestern University. One of the authors (GM) certifies receipt of personal payments or benefits, during the study period, in an amount of USD 10,000 to USD 100,000 from Zimmer Biomet.
All ICMJE Conflict of Interest Forms for authors and *Clinical Orthopaedics and Related Research®* editors and board members are on file with the publication and can be viewed on request.
Ethical approval for this study was obtained from Northwestern University, Chicago, IL, USA (number STU00210986).
This work was performed at Northwestern University, Chicago, IL, USA.

[1] Department of Biomedical Engineering, Northwestern University, Evanston, IL, USA

[2] Shirley Ryan AbilityLab, Chicago, IL, USA

[3] Feinberg School of Medicine, Northwestern University, Chicago, IL, USA

[4] Department of Epidemiology, Graduate School of Public Health, University of Pittsburgh, Pittsburgh, PA, USA

[5] Department of Orthopaedic Surgery, Northwestern University, Chicago, IL, USA

[6] Department of Physical Medicine and Rehabilitation, Northwestern University, Chicago, IL, USA

[7] Department of Physical Therapy and Human Movement Sciences, Northwestern University, Chicago, IL, USA

M. S. Coats-Thomas ✉, 645 N Michigan Ave, Suite 1100, Chicago, IL 60611, USA, Email: margaret.coats-thomas@northwestern.edu

Wolters Kluwer

impair external rotation strength and may contribute to eventual TSA failure. Pain and intramuscular fat within the RC muscles may impact external rotation strength measures and are important to consider.

Questions/purposes (1) Is there relative shoulder external rotation weakness in patients with eccentric compared with concentric deformities? (2) Is there higher resting or torque-dependent pain in patients with eccentric compared with concentric deformities? (3) Do patients with eccentric deformities have higher posterior-to-anterior RC intramuscular fat percent ratios than patients with concentric deformities?

Methods From February 2020 to November 2021, 65% (52 of 80) of patients with OA met study eligibility criteria. Of these, 63% (33 of 52) of patients enrolled and provided informed consent. From a convenience sample of 21 older adults with no history of shoulder pain, 20 met eligibility criteria as control participants. Of the convenience sample, 18 patients enrolled and provided informed consent. In total for this prospective, cross-sectional study, across patients with OA and control participants, 50% (51 of 101) of participants were enrolled and allocated into the eccentric (n = 16), concentric (n = 17), and control groups (n = 18). A 3-degree-of-freedom load cell was used to sensitively quantify strength in all three dimensions surrounding the shoulder. Participants performed maximal isometric contractions in 26 1-, 2-, and 3-degree-of-freedom direction combinations involving adduction/abduction, internal/external rotation, and/or flexion/extension. To test for relative external rotation weakness, we quantified relative strength in opposing directions (three-dimensional [3D] strength balance) along the X (+adduction/-abduction), Y (+internal/-external rotation), and Z (+flexion/-extension) axes and compared across the three groups. Patients with OA rated their shoulder pain (numerical rating 0-10) before testing at rest (resting pain; response to "How bad is your pain today?") and with each maximal contraction (torque-dependent pain; numerical rating 0-10). Resting and torque-dependent pain were compared between patients with eccentric and concentric deformities to determine if pain was higher in the eccentric group. The RC cross-sectional areas and intramuscular fat percentages were quantified on Dixon-sequence MRIs by a single observer who performed manual segmentation using previously validated methods. Ratios of posterior-to-anterior RC fat percent (infraspinatus + teres minor fat percent/subscapularis fat percent) were computed and compared between the OA groups.

Results There was no relative external rotation weakness in patients with eccentric deformities (Y component of 3D strength balance, mean ± SD: -4.7% ± 5.1%) compared with patients with concentric deformities (-0.05% ± 4.5%, mean difference -4.7% [95% CI -7.5% to -1.9%]; p = 0.05). However, there was more variability in 3D strength balance in the eccentric group (95% CI volume, $\%^3$: 893) compared with the concentric group (95% CI volume, $\%^3$: 579). In patients with eccentric compared with concentric deformities, there was no difference in median (IQR) resting pain (1.0 [3.0] versus 2.0 [2.3], mean rank difference 4.5 [95% CI -6.6 to 16]; p = 0.61) or torque-dependent pain (0.70 [3.0] versus 0.58 [1.5], mean rank difference 2.6 [95% CI -8.8 to 14]; p = 0.86). In the subset of 18 of 33 patients with OA who underwent MRI, seven patients with eccentric deformities demonstrated a higher posterior-to-anterior RC fat percent ratio than the 11 patients with concentric deformities (1.2 [0.8] versus 0.70 [0.3], mean rank difference 6.4 [95% CI 1.4 to 11.5]; p = 0.01).

Conclusion Patients with eccentric deformities demonstrated higher variability in strength compared with patients with concentric deformities. This increased variability suggests patients with potential subtypes of eccentric wear patterns (posterior-superior, posterior-central, and posterior-inferior) may compensate differently for underlying anatomic changes by adopting unique kinematic or muscle activation patterns.

Clinical Relevance Our findings highlight the importance of careful clinical evaluation of patients presenting with eccentric deformities because some may exhibit potentially detrimental strength deficits. Recognition of such strength deficits may allow for targeted rehabilitation. Future work should explore the relationship between strength in patients with specific subtypes of eccentric wear patterns and potential forms of kinematic or muscular compensation to determine whether these factors play a role in TSA failures in patients with eccentric deformities.

Introduction

Glenohumeral osteoarthritis (OA) is associated with pain, weakness, and functional limitations in older adults. Glenoid erosion with OA can result in a concentric (Walch Type A1 and A2) or eccentric deformity (Walch Type B1, B2, and B3) [6]. The failure rate of anatomic total shoulder arthroplasty (TSA) in patients with eccentric deformities is substantially higher than in patients with concentric deformities, despite advances in surgical techniques [10, 22, 26, 35, 37, 41]. A potential cause of persistent TSA failure in patients with eccentric deformities is disruption of the force couple between the posterior (infraspinatus and teres minor) and anterior (subscapularis) rotator cuff (RC) muscles [11, 12]. Increased posterior RC intramuscular fat, which impairs external rotation strength [30, 44], has been identified preoperatively in patients with eccentric deformities [12]. External rotation weakness that persists postoperatively could result in asymmetric glenoid loading [34, 40] and contribute to subsequent glenoid implant failure [9, 14, 27].

Factors, including pain and RC muscle size, may impact measures of external rotation strength. Prior evidence suggests relative external-to-internal rotation strength is similar between patients with OA (across all glenoid deformity types) [37] and healthy adults [3], but the influence of pain has not, to our knowledge, been considered. A patient may demonstrate apparent weakness in a certain direction if their effort was limited by pain. Although increased intramuscular fat has been identified in the posterior RC in patients with eccentric compared with concentric deformities [12], ratios comparing the relative amount of remaining muscle (fat-adjusted) have not been reported. Lastly, strength assessments in patients with OA have been performed in a single dimension using hand-held dynamometers. Such devices only measure the component of a generated torque aligned with the measurement direction, thus allowing patients to maximize torque in the measurement direction by generating off-axis torques in other directions (such as, abduction to enhance external rotation) [33]. Assessing strength in three dimensions (along flexion/extension, internal/external rotation, and adduction/abduction simultaneously) overcomes these limitations by minimizing off-axis torque generation. Thus, three-dimensional (3D) measures may be more sensitive to detect weakness in the direction of interest. Considering these factors, it is unknown whether patients with eccentric deformities demonstrate relative external rotation weakness. Rehabilitation after TSA that does not detect or correct preexisting external rotation weakness may contribute to higher failure rates in patients with eccentric deformities. Identification of external rotation weakness in patients with eccentric deformities may elucidate mechanisms contributing to bony deformity development and TSA failure, allowing for modification of postoperative rehabilitation with targeted strengthening.

Therefore, we asked: (1) Is there relative shoulder external rotation weakness in patients with eccentric compared with concentric deformities? (2) Is there higher resting or torque-dependent pain in patients with eccentric compared with concentric deformities? (3) Do patients with eccentric deformities have higher posterior-to-anterior RC intramuscular fat percent ratios than patients with concentric deformities?

Patients and Methods

Study Design and Setting

For this prospective, cross-sectional study, participants were recruited over a 17-month period from February 2020 to November 2021, when the clinic was open for elective consultations during the COVID-19 pandemic.

Participants

Patients with a diagnosis of primary glenohumeral OA evaluated by a fellowship-trained orthopaedic surgeon (GM) were recruited. Primary glenohumeral OA with an intact RC was diagnosed based on an examination and imaging findings. The surgeon (GM) classified glenoid deformities according to the Walsh classification [6] for group allocation (eccentric or concentric). Patients with prior shoulder fracture, surgery, infection, or shoulder pain greater than a 6 of 10 at rest were excluded. Age-matched older adults without shoulder pain (< 1 of 10) were recruited as control participants from the surrounding local community and excluded if they previously sought care for shoulder pain. Potential participants with neurologic disease, systemic inflammatory conditions, shoulder pain with cervical spine motion, prior breast cancer treatment, and active cancer were excluded. Sixty-five percent (52 of 80) of patients with OA screened for eligiblity met the study criteria. Of these, 63% (33 of 52) of patients with OA enrolled and provided informed consent. From a convenience sample of 21 older adults with no history of shoulder pain, 20 met eligibility criteria as control participants. Of the convenience sample, 18 control participants enrolled and provided informed consent. Of the 50% (51 of 101) of patients with OA and control participants enrolled, 100% (51 of 51) completed strength testing, and based on eligiblity, a subset of patients with OA (55% [18 of 33]) underwent an MRI for the study.

Descriptive Data

In total, 51 participants were enrolled and allocated into the eccentric (n = 16), concentric (n = 17), and control groups (n = 18) (Table 1). All participants completed the Penn shoulder score [24] and provided demographic information. There were no differences between groups on the basis of age, gender, BMI, or dominance of the side tested. Patients with eccentric (median 1.0 [IQR 3.0]) and concentric (2.0 [2.3]) deformities had higher resting pain than control participants (0.0 [0.0]; $p < 0.001$). Patients with eccentric (62 [23]) and concentric (67 [26]) deformities had lower total Penn shoulder scores than control participants (100 [4.2]; $p < 0.001$). The minimum clinically important difference for improvement for the Penn shoulder score is 11 points [24], although after TSA, patients have demonstrated, on average, a 50-point improvement from pre- to postoperatively [28].

Data Measurement

Strength

The tested arm was fitted with a fiberglass cast extending from the upper arm to the wrist in 90° of elbow flexion. The casted arm was attached to a 6-degree-of-freedom load cell (45E15A4, JR3) in 45° of shoulder elevation, 30° anterior to the coronal plane, and neutral rotation (Fig. 1). Force and torque measurements were made at the load cell and transformed to a glenohumeral coordinate system [43].

Table 1. Participant demographics, pain, and disability

Characteristic	Concentric (n = 17)	Eccentric (n = 16)	Control (n = 18)	p value
Age in years[a]	70 (7.3)	69 (15)	68 (21)	0.81
Gender (men)[b]	53% (9)	75% (12)	61% (11)	0.42
Hand dominance (right)[b]	88% (15)	81% (13)	100% (18)	0.18
Side tested (dominant)[b]	35% (6)	44% (7)	44% (8)	0.83
BMI in kg/m^2[a]	27 (5.0)	31 (9.2)	26 (4.9)	0.11
Resting pain[a]	2.0 (2.3)	1.0 (3.0)	0.0 (0.0)	< 0.001 Eccentric vs concentric: 0.61 Eccentric vs control: < 0.001 Concentric vs control: < 0.002
Total Penn shoulder score[a]	67 (26)	62 (23)	100 (4.2)	< 0.001 Eccentric vs concentric: 0.71 Eccentric vs control: < 0.001 Concentric vs control: < 0.001
Pain subscore (0-30)[a]	24 (10)	22 (9.5)	30 (0)	< 0.001 Eccentric vs concentric: 0.66 Eccentric vs control: < 0.001 Concentric vs control: < 0.001
Satisfaction subscore (0-10) [a]	3.0 (4.8)	3.0 (5.5)	10 (1.0)	< 0.001 Eccentric vs concentric: 0.85 Eccentric vs control: < 0.001 Concentric vs control: < 0.001
Function subscore (0-60)[a]	43 (16)	39 (15)	60 (2)	< 0.001 Eccentric vs concentric: 0.73 Eccentric vs control: < 0.001 Concentric vs control: < 0.001

Data presented as median (IQR) or % (n); all comparisons were made across shoulders.

[a] p values were calculated using a Kruskal-Wallis test between groups.

[b] p values were calculated using a chi-squared test between groups.

After submaximal practice trials, participants performed 3-second maximal isometric contractions in 26 equally spaced, randomly ordered directions with 30-second breaks between trials. Participants were guided by 3D visual feedback of the target torque direction, preventing off-axis torque generation. Target directions included 1-degree-of-freedom targets (flexion, adduction, or internal rotation independently) and combined 2- or 3-degree-of-freedom targets (extension, abduction, and external rotation simultaneously).

To evaluate for external rotation weakness, we quantified relative strength in opposing directions (strength balance). First, the maximum torque (Nm) achieved in each target direction was determined as described (Fig. 2A-B) [5]. Using a principal components analysis of the 26 maximal torques, we determined the magnitude (Nm) and direction of the three principal axes spanning the space of achieved 3D torques. The overall strength magnitude was computed as the Euclidian norm of the three principal axis magnitudes (Nm) (Fig. 2C), normalized by weight (Nm/kg). Strength balance was derived by computing the 3D center of the torque space as the vector mean of the 26 measures, normalized by strength magnitude (Fig. 2D). A strength balance (% of strength magnitude) at the origin suggests equivalent strength between internal and external rotation. A strength balance that shifts toward internal rotation (+ Y), adduction (+ X), or flexion (+ Z) suggests relative weakness in external rotation (- Y), abduction (- X), or extension (- Z).

Effects of Pain and Percentage of Fat

Patients with OA rated their resting pain before testing ("How bad is your pain today?") and during each strength trial using a verbal numeric scale from 0 to 10. Pain ratings were plotted along the associated target direction to visualize pain throughout the 3D space (Fig. 2B). The mean of all 26

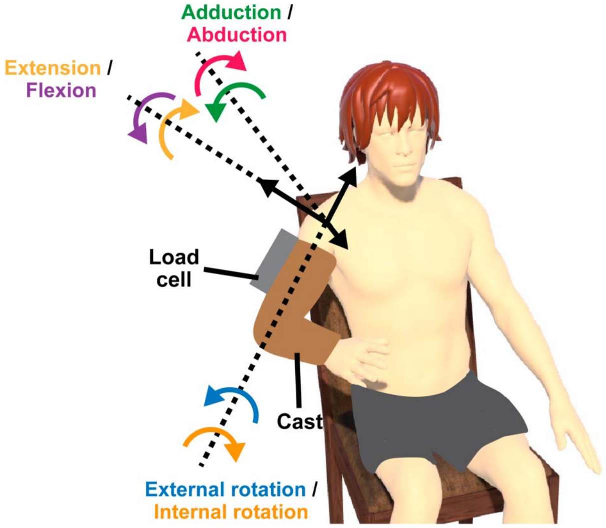

Fig. 1 This figure shows the experimental setup. Participants performed maximal isometric contractions while their arm was attached to a 6-degree-of-freedom load cell via a premade fiberglass cast. Straps were used to secure the trunk, and scapular motion was not fixed.

pain rating magnitudes was computed to determine the torque-dependent pain. Resting and torque-dependent pain elucidate whether the eccentric group experiences more pain at baseline or when performing isometric contractions. Since pain can limit strength and could thus affect our results, we also examined its influence in two other ways. First, we evaluated if there was more or less pain in specific directions in the eccentric group. To do this, each patient's 3D pain ratings across all 26 directions were summed to determine pain balance (Fig. 2D). Pain balance at the origin indicates equal pain in all directions, whereas a shift toward external over internal rotation suggests greater pain with external rotation. If a patient rated their pain as a 10 of 10 for all 1-, 2-, and 3-degree-of-freedom targets involving a direction (such as internal rotation) and 0 of 10 for all targets involving the opposing direction (such as external rotation), the maximum possible pain balance value along the associated axis (such as Y) would be 61. Second, we tested if pain limited torque generation in some but not others on a patient-by-patient basis. To do this, we determined the overall average torque (normalized to strength magnitude) generated in each direction across patients with OA. The overall average torque was subtracted from the torque generated in each direction to determine the patient-specific relative torque in the 26 directions tested.

To characterize RC muscle degeneration, eligible patients with OA with concentric deformities (n = 11) and with eccentric deformities (n = 7) underwent MRI for the study. Patients with MRI-incompatible implants,

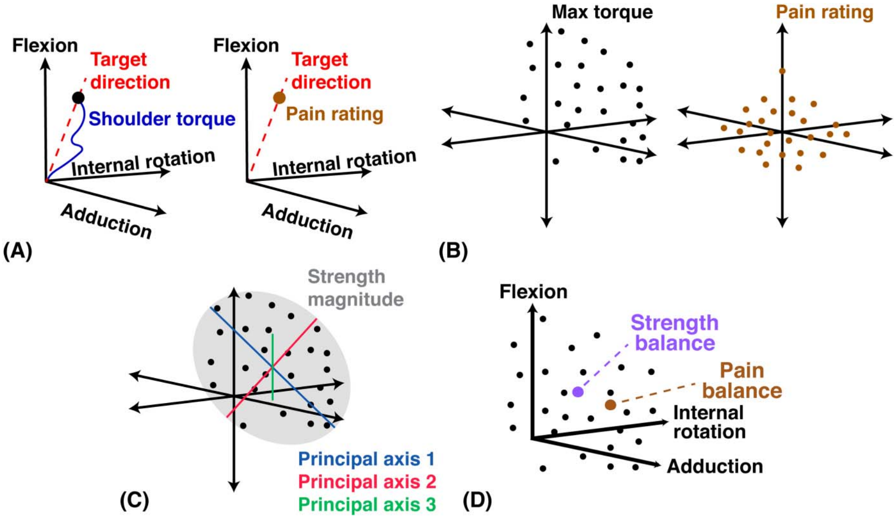

Fig. 2. A-D These graphs show the derivation of strength balance, including (**A**) torque trajectory from a single trial, demonstrating maximum torque achieved (black dot) along the target direction (red dotted line), along with the associated pain rating during torque generation (brown dot). (**B**) This figure illustrates the maximum torques achieved in all 26 directions and associated 3D pain ratings. (**C**) The overall strength magnitude was computed by performing a principal components analysis on the 26 maximal torques and taking the Euclidian norm of the three principal axis magnitudes normalized to weight. (**D**) Strength balance was computed by taking the vector mean of the 26 3D maximal torque vectors, then normalizing the mean by strength magnitude. Pain balance was computed by summing 3D pain ratings across all 26 directions.

claustrophobia, or body size prohibiting closed MRI were excluded. Sagittal oblique images were acquired with a 3D two-point Dixon fat-water imaging sequence to quantify intramuscular fat [13, 16, 36] using a 3T Siemens MR scanner (Prisma, Siemens) and a 16-channel phased array shoulder coil.

The cross-sectional area and intramuscular fat percentage (fat%) were quantified using Analyze software (Analyze 14.0, Analyze Direct). Manual segmentation was performed inside the anterior and posterior RC fascial borders at the characteristic Y-view [25] after reorientation to the scapular plane [8]. The infraspinatus and teres minor muscles were combined, representing the posterior RC [39]. Quantification of cross-sectional area and fat% at the Y-view has been validated with muscle volume [25], regional distribution of RC intramuscular fat [19], and clinical assessments of intramuscular fat [17, 18, 29]. The fat% for each muscle was computed by dividing the fat signal intensity by the fat plus water signal intensities and multiplying by 100. Muscle cross-sectional areas were corrected for fat% (fat-adjusted muscle cross-sectional area) by subtracting the fat% cross-sectional area (original muscle cross-sectional area*fat%). The posterior-to-anterior RC fat% ratio was computed by dividing the fat% of the infraspinatus and teres minor by that of the subscapularis. Additionally, the fat-adjusted cross-sectional area ratio was computed by dividing the fat-adjusted cross-sectional area of the infraspinatus and teres minor by that of the subscapularis.

Study Size

Based on pilot data, an a priori power analysis revealed that 12 participants would be required per group to detect differences in 3D strength between groups, with an anticipated effect size of 0.97 and 80% power.

Bias

We strove to recruit equal numbers of age-matched men and women in each group, as evidenced by the lack of a difference between groups on the basis of gender or age. Our analyses of strength incorporated gender, age, and dominance of the side tested as confounding factors, thus removing additional variability resulting from these parameters. We used ratios when evaluating RC muscle cross-sectional area and fat percentages, allowing for comparison across men and women.

Primary and Secondary Study Outcomes

Our primary study goal was to determine whether patients with eccentric compared with concentric deformities demonstrate relative external rotation weakness. To achieve this, we measured relative shoulder strength in opposing directions (strength balance) as participants performed maximal isometric contractions in 26 distinct directions.

Our secondary study goals were to determine whether patients with eccentric deformities exhibit higher resting pain, torque-dependent pain, or posterior-to-anterior RC intramuscular fat percent ratios than patients with concentric deformities. To achieve this, patients rated their shoulder resting pain and pain during each isometric contraction (torque-dependent pain). Additionally, we quantified the posterior-to anterior RC fat percent ratios from MR images.

Ethical Approval

This study was approved by our institutional review board. Participants gave written informed consent for participation.

Statistical Analysis

To test our primary hypothesis that patients with eccentric deformities demonstrate relative external rotation weakness compared with patients with concentric deformities, we used a multivariable regression. We modeled 3D strength balance as dependent on group and confounding demographic effects of age, gender, and dominance of the side tested. We used a Hotelling t-square statistic to test for group differences. Although not our primary study goal, we additionally tested for between-group (independent variable) differences in strength magnitude (dependent variable) using a univariate linear model. Independent factors included age, gender, and dominance of the side tested.

Secondarily, we evaluated for the effects of pain and fat% on strength results. To determine whether patients with eccentric deformities exhibited more pain, we compared the resting and torque-dependent pain ratings between groups using Kruskal-Wallis tests. To determine whether patients with eccentric deformities had higher posterior-to-anterior RC fat percent ratios, we compared these ratios between patients with eccentric and concentric deformities using Kruskal-Wallis tests.

Although not our secondary study goals, we performed additional analyses on pain and RC cross-sectional areas. To determine whether there were direction-specific differences in pain between groups, we tested for differences in the X, Y, and Z components of pain balance one at a time using three separate Kruskal-Wallis tests. We used a linear mixed-effects model to determine whether the patient-specific relative torque (dependent variable) was related to

Table 2. Three-dimensional strength balance

	Control (n = 18)		Concentric (n = 17)				Eccentric (n = 16)			
	Mean ± SD	95% CI volume, %^{3}	Mean ± SD	95% CI volume, %^{3}	Mean difference from control (95% CI)	p value	Mean ± SD	95% CI volume, %^{3}	Mean difference from control (95% CI)	p value
X (adduction-abduction	-0.50% ± 2.4%	129	-3.5% ± 4.6%	579	-3.0 (-5.1 to -0.90)	0.005	-1.8% ± 7.1%	893	-1.3 (-4.4 to 1.8)	< 0.001
Y (internal rotation-external rotation)	2.9% ± 4.0%		-0.05% ± 4.5%		-2.9 (-5.3 to -0.45)		-4.7% ± 5.1%		-7.6 (-10 to -5.0)	
Z (flexion-extension)	3.0% ± 3.2%		1.9% ± 6.3%		-1.1 (-4.0 to 1.8)		3.5% ± 4.6%		0.54 (-1.7 to 2.8)	

All p values were calculated using the Hotelling t-square statistic.

the patient's pain rating in all directions (independent variable). Finally, Kruskal-Wallis tests were used to determine whether there were differences in the fat-adjusted cross-sectional area ratios between patients with eccentric deformities and those with concentric deformities.

For all tests, a significance level of $\alpha = 0.05$ was used. Bonferroni corrections were used to account for multiple comparisons.

Results

Differences in External Rotation Strength Between Eccentric and Concentric Deformities

There was no relative external rotation weakness in patients with eccentric deformities (Y component of 3D strength balance, mean ± SD: -4.7% ± 5.1%) compared with patients with concentric deformities (-0.05% ± 4.5%, mean difference -4.7% [95% confidence interval -7.5% to -1.9%]; p = 0.05) (Fig. 3). However, patients with eccentric and concentric deformities demonstrated relative strength in external rotation compared with control participants (Table 2). There was more variability in 3D strength balance in the eccentric group (95% CI volume, %^{3}: 893) than in the concentric group (95% CI volume, %^{3}: 579) and control group (95% CI volume, %^{3}: 129). Weight-normalized strength magnitude, a measure of overall strength, was no different between patients with eccentric (0.22 ± 0.11 Nm/kg) and concentric deformities (0.25 ± 0.10 Nm/kg, mean difference -0.04 [95% CI -0.10 to 0.02]; p = 0.32) (Fig. 4). Strength magnitude was 36% (0.12 of 0.33) lower in patients with eccentric deformities (0.22 ± 0.11 Nm/kg) compared with control participants (0.33 ± 0.10 Nm/kg, mean difference -0.12 [95% CI -0.18 to -0.06]; p = 0.002). Strength magnitude was no different between patients with concentric deformities (0.25 ± 0.10 Nm/kg) and control participants (0.33 ± 0.10 Nm/kg, mean difference -0.08 [95% CI -0.14 to -0.02]; p = 0.03).

Resting and Torque-dependent Pain

There was no difference between the eccentric and concentric deformity groups in median (IQR) resting pain (1.0 [3.0] versus 2.0 [2.3], mean rank difference 4.5 [95% CI -6.6 to 16]; p = 0.61) or torque-dependent pain (0.70 [3.0] versus 0.58 [1.5], mean rank difference 2.6 [95% CI -8.8 to 14]; p = 0.86). The X, Y, and Z components of pain balance also did not differ between deformity groups (X: -1.4 [4.0] versus -0.15 [2.6], mean rank difference -1.6 [95% CI -8.1 to 5.0]; p = 0.64; Y: 0.0 [1.9] versus 0.0 [1.7], mean rank difference 3.2 [95% CI -3.4 to 9.7]; p = 0.35; Z: 0.0 [2.3] versus 0.0 [1.4], mean rank difference -0.06 [95% CI -6.6 to 6.4]; p = 0.99) (Fig. 5), suggesting no direction-specific pain differences. Finally, there was no relationship between pain rating and

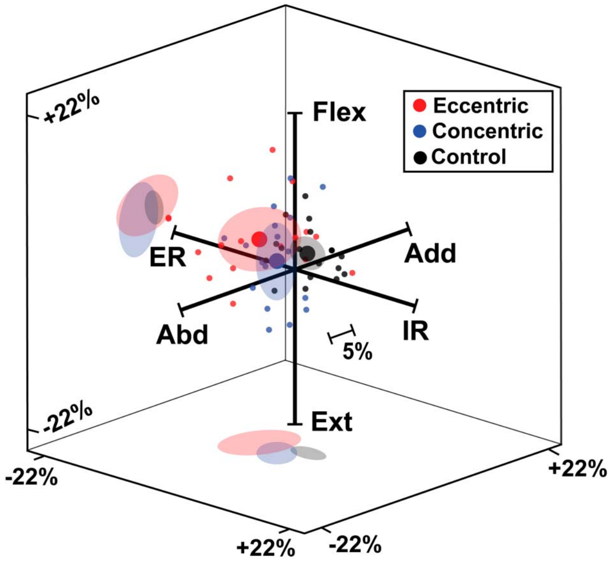

Fig. 3. This graph shows a 3D view of strength balance for all participants (smaller dots) as well as group means (larger dots), with shaded ellipses representing 95% CIs for the group means. Two-dimensional projections (XY and XZ) of 95% CIs are included. Add/Abd = adduction/abduction; IR/ER = internal/external rotation; Flex/Ext = flexion/extension.

patient-specific relative torque ($r^2 = 0.001$; $p = 0.29$) in patients with OA who experienced pain with testing (79%; 26 of 33 patients).

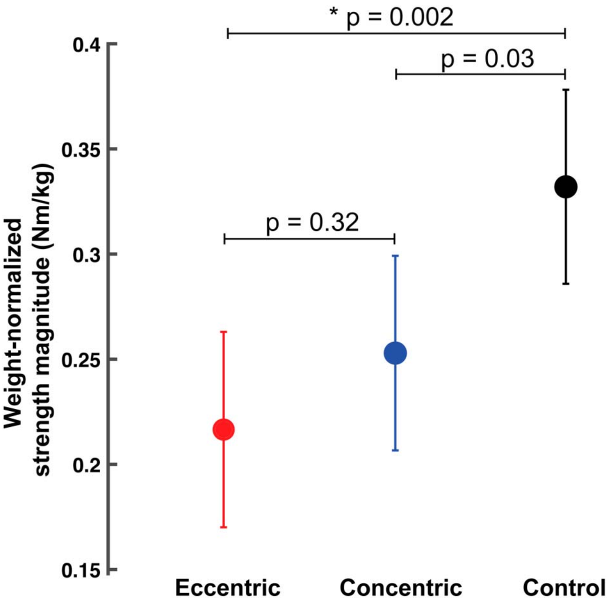

Fig. 4. This graph shows the mean (95% CI) weight-normalized strength magnitude by group.

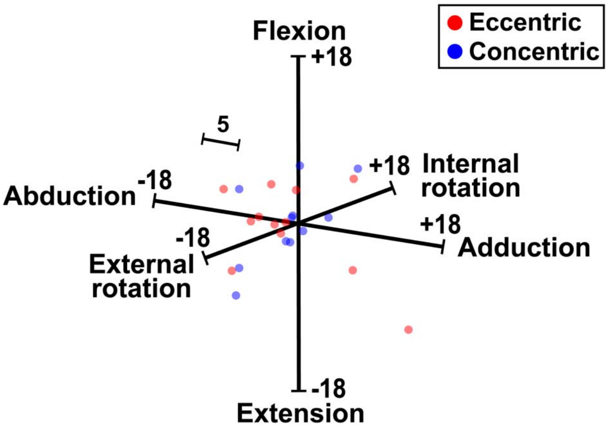

Fig. 5. This graph shows pain balance in each patient with OA.

Shoulder Bony Morphology and Posterior-to-anterior RC Fat Ratios

In the subgroup of patients with MRI, the seven patients with eccentric deformities demonstrated a higher posterior-to-anterior RC fat% ratio than the 11 patients with concentric deformities (median 1.2 [IQR 0.8] versus 0.7 [0.3], mean rank difference 6.4 [95% CI 1.4 to 11.5]; p = 0.01) (Table 3). There was no difference in the fat-adjusted posterior-to-anterior RC cross-sectional area ratio between eccentric and concentric deformity groups (0.7 [0.4] versus 0.8 [0.1], mean rank difference -0.8 [95% CI -5.9 to 4.2]; p = 0.75). A subgroup of patients with eccentric deformities (57% [4 of 7]) demonstrated a fat-adjusted posterior-to-anterior RC cross-sectional area ratio at least 20% lower than the median in patients with concentric deformities.

Discussion

It is unknown what leads to eccentric deformity development and why anatomic TSAs in these patients exhibit higher failure rates [10, 22, 41] despite surgical advances [26, 35]. Clinical theory suggests persistent disruption of the posterior-to-anterior RC force couple that results from posterior RC intramuscular degeneration [11, 12], which impairs external rotation strength [30, 44], may contribute to eventual TSA failure. Rehabilitation after TSA that does not correct preexisting external rotation weakness will be of minimal benefit as persistent weakness may promote failure. Identification of external rotation weakness in patients with eccentric deformities may elucidate mechanisms contributing to bony deformity development and TSA failure, allowing for treatment modification with targeted strengthening. Interestingly, we found no weakness in external rotation relative to internal rotation in patients with eccentric deformities compared

Table 3. Posterior-to-anterior rotator cuff intramuscular fat percentage and cross-sectional area ratios

	Concentric			Eccentric				
	IFTM	SC	Ratio	IFTM	SC	Ratio	Difference in mean rank (95% CI)	p value
Percentage of fat	4.8 (3.0)	7.0 (5.3)	0.7 (0.3)	10.2 (11.3)	7.8 (3.5)	1.2 (0.8)	6.4 (1.4 to 11.5)	0.01
NFA cross-sectional area in mm^2	1520 (655)	1870 (713)	0.8 (0.1)	1660 (510)	1900 (713)	0.8 (0.4)	0.1 (-4.9 to 5.2)	0.96
FA cross-sectional area in mm^2	1330 (630)	1670 (739)	0.8 (0.1)	1430 (455)	1750 (729)	0.7 (0.4)	-0.8 (-5.9 to 4.2)	0.75

All values are reported as the median (IQR); all p values were calculated between group ratios using a Kruskal-Wallis test; IFTM = infraspinatus and teres minor; SC = subscapularis; NFA = nonfat-adjusted; FA = fat-adjusted.

with patients with concentric deformities. However, patients with eccentric deformities demonstrated higher strength variability, which suggests there may be potential subtypes of eccentric wear patterns (posterior-superior, posterior-central, and posterior-inferior) and patients with these subtypes may compensate differently for underlying anatomic changes by adopting unique kinematic or muscle activation patterns. These findings highlight the importance of careful clinical evaluation in patients presenting with eccentric deformities as some may exhibit potentially detrimental strength deficits. Recognition of such deficits may allow for targeted rehabilitation.

Limitations

Our study has limitations. Our study was based on theorized force couple disruption between the anterior and posterior RC muscles [12]; however, consistent with other studies [3, 23, 37], larger primary shoulder movers and compensatory scapulothoracic motion may contribute to strength, given the lack of scapular stabilization. Strength as measured in the current study is consistent with clinical measures of external and internal rotation strength, as patients use both RC muscles and primary shoulder movers; however, results may differ if 3D strength is assessed in positions targeting specific RC muscles [21]. Additionally, we were only able to assess strength in a single posture in the current study. As muscle moment arms change with posture [1], the current findings, which provide useful information about strength in the posture selected, cannot be generalized to other postures. However, the posture selected is one all patients with OA could achieve and is used with common daily activities.

More variability than anticipated was observed in patients with OA. A post hoc power analysis revealed we were underpowered (required n = 22) given this variability, which may contribute to our finding of no relative external rotation weakness in patients with eccentric deformities. Despite our finding of no difference, these results are the first to characterize strength in 3D in patients with OA with eccentric and concentric deformities and address an unanswered question regarding potential force couple disruption in patients with eccentric deformities. Additionally, our results identify an important difference between deformity groups: the amount of variability in 3D strength. The observed variability was unexpected but may be explained by the existence of distinct eccentric deformity subtypes, which was beyond the scope of the current study. Although not one of our study purposes, it will be important in the future to examine how 3D strength may differ across eccentric deformity subtypes in a larger group of patients.

Our focus was characterizing strength in patients with primary glenohumeral OA, and thus our results are not generalizable to patients with glenohumeral OA secondary to rheumatologic disorders. It will be important to explore how strength compares between patients with eccentric deformities and patients with concentric deformities because these diagnoses are risk factors for postoperative complications [2]. The current study examined maximal isometric strength in 26 distinct directions to evaluate for relative external rotation weakness. Future work to determine whether endurance or fatigue are factors related to potential force couple disruption may be beneficial.

With regard to our secondary study goals, MRIs were only collected in a subset of patients, limiting the information we have on RC fat infiltration to this subset. Despite the small sample size, the differences observed between deformity groups in the amount of fat in the posterior relative to the anterior RC agree with existing evidence [4, 12, 20, 42]. Additionally, we examined all primary and secondary study outcome metrics in the subsets of patients with and without MRIs in each deformity group and confirmed the subsets were representative samples. Given that it was not possible to obtain advanced imaging in all participants, we were not able to reliably classify deformity severity within the eccentric and concentric groups and thus could not specifically evaluate how deformity severity (such as the degree of retroversion) may influence our measures. Our results are still representative of these overall populations and are the first to evaluate the influence of pain on observed strength in patients with OA; however, further work evaluating how strength may vary with deformity severity would be beneficial.

Differences in External Rotation Strength Between Eccentric and Concentric Deformities

Our findings suggest that there is no relative external rotation weakness in patients with eccentric deformities compared with patients with concentric deformities. In our study, strength balance may not have differed between deformity groups because there was unexpectedly higher variability in the eccentric group than in the concentric group. Greater variation in strength balance in patients with eccentric deformities may be owing to alterations in joint kinematics [7, 15] or muscle activation patterns adopted to compensate for underlying anatomic changes in the setting of a deformity. Higher variability in strength balance may also be attributed to patients with existing subtypes of eccentric glenoid wear patterns (posterior-superior, posterior-central, and posterior-inferior [32]) compensating differently and may potentially explain why TSA failure rates are technique-dependent [26]. Further, the increased variability suggests the utility of a more individualized approach to surgical and postoperative management in patients with eccentric deformities. In addition to greater variability, we found greater strength in external relative to internal rotation in both OA groups, contrary to a prior study demonstrating greater strength in internal relative to external rotation in patients with OA [37]. Our findings may differ because our 3D methods prevent off-axis torque generation. In contrast, the prior study used a one-dimensional hand-held dynamometer, which allows participants to maximize torque in the measurement direction by generating off-axis torques [33]. Measurements from a single-dimension method could be less sensitive than those from a 3D method to detect weakness in the direction of interest [5]. Devising accurate and efficient methods to quantify strength in 3D for clinical use may be of great benefit.

Resting and Torque-dependent Pain

Our findings suggest there was no difference in the pain experienced by patients with eccentric deformities and the pain experienced by those with concentric deformities, and that pain did not influence measures of strength balance. Given these findings, it is unlikely that pain concealed underlying strength differences between the groups. Analysis of this confounder is important as pain has been shown to decrease RC muscle force production and voluntary muscle activation [38]. Although the pain experienced did not differ between deformity groups, future work exploring the implications of pain on muscle activation in both deformity groups is warranted as differences in muscle activation may influence measured strength.

Shoulder Bony Morphology and Posterior-to-anterior RC Fat Ratios

Our results show the posterior-to-anterior RC fat% ratio was higher in patients with eccentric deformities than in patients with concentric deformities, which is in agreement with prior studies showing greater posterior RC intramuscular fat in patients with eccentric deformities [4, 12, 20, 42]. Our quantitative methods show that the median fat% in the posterior RC in patients with eccentric deformities (10.2%) fell within the range identified for Goutallier Grade 2 fatty degeneration (6.44% to 14.86%), whereas that in patients with concentric deformities (4.83%) fell within the range for Goutallier Grade 1 (1.1% to 9.70%) [31]. Our results also agree with prior work showing no difference in the volume ratio (nonfat-adjusted) of the posterior-to-anterior RC between patients with eccentric deformities and those with concentric deformities [4]. Although not previously reported, we found that the relative remaining muscle, represented by the posterior-to-anterior RC fat-adjusted cross-sectional area ratio, did not differ between groups.

The lack of a between-group difference in the posterior-to-anterior RC fat-adjusted cross-sectional area ratio may be attributed to high variability in the eccentric group. In the subgroup of patients with eccentric deformities demonstrating a posterior-to-anterior RC fat-adjusted cross-sectional area ratio at least 20% lower than the median in patients with concentric deformities, posterior RC weakness may exist. This weakness may be compensated by the surrounding shoulder musculature through scapulothoracic motion and the remaining posterior RC muscle. Such compensation may have prevented our robust 3D methods from detecting a difference in strength balance. Any underlying RC strength imbalance that is offset through compensation by larger surrounding shoulder muscles may be a concern for TSA failure.

Conclusion

Patients with eccentric deformities demonstrated no relative external to internal rotation weakness compared with patients with concentric deformities, but they exhibited greater variability in strength measured with 3D methods.

More intramuscular fat was found in the posterior RC in patients with eccentric compared with concentric deformities, as reported previously [4, 12, 20, 42]. The size of the posterior relative to the anterior RC, after adjusting for intramuscular fat, did not differ between deformity groups. The increased variability in patients with eccentric deformities suggests patients with potential subtypes of eccentric wear patterns may compensate differently for underlying bony changes. Overall, this variability highlights the potential importance of a more individualized approach to surgical and postoperative management in these patients. Future work should use motion tracking and electromyography to explore increased variability in patients with eccentric deformities and potential forms of kinematic or muscular compensation to determine whether these factors play a role in TSA failure. Although we did not observe differences preoperatively, it will be important to evaluate whether strength differences exist between patients with eccentric deformities and those with concentric deformities who have undergone TSA.

Acknowledgments We thank Timothy M. Haswell MS for his technical assistance during experimental setup design and data collection and Constantine P. Nicolozakes PhD for his assistance with study design.

References

1. Ackland DC, Pak P, Richardson M, Pandy MG. Moment arms of the muscles crossing the anatomical shoulder. *J Anat*. 2008;213: 383-390.
2. Aibinder W, Schoch B, Parsons M, et al. Risk factors for complications and revision surgery after anatomic and reverse total shoulder arthroplasty. *J Shoulder Elbow Surg*. 2021;30: e689-e701.
3. Andrews AW, Thomas MW, Bohannon RW. Normative values for isometric muscle force measurements obtained with hand-held dynamometers. *Phys Ther*. 1996;76:248-259.
4. Arenas-Miquelez A, Liu VK, Cavanagh J, et al. Does the Walch Type B shoulder have a transverse force couple imbalance? A volumetric analysis of segmented rotator cuff muscles in osteoarthritic shoulders. *J Shoulder Elbow Surg*. 2021;30:2344-2354.
5. Baillargeon EM, Ludvig D, Sohn MH, Nicolozakes CP, Seitz AL, Perreault EJ. Experimentally quantifying the feasible torque space of the human shoulder. *J Electromyogr Kinesiol*. 2022;62:1-10.
6. Bercik MJ, Kruse K 2nd, Yalizis M, Gauci MO, Chaoui J, Walch G. A modification to the Walch classification of the glenoid in primary glenohumeral osteoarthritis using three-dimensional imaging. *J Shoulder Elbow Surg*. 2016;25:1601-1606.
7. Bruttel H, Spranz DM, Wolf SI, Maier MW. Scapulohumeral rhythm in patients after total shoulder arthroplasty compared to age-matched healthy individuals. *Gait Posture*. 2020;82:38-44.
8. Chalmers PN, Salazar D, Chamberlain A, Keener JD. Radiographic characterization of the B2 glenoid: is inclusion of the entirety of the scapula necessary? *J Shoulder Elbow Surg*. 2017;26:855-860.
9. Collins D, Tencer A, Sidles J, Matsen F 3rd. Edge displacement and deformation of glenoid components in response to eccentric loading. The effect of preparation of the glenoid bone. *J Bone Joint Surg Am*. 1992;74:501-507.
10. Denard PJ, Walch G. Current concepts in the surgical management of primary glenohumeral arthritis with a biconcave glenoid. *J Shoulder Elbow Surg*. 2013;22:1589-1598.
11. Domos P, Checchia CS, Walch G. Walch B0 glenoid: pre-osteoarthritic posterior subluxation of the humeral head. *J Shoulder Elbow Surg*. 2018;27:181-188.
12. Donohue KW, Ricchetti ET, Ho JC, Iannotti JP. The association between rotator cuff muscle fatty infiltration and glenoid morphology in glenohumeral osteoarthritis. *J Bone Joint Surg Am*. 2018;100:381-387.
13. Elliott JM, Walton DM, Rademaker A, Parrish TB. Quantification of cervical spine muscle fat: a comparison between T1-weighted and multi-echo gradient echo imaging using a variable projection algorithm (VARPRO). *BMC Med Imaging*. 2013;13:1-8.
14. Farron A, Terrier A, Büchler P. Risks of loosening of a prosthetic glenoid implanted in retroversion. *J Shoulder Elbow Surg*. 2006; 15:521-526.
15. Fayad F, Roby-Brami A, Yazbeck C, et al. Three-dimensional scapular kinematics and scapulohumeral rhythm in patients with glenohumeral osteoarthritis or frozen shoulder. *J Biomech*. 2008; 41:326-332.
16. Fischer MA, Pfirrmann CW, Espinosa N, Raptis DA, Buck FM. Dixon-based MRI for assessment of muscle-fat content in phantoms, healthy volunteers and patients with achillodynia: comparison to visual assessment of calf muscle quality. *Eur Radiol*. 2014;24:1366-1375.
17. Fuchs B, Weishaupt D, Zanetti M, Hodler J, Gerber C. Fatty degeneration of the muscles of the rotator cuff: assessment by computed tomography versus magnetic resonance imaging. *J Shoulder Elbow Surg*. 1999;8:599-605.
18. Goutallier D, Postel J, Bernageau J, Lavau L, Voisin M. Fatty muscle degeneration in cuff ruptures: pre- and postoperative evaluation by CT scan. *Clin Orthop Relat Res*. 1994;304:78-83.
19. Hansen LM, Garg A, Khanna R, et al. Clinical Y-view versus 3-dimensional assessments of intramuscular fat in patients with full-thickness rotator cuff tears. *Clin Imaging*. 2021;77:13-16.
20. Hartwell MJ, Harold RE, Sweeney PT, Seitz AL, Marra G, Saltzman MD. Imbalance in axial-plane rotator cuff fatty infiltration in posteriorly worn glenoids in primary glenohumeral osteoarthritis: an MRI-based study. *Clin Orthop Relat Res*. 2021; 479:2471-2479.
21. Kelly BT, Kadrmas WR, Speer KP. The manual muscle examination for rotator cuff strength: an electromyographic investigation. *Am J Sports Med*. 1996;24:581-588.
22. Kiet TK, Feeley BT, Naimark M, et al. Outcomes after shoulder replacement: comparison between reverse and anatomic total shoulder arthroplasty. *J Shoulder Elbow Surg*. 2015;24:179-185.
23. Lapner PLC, Wood KS, Zhang T, Athwal GS. The return of subscapularis strength after shoulder arthroplasty. *J Shoulder Elbow Surg*. 2015;24:223-228.
24. Leggin BG, Michener LA, Shaffer MA, Brenneman SK, Iannotti JP, Williams GR Jr. The Penn shoulder score: reliability and validity. *J Orthop Sports Phys Ther*. 2006;36:138-151.
25. Lehtinen JT, Tingart MJ, Apreleva M, Zurakowski D, Palmer W, Warner JJ. Practical assessment of rotator cuff muscle volumes using shoulder MRI. *Acta Orthop Scand*. 2003;74:722-729.
26. Luedke C, Kissenberth MJ, Tolan SJ, Hawkins RJ, Tokish JM. Outcomes of anatomic total shoulder arthroplasty with B2 glenoids: a systematic review. *JBJS Rev*. 2018;6:e7.
27. Mansat P, Briot J, Mansat M, Swider P. Evaluation of the glenoid implant survival using a biomechanical finite element analysis: influence of the implant design, bone properties, and loading location. *J Shoulder Elbow Surg*. 2007;16(suppl):S79-83.

28. Matsen FA 3rd, Iannotti JP, Churchill RS, et al. One and two-year clinical outcomes for a polyethylene glenoid with a fluted peg: one thousand two hundred seventy individual patients from eleven centers. *Int Orthop*. 2019;43:367-378.
29. Miller CT, Buck FM, Mamisch-Saupe N, Gerber C. Good correlation of Goutallier rating of supraspinatus fatty changes on axial and reformatted parasagittal computed tomographic images. *J Comput Assist Tomogr*. 2014;38:340-343.
30. Nakamura Y, Yokoya S, Harada Y, Shiraishi K, Adachi N, Ochi M. The prospective evaluation of changes in fatty infiltration and shoulder strength in nonsurgically treated rotator cuff tears. *J Orthop Sci*. 2017;22:676-681.
31. Nardo L, Karampinos DC, Lansdown DA, et al. Quantitative assessment of fat infiltration in the rotator cuff muscles using water-fat MRI. *J Magn Reson Imaging*. 2014;39:1178-1185.
32. Otto A, Scheiderer B, Murphy M, et al. Biconcave glenoids show 3 differently oriented posterior erosion patterns. *J Shoulder Elbow Surg*. 2021;30:2620-2628.
33. Pan P, Peshkin MA, Colgate JE, Lynch KM. Static single-arm force generation with kinematic constraints. *J Neurophysiol*. 2005;93:2752-2765.
34. Parsons IM, Apreleva M, Fu FH, Woo SLY. The effect of rotator cuff tears on reaction forces at the glenohumeral joint. *J Orthop Res*. 2002;20:439-446.
35. Sears BW, Johnston PS, Ramsey ML, Williams GR. Glenoid bone loss in primary total shoulder arthroplasty: evaluation and management. *J Am Acad Orthop Surg*. 2012;20:604-613.
36. Smith AC, Parrish TB, Abbott R, et al. Muscle-fat MRI: 1.5 Tesla and 3.0 Tesla versus histology. *Muscle Nerve*. 2014;50:170-176.
37. Sperling JW, Kaufman K, Schleck C, Cofield RH. A biomechanical analysis of strength and motion following total shoulder arthroplasty. *Int J Shoulder Surg*. 2008;2:1-3.
38. Stackhouse SK, Eisennagel A, Eisennagel J, Lenker H, Sweitzer BA, McClure PW. Experimental pain inhibits infraspinatus activation during isometric external rotation. *J Shoulder Elbow Surg*. 2013;22:478-484.
39. Tingart MJ, Apreleva M, Lehtinen JT, Capell B, Palmer WE, Warner JJ. Magnetic resonance imaging in quantitative analysis of rotator cuff muscle volume. *Clin Orthop Relat Res*. 2003;415:104-110.
40. Walch G, Badet R, Boulahia A, Khoury A. Morphologic study of the glenoid in primary glenohumeral osteoarthritis. *J Arthroplasty*. 1999;14:756-760.
41. Walch G, Moraga C, Young A, Castellanos-Rosas J. Results of anatomic nonconstrained prosthesis in primary osteoarthritis with biconcave glenoid. *J Shoulder Elbow Surg*. 2012;21:1526-1533.
42. Walker KE, Simcock XC, Jun BJ, Iannotti JP, Ricchetti ET. Progression of glenoid morphology in glenohumeral osteoarthritis. *J Bone Joint Surg Am*. 2018;100:49-56.
43. Wu G, van der Helm FC, Veeger HE, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion–part II: shoulder, elbow, wrist and hand. *J Biomech*. 2005;38:981-992.
44. Yoon JP, Jung JW, Lee CH, et al. Fatty degeneration of the rotator cuff reflects shoulder strength deficits in patients with rotator cuff tears. *Orthopedics*. 2018;41:e15-e21.