# Associations Among Shoulder Strength, Glenohumeral Joint Motion, and Clinical Outcome After Rotator Cuff Repair

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## Abstract

Rotator cuff tears are a common condition causing pain and disability, but the relationships among clinical measures of shoulder function and measures of glenohumeral joint (GHJ) function are not well known.

In the study reported here, dynamic in vivo GHJ motion was measured during abduction from biplane radiographs in 22 rotator cuff repair (RCR) patients and 36 control subjects. Isometric shoulder strength was measured and clinical outcomes were assessed using the Western Ontario Rotator Cuff (WORC) Index. Associations among WORC, GHJ motion, and several shoulder strength ratios were assessed with linear regression. An association was detected between higher ER/ABD (external rotation/coronal-plane abduction) strength ratio and a humerus positioned more inferiorly relative to the glenoid in control subjects and RCR patients. Higher ER/ABD strength ratio was also associated with better clinical outcome in RCR patients.

These findings suggest a relationship between ER/ABD strength ratio and a more centrally located average superior/inferior contact center in RCR patients and control subjects. The ER/ABD strength ratio can be easily measured in a clinical setting and therefore can be used in larger studies to investigate its relation to clinical outcomes over time or perhaps to predict superior migration of the humeral head.

Rotator cuff tears are common, affecting about 50% of the population older than 60 years.[1] Patients with rotator cuff tears are often treated nonoperatively with physical therapy, activity modification, and analgesics. In cases resistant to nonoperative interventions, surgical rotator cuff repair (RCR) is often performed. Provencher and colleagues[2] wrote that the goal of RCR is to "reconstitute glenohumeral joint [GHJ] function by restoring normal rotator cuff kinematics." More generally, the goal of any clinical intervention for rotator cuff tears is to decrease or eliminate pain and restore normal shoulder function.

Shoulder function can be evaluated in many ways. Clinically, it is often characterized using objective measures (eg, range of motion,[3-5] stability, strength[6-9]) and patient questionnaires that assess pain and function.[10,11] In cadaveric studies, it is often characterized with measures of joint kinematics,[12-14] joint forces or pressures,[15-17] or soft-tissue stresses and strains.[18-20] Although the clinical outcome measures are valuable in evaluating the efficacy of a particular therapeutic intervention, these outcomes do not necessarily provide any specific insight into the underlying GHJ function. In contrast, cadaveric studies provide detailed information about GHJ function and the role of individual factors in GHJ function, but these findings do not necessarily provide insight into complex in vivo clinical conditions.

It can be difficult to reconcile our understanding of clinical outcomes with our understanding of GHJ function. For example, investigators have reported good clinical outcomes (high patient satisfaction) of surgical repair of torn rotator cuffs despite incomplete rotator cuff healing.[21,22] Similarly, anecdotal clinical reports of patients having normal shoulder function despite a documented full-thickness rotator cuff tear are not uncommon.

We previously reported finding relationships between clinical outcomes and shoulder strength as well as GHJ motion in healthy control subjects and RCR patients.[6] In that study, shoulder strength was normalized with respect to patients' contralateral shoulder. However, about half the RCR patients had a documented rotator cuff tear in that shoulder, which may have affected shoulder strength and therefore confounded those results.

The primary objective of the present study was to further analyze our earlier data[6] by reporting shoulder strength

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ratios—an approach that normalizes measures of shoulder strength within the same shoulder—to assess the relationships among clinical outcome, shoulder strength, and measures of in vivo GHJ motion in the same shoulder.

## Materials and Methods

The institutional review board of Henry Ford Hospital approved this study. After providing informed consent, 58 subjects (22 patients, 36 controls) enrolled. The patients (mean age, 63.5 years; SD, 9.7 years) had arthroscopic surgical repair of an isolated supraspinatus tendon tear about 2 years before testing. In 16 of these patients, the rotator cuff tear occurred in the dominant shoulder. Each patient's contralateral shoulder was asymptomatic. The controls (mean age, 30.2 years; SD, 7.9 years) had no history of shoulder injury, surgery, or symptoms, and all reported normal bilateral shoulder function, with no history of shoulder injury or upper extremity surgery that could potentially compromise shoulder function.

Subjects were positioned with the shoulder centered within the 3-dimensional (3-D) imaging volume of a biplane radiography system[6,23-25] consisting of two 100-kW pulsed x-ray generators (CPX 3100CV; EMD Technologies, Saint-Eustache, Canada) and two 40-cm image intensifiers (AI5765HVP; Shimadzu, Kyoto, Japan) coupled to synchronized high-speed video cameras (Phantom v9.1; Vision Research, Wayne, New Jersey). Images were acquired at 60 Hz as subjects performed coronal-plane abduction from a position of adduction and neutral rotation to about 120° of abduction over 2 seconds. Measures of GHJ motion were averaged over 3 trials for each subject. Both shoulders were tested, and testing order was randomized. After testing, bilateral computed tomography (CT) scans of the entire humerus and scapula were acquired (LightSpeed 16; GE Medical Systems, Piscataway, New Jersey). The scans had a slice thickness of 1.25 mm and an in-plane resolution of about 0.5 mm per pixel. The humerus and scapula were manually segmented from other bones and soft-tissue and reconstructed into a 3-D bone model (Mimics 10.1; Materialise, Leuven, Belgium).

GHJ motion was assessed by tracking the 3-D position of the humerus and scapula from images acquired from the biplane radiography system. This model-based tracking technique has been shown to track 3-D shoulder motion to an accuracy of ± 0.4 mm and ± 0.5°.[26] As previously described,[6,24,27,28] GHJ contact patterns were estimated for each shoulder by combining joint motion measured from the biplane radiographs with the subject-specific bone models. Specifically, the GHJ contact center was estimated by calculating the minimum distance between the glenoid and humerus at every point on the glenoid, and then determining the centroid of this distance map. The contact center was expressed relative to a glenoid-based coordinate system, and the process was repeated for all frames of every trial. These calculations resulted in a contact path—a time series of GHJ contact center data. These data were used to determine the dynamic contact location by calculating the average anterior/posterior (A/P) contact center and the average superior/inferior (S/I) contact center over each trial. Dynamic joint excursion—amount of GHJ translation during shoulder motion—was estimated by calculating the A/P and S/I contact center range over each trial. To account for differences in subject size, these joint contact center data were normalized relative to each shoulder's glenoid height (in S/I direction) and width (in A/P direction) as determined from the subject-specific bone models.

As previously described,[6,29] isometric shoulder strength was tested using an isokinetic dynamometer (System 2; Biodex Medical Systems, Shirley, New York). Strength testing was performed for coronal-plane abduction (ABD) at 30° of abduction, sagittal-plane elevation (ELEV) at 30° of elevation, internal rotation (IR) at 15° of frontal-plane elevation and 0° of humeral rotation, and external rotation (ER) at 15° of frontal-plane elevation and 0° of humeral rotation. Three trials were performed at each position; the average of the 3 trials was recorded as the subject's maximum strength. Both shoulders were tested, and testing order was randomized.

To investigate potential relationships between shoulder strength and GHJ motion, it was first necessary to normalize the strength data to account for gross differences in strength between subjects. Although this is often accomplished by expressing strength in a shoulder relative to the contralateral shoulder, as was done in our previous study,[6] this approach is not applicable when attempting to assess relationships between shoulder strength and joint motion within the same shoulder.

The glenohumeral joint contact center was estimated by calculating the minimum distance between the glenoid and humerus at every point on the glenoid, and then determining the centroid of this distance map.

Consequently, we used the strength data from within each shoulder to calculate strength ratios that estimate a contribution of the rotator cuff to overall shoulder strength. These strength ratios were defined as ER/ABD, ER/ELEV, (ER+IR)/ABD, (ER+IR)/ELEV, and (ER+IR)/(ABD+ELEV). To mathematically estimate the role of the rotator cuff, the numerator in each strength ratio uses measures of ER and IR strength, which electromyographic (EMG) studies have indicated are accomplished primarily by rotator cuff muscles.[30-33] The denominator of each ratio then uses measures of ABD and ELEV strength, as EMG studies have indicated that these actions are accomplished primarily by the deltoid muscles and that the rotator cuff plays a secondary role. This approach is further supported by nerve block studies; Gerber and colleagues[34] reported that temporary

Table I. **Correlation Coefficients and *P* Values (in Parentheses) for Associations Among 5 Strength Ratios, Measures of GHJ Motion, and Clinical Outcome as Reported Using WORC Index**

| | Control Subjects' Dominant Shoulder | | | | Rotator Cuff Patients' Repaired Shoulder | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean Joint Contact Center | | Range of Joint Contact Center | | Mean Joint Contact Center | | Range of Joint Contact Center | | |
| Strength Ratio | A/P | S/I | A/P | S/I | A/P | S/I | A/P | S/I | WORC Index |
| ER/ABD | −0.23 (0.27) | −0.34[a] (0.05) | −0.12 (0.50) | −0.06 (0.72) | −0.15 (0.51) | −0.37[b] (0.10) | −0.20 (0.37) | 0.11 (0.66) | −0.46[a] (0.04) |
| ER/ELEV | −0.07 (0.19) | −0.10 (0.57) | −0.20 (0.26) | −0.19 (0.28) | 0.19 (0.42) | −0.19 (0.41) | −0.15 (0.50) | 0.04 (0.89) | −0.14 (0.54) |
| (ER+IR)/ABD | −0.23 (0.36) | −0.02 (0.91) | −0.15 (0.39) | −0.27 (0.12) | −0.35 (0.12) | −0.40 (0.08) | −0.54[a] (0.01) | 0.05 (0.81) | −0.20 (0.38) |
| (ER+IR)/ELEV | −0.16 (0.34) | −0.06 (0.72) | −0.12 (0.51) | −0.26 (0.13) | 0.07 (0.75) | −0.13 (0.59) | −0.46[a] (0.04) | 0.03 (0.91) | 0.25 (0.27) |
| (ER+IR)/(ABD+ELEV) | −0.14 (0.33) | −0.05 (0.76) | −0.14 (0.43) | −0.31[b] (0.07) | −0.12 (0.59) | −0.27 (0.24) | −0.55[a] (0.01) | 0.05 (0.83) | 0.07 (0.76) |

Abbreviations: ABD, coronal-plane abduction; A/P, anterior/posterior; ELEV, sagittal-plane elevation; ER, external rotation; GHJ, glenohumeral joint; IR, internal rotation; S/I, superior/inferior; WORC, Western Ontario Rotator Cuff.
[a]$P \le .05$. [b]$P \le .10$.

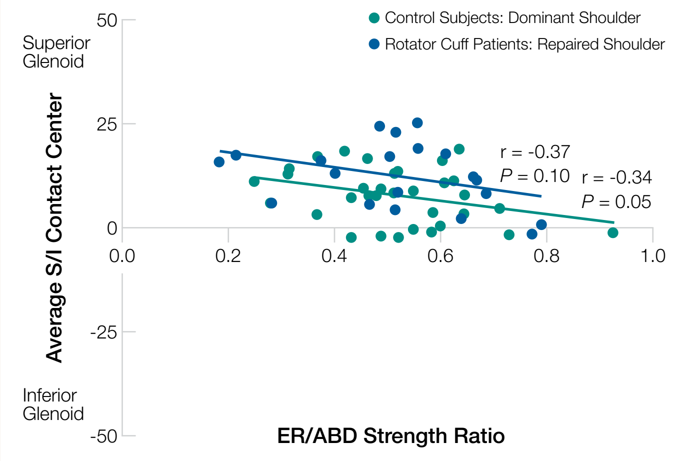


Figure 1. Higher ER/ABD (external rotation/coronal-plane abduction) strength ratio was associated with the humerus being positioned more inferiorly relative to the glenoid.

paralysis of the infraspinatus reduced ER strength by 70% and ABD strength by only 45%. Thus, the strength ratios are formulated as (rotator cuff)/(rotator cuff + deltoids).

After testing, clinical outcomes were assessed using the Western Ontario Rotator Cuff (WORC) Index. The WORC Index is a disease-specific quality-of-life subjective assessment that provides a cumulative score based on the domains of physical symptoms, sport/recreation, work function, lifestyle function, and emotional function.[35] Lower scores indicate a more satisfactory clinical outcome.

For each strength ratio, its association with the WORC Index, joint contact centers (A/P, S/I), and joint contact ranges (A/P, S/I) was assessed with linear regression and correlation. The association between the WORC Index and the joint contact centers and ranges was assessed with linear regression and correlation. Differences in mean strength ratios between control subjects and RCR patients were assessed with t test. Significance was set at $P < .05$ and trends at $P < .1$.

## Results

### Strength Ratios Versus GHJ Joint Motion

Overall, the data indicated relatively few associations between the strength ratios and measures of GHJ motion (**Table I**). The ER/ABD strength ratio was significantly associated with the average S/I contact center in the control subjects (r = −0.34, P = .05; **Figure 1**). This relationship demonstrated a statistical trend in the RCR patients (r = −0.37, P = .10; **Figure 1**). Specifically, higher ER/ABD strength ratio was associated with the humerus being positioned more inferiorly relative to the glenoid.

The A/P joint contact center range was significantly associated with 3 of the strength ratios in the RCR patients (**Table I, Figure 2**). Specifically, the range of the A/P joint contact center was significantly associated with the (ER+IR)/ABD strength ratio (r = −0.54, P = .01), the (ER+IR)/ELEV strength ratio (r = −0.46, P = .04), and the (ER+IR)/(ABD+ELEV) strength ratio (r = −0.55, P = .01). In each case, higher strength ratio was associated with lower A/P joint contact center range.

### Strength Ratios Versus Clinical Outcome

The ER/ABD strength ratio was also associated with the WORC Index in the RCR patients (P = .04, **Figure 3**). Specifically, higher ER/ABD strength ratio was associated with a better clinical outcome. This relationship was not available in the control subjects, as only RCR patients completed the WORC questionnaire.

### Strength Ratios

The study failed to detect a statistically significant difference between control subjects and RCR patients in any of the 5 strength ratios (P > .13, **Table II**).

## Discussion

Our objective in this study was to further analyze previously reported data[6] by reporting shoulder strength ratios—an approach that normalizes measures of shoulder strength within the same shoulder—to assess the relationships among clinical outcome, shoulder strength, and measures of in vivo GHJ motion in the same shoulder. The conclusions of our previous study[6] were not altered by this secondary analysis of the data, but this new approach with strength ratios allowed us to identify ER/ABD as an important outcome measure, as it was significantly associated with measures of both GHJ motion and clinical outcome. However, relatively few other statistically significant associations were found among the other outcome measures.

Although this study did not detect a statistically significant difference between control subjects and RCR patients in any of the 5 strength ratios (P > .13), it is important to recognize that there was considerable variability in the strength ratios within each subject population (**Table II**). Specifically, the coefficient of variation of the mean strength ratios ranged from 23% to 35% in the RCR patients and from 27% to 37% in the control subjects (**Table II**). These values are consistent with those reported by Hughes and colleagues.[36] In their study, the coefficient of variability in the dominant shoulder of healthy volunteers ranged from 24% to 40%, depending on the specific strength ratio measurement. Our interpretation of this finding is that the mean of strength ratios is an ineffective measure for differentiating these particular subject populations.

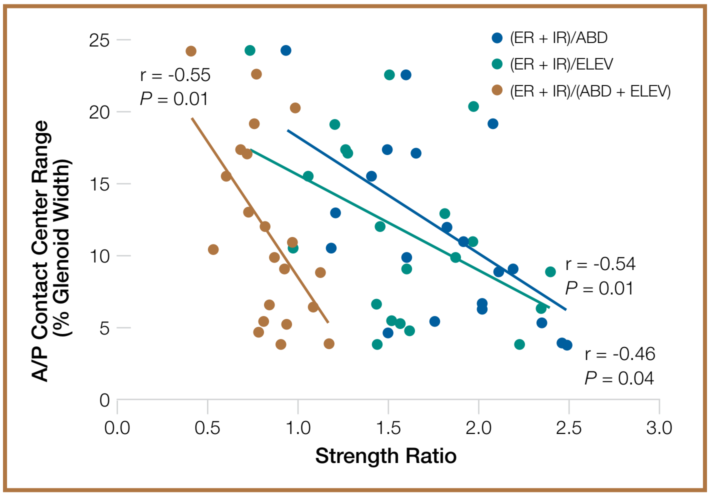


Figure 2. Range of A/P (anterior/posterior) joint contact center was associated with 3 calculated strength ratios: (ER+IR)/ABD, (ER+IR)/ELEV, and (ER+IR)/(ABD+ELEV). (ER indicates external rotation; IR, internal rotation; ABD, coronal-plane abduction; ELEV, sagittal-plane elevation.) In each case, higher strength ratio was associated with lower range of A/P joint contact center.

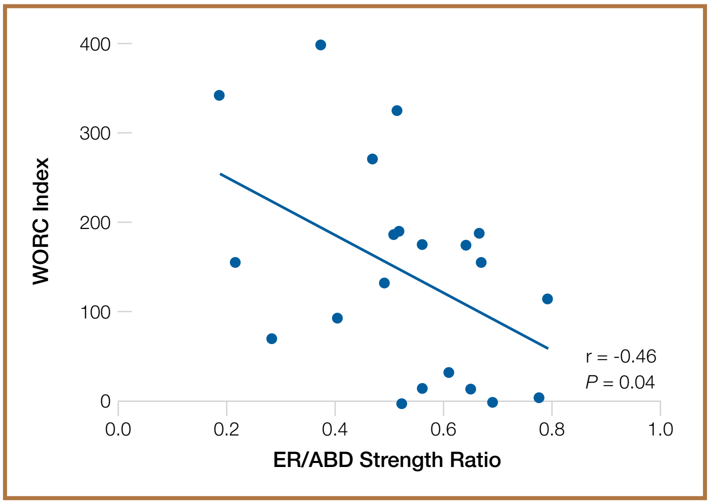


Figure 3. Higher ER/ABD (external rotation/coronal-plane abduction) strength ratio 24 months after surgery was associated with better clinical outcome.

The finding demonstrating the relationship between the ER/ABD strength ratio and GHJ motion suggests that high ER strength may contribute significantly to positioning the humerus centrally on the glenoid. This interpretation is consistent with the concept that the rotator cuff's transverse force couple—the coupling of anterior (subscapularis) and posterior (infraspinatus, teres minor) muscle forces—may be sufficient to stabilize the humerus against the glenoid even when the supraspinatus tendon is torn.[37] Thus, low ER strength may allow the humerus to translate superiorly relative to the glenoid. Alternatively, this relationship between ER/ABD strength ratio and GHJ motion may indicate that a humerus positioned more inferiorly on the glenoid is capable of generating higher ER strength. The articular surfaces of the humerus and glenoid are highly congruent,[38] and thus it is likely that the most stable base of support for generating high forces occurs when the humerus is located most centrally relative to the glenoid.

The finding that suggests that ER strength may help center the humerus on the glenoid is interesting, particularly when considering age-related changes in strength. Previous research has suggested that there may be a preferential loss in ER strength with age. Specifically, Hughes and colleagues[29] reported that ER strength decreases about 40% from age 20 years to 70 years. In contrast, ABD strength was reported to decrease by only 31% from age 20 years to 70 years.[29] If there is a preferential loss of ER strength with age, then the ER/ABD strength ratio should

Table II. **Descriptive Statistics Comparing 5 Strength Ratios Between Control Subjects and RCR Patients[a]**

| | Control Subjects' Dominant Shoulder | | | | Rotator Cuff Patients' Repaired Shoulder | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Strength Ratio | Mean | SD | Min | Max | Mean | SD | Min | Max | *P* |
| ER/ABD | 0.52 | 0.14 | 0.25 | 0.93 | 0.53 | 0.17 | 0.18 | 0.79 | .83 |
| ER/ELEV | 0.51 | 0.17 | 0.21 | 0.99 | 0.46 | 0.16 | 0.21 | 0.76 | .30 |
| (ER+IR)/ABD | 1.62 | 0.44 | 0.74 | 3.46 | 1.80 | 0.42 | 0.94 | 2.48 | .13 |
| (ER+IR)/ELEV | 1.58 | 0.59 | 0.82 | 3.73 | 1.58 | 0.44 | 0.73 | 2.39 | .96 |
| (ER+IR)/(ABD+ELEV) | 0.79 | 0.23 | 0.42 | 1.74 | 0.83 | 0.18 | 0.41 | 1.17 | .46 |

Abbreviations: ABD, coronal-plane abduction; ELEV, sagittal-plane elevation; ER, external rotation; IR, internal rotation; RCR, rotator cuff repair.
[a]Study failed to detect difference between control subjects and rotator cuff repair patients in any strength ratio mean values (*P* > .13).

decrease with age, resulting in superior migration of the humerus relative to the glenoid. Development of rotator cuff tears has been postulated to be associated with altered GHJ motion (subacromial impingement[39]). The importance of ER strength and the probability that ER strength decreases with age or with a rotator cuff tear highlight the importance of using a ratio to normalize strength within the same shoulder. Compromise of the ER strength of the contralateral shoulder may alter the resultant measure of ER strength on the side of interest. The findings here suggest that changes in strength—more specifically, a decrease in the ER/ABD strength ratio—may contribute to subacromial impingement and development of a rotator cuff tear.

The association reported here, between the ER/ABD strength ratio and the S/I contact center, suggests that even relatively small increases in ER strength may be sufficient to reposition the humerus more centrally on the glenoid.

A wide variety of therapeutic interventions can be used to manage rotator cuff tears. Exercises aimed at increasing shoulder strength are an important component of most physical therapy protocols,[40] even though there have been mixed research results regarding the efficacy of physical therapy for increasing shoulder strength.[41,42] The association reported here, between the ER/ABD strength ratio and the S/I contact center, suggests that even relatively small increases in ER strength may be sufficient to reposition the humerus more centrally on the glenoid. Given that the subacromial space has been reported to range from 5 mm to 10 mm, depending on arm position,[23,43] it is plausible that subtle changes in GHJ position could have relatively large effects on the subacromial space and the corresponding pain that occurs with impingement.

The statistically significant association between the A/P joint contact center range and the 3 strength ratios in the RCR patients was an unexpected finding. In particular, the higher strength ratios—suggesting higher ER and IR strength as a percentage of overall shoulder strength—were significantly associated with a lower range of the A/P joint contact center. This association was statistically significant only in the RCR patients, not in the control subjects—suggesting there may be differences in neuromuscular control strategies between these populations. This interpretation would be consistent with previous research, in which patients with chronic rotator cuff tears were found to have altered muscle activation patterns[44] and corticospinal excitability[45] in comparison with healthy volunteers. It is plausible that GHJ stability decreases as a result of a rotator cuff tear, or of age-related changes in the passive stabilizers,[46] and that A/P stability thus becomes more highly dependent on the dynamic stability provided by the internal (subscapularis) and external (infraspinatus, teres minor) rotators. This explanation is further supported by the observation that only the strength ratios that included components of both ER and IR strength were significantly associated with the A/P joint contact center range, suggesting that both ER strength and IR strength together are important in minimizing A/P motion.

The finding that increased shoulder strength is related to better clinical outcome is not unprecedented. Nho and colleagues[47] reported that increased shoulder strength was predictive of better American Shoulder and Elbow Surgeons (ASES) scores. Similarly, elevation strength and abduction strength have been shown to be associated with WORC Index scores.[48] However, though measures of shoulder strength and clinical outcome are often reported together as part of the overall assessment of shoulder function after RCR,[3] associations between strength and clinical outcome measures are reported far less often. To our knowledge, the present study is the first to report measures of shoulder strength normalized within the same shoulder and to relate them to both clinical outcome and in vivo measures of shoulder motion in that same shoulder. This is an important first step in further elucidating the relationships among shoulder strength, shoulder motion, and clinical outcomes.

Associations among shoulder (or muscle) strength and shoulder motion have been investigated using several experimental approaches, but none of these approaches are without limitations. For example, research has been conducted to establish associations between shoulder strength and gross joint kinematics measured using optical motion-capture systems,[49,50] but these conventional motion-capture techniques, which use skin-mounted markers, are susceptible to skin motion and therefore have limited accuracy in assessing GHJ motion. In addition, cadaveric studies have explored the relationships between simulated muscle forces and GHJ motion or stability,[51,52] but the extent to which these applied muscle forces reproduce in vivo conditions remains largely unknown. Although our approach overcomes many of these limitations by providing accurate (±0.5 mm, ±0.5°[26]) measures of GHJ motion under dynamic in vivo conditions, a limitation of this study and all in vivo studies is that techniques for accurately measuring individual muscle forces do not exist.

This study has several other limitations. First, there was a significant difference in mean age between the control and patient populations, and therefore we cannot exclude the possibility that population differences are due solely to a rotator cuff tear and surgical repair. The rationale for selecting a younger control population was that the prevalence of asymptomatic rotator cuff tears in an older population makes it difficult to obtain a control population of age-matched subjects.[1] However, the primary study objective was not to make direct statistical comparisons between control and patient populations but to assess associations among shoulder strength, GHJ motion, and clinical outcomes in 2 subject populations. Another limitation was that the extent to which maximum isometric strength can be used to predict muscle function during a submaximal shoulder task is unknown. Last, the technique used to estimate GHJ contact patterns does not include articular cartilage, so we based our estimates of joint contact locations only on bone. However, the same technique was applied to all patients and control subjects, so the relative differences remain comparable.

## Conclusion

This study builds on our previous findings by introducing the concept of shoulder strength ratios, which allow shoulder strength to be normalized in a way that is not influenced by the condition of the contralateral shoulder. With use of these ratios, relationships between strength and motion within the same shoulder can be investigated; we found that higher ER/ABD strength ratio is related to a more centrally located average S/I contact center in both postoperative RCR patients and control subjects. In addition, a significant relationship was established between this strength ratio and patient-assessed clinical outcome. The ER/ABD strength ratio has clinical utility, as ER strength and ABD strength can be easily measured (either qualitatively or quantitatively) in a clinical setting and could therefore be used in larger studies to investigate its relation to clinical outcomes over time or perhaps to predict superior migration of the humeral head. These findings improve our understanding of shoulder function by demonstrating important relationships among shoulder strength, in vivo joint motion, and clinical outcome in the same shoulder.

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