The American Journal of Sports Medicine

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Am J Sports Med 2015 43: 2800 originally published online September 21, 2015
DOI: 10.1177/0363546515602249

Effect of Arthroscopic Stabilization on In Vivo Glenohumeral Joint Motion and Clinical Outcomes in Patients With Anterior Instability

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Background: Glenohumeral joint (GHJ) dislocations are common, and the resulting shoulder instability is often treated with arthroscopic stabilization. These procedures result in favorable clinical outcomes, but abnormal GHJ motion may persist, which may place patients at risk for developing osteoarthritis. However, the effects of shoulder instability and arthroscopic stabilization on GHJ motion are not well understood.

Hypothesis: GHJ motion is significantly influenced by anterior instability and arthroscopic stabilization, but postsurgical measures of GHJ motion are not different from those of control subjects.

Study Design: Controlled laboratory study.

Methods: In vivo GHJ motion was measured by applying a computed tomographic model-based tracking technique to biplane radiographic images acquired during an apprehension test in healthy control subjects (n = 11) and anterior instability patients (n = 11). Patients were tested before surgery and at 6 months after surgery. Control subjects were tested once. Shoulder strength, active range of motion (ROM), and the Western Ontario Shoulder Instability (WOSI) index were also measured.

Results: Before surgery, the humerus of the instability patients during the apprehension test was located significantly more anteriorly on the glenoid (7.9% of glenoid width; 2.1 mm) compared with that of the controls (P = .03), but arthroscopic stabilization moved this joint contact location posteriorly on the glenoid (4.7% of glenoid width; 1.1 mm; P = .03). After surgery, GHJ excursion during the apprehension test was significantly lower (14.7% of glenoid width; 3.6 mm) compared with presurgical values (19.4% of glenoid width; 4.7 mm; P = .01) and with that of the controls (22.4% of glenoid width; 5.7 mm; P = .01). The external and internal rotation strength of patients was significantly lower than that of the controls before surgery ($P < .05$), but differences in strength did not persist after surgery ($P > .17$). External rotation ROM in patients was significantly lower than that in control subjects both before and after arthroscopic stabilization ($P < .01$). The WOSI score improved significantly, from 48.3 ± 13.1 presurgery to 86.3 ± 16.5 after surgery (P = .0002).

Conclusion: In patients with anterior instability, arthroscopic stabilization significantly improves measures of strength, ROM, and clinical outcome. However, GHJ excursion is not fully restored to levels seen in the control subjects.

Clinical Relevance: Although arthroscopic stabilization satisfactorily restores most clinical outcome measures, GHJ excursion and external rotation ROM remain compromised compared with healthy control subjects and may contribute to the development of osteoarthritis in patients with anterior instability.

Keywords: glenohumeral joint motion; anterior instability; arthroscopic stabilization; clinical outcomes

The shoulder is the most commonly dislocated major joint in the body, accounting for about half of all major joint dislocations each year.[30] Approximately 80% to 90% of all shoulder dislocations are traumatic in nature and occur in the anterior direction.[36] These dislocation events damage the glenohumeral joint (GHJ) soft tissues, specifically the labrum, ligaments, and joint capsule, and in turn, this damage causes GHJ instability. This persistent instability is one of the most common pathologic conditions of the shoulder and results in pain, decreased activity levels, and decreased quality of life. However, long-term outcomes indicate patients are at risk of glenohumeral osteoarthritis with both surgical and nonsurgical treatment.[8-10,16,21] The development of osteoarthritis has been associated with altered joint motion in the knee,[11] and it is likely that joint

The American Journal of Sports Medicine, Vol. 43, No. 11
DOI: 10.1177/0363546515602249

motion is altered with GHJ instability and consequently increases the risk of osteoarthritis. However, the effects of shoulder instability and its associated surgical treatment on GHJ mechanics, particularly under in vivo conditions, are not well understood.

Previous research has reported GHJ translations in patients diagnosed with joint instability using a variety of measurement techniques. For example, Hawkins and colleagues[20] used single-plane radiography to measure GHJ translations in shoulder instability patients and reported that anterior translations ranged from approximately 5 to 8 mm. Using advanced magnetic resonance imaging (MRI)–based techniques, von Eisenhart-Rothe and colleagues[42] quantified GHJ motion and reported GHJ translations of the unstable shoulder in instability patients to be 1 to 2 mm greater than their healthy contralateral shoulder. Conversely, Ogston and Ludewig[34] used an electromagnetic tracking system to assess shoulder motion and reported no differences in shoulder motion between healthy control subjects and instability patients. Magit and colleagues[27] also used an electromagnetic tracking system to measure anterior/posterior GHJ translations in patients with anterior instability and reported values significantly greater than the aforementioned studies, with translations averaging 30 mm across all patients. The wide range of previously reported GHJ translations is likely due in part to differences in patient populations and testing protocols but is also a result of the use of motion measurement systems that were not designed to provide highly accurate (submillimeter and subdegree) measures of in vivo joint motion. Consequently, there remains considerable uncertainty regarding the magnitude and direction of GHJ motion in patients with shoulder instability. In addition, although many studies have evaluated surgical repair techniques for GHJ instability in cadaveric experiments,[12,13,18,37,38] studies aimed at determining the effect of surgical repair on in vivo GHJ motion in patients with instability are reported far less often.

The objective of this study was to determine the effect of anterior shoulder instability and its treatment with arthroscopic stabilization on in vivo GHJ motion and, secondarily, clinical outcomes. Our approach was to use an accurate ($\pm$0.4 mm and $\pm$0.5°)[6] biplane radiograph imaging system to quantify the location of the GHJ contact center and its excursion during an apprehension test in healthy control subjects as well as in anterior GHJ instability patients before arthroscopic stabilization surgery and at 6 months after surgery. We hypothesized that (1) instability patients would have altered GHJ motion before surgery, (2) GHJ motion would change between pre- and postsurgical time points, and (3) postsurgical measures of GHJ motion would not be different from those of control subjects. Secondarily, we hypothesized that clinical outcomes (strength, range of motion [ROM], patient-reported quality of life questionnaire) would significantly improve after surgery.

METHODS

After institutional review board approval and informed consent, 22 subjects were enrolled in this study. Eleven of the subjects were patients (age, 20.5 $\pm$ 4.9 years; range, 16-29 years) who had a diagnosis of anterior GHJ instability after a positive apprehension test. To qualify for the study, each patient had to have had at least 1 "acute glenohumeral instability event," as defined in a recent study from Owens and colleagues,[35] to include both dislocations requiring manual reduction and subluxations. The range of dislocations requiring manual reduction was 0 to 3, with a mean of 0.9. The range of subluxation events was 0 to 2, with a mean of 1.5. Patients were also required to have bony defects less than approximately 5% of the glenoid width and an asymptomatic contralateral shoulder. Width of bony defects was assessed by the senior surgeon (V.M.) from computed tomography (CT) scans using the technique previously reported by Sugaya and colleagues,[41] which calculates the defect size as a ratio of the area of any bone fragment to the area of a circle fit based on the inferior portion of the glenoid. The range of bony defects in this patient population was 0% to 5%, with 9 of the 11 patients having no bony defect. In addition, 11 control subjects (age, 27.0 $\pm$ 4.2 years; range, 19-34 years) with no history of shoulder injury, surgery, or symptoms also enrolled in the study.

Subject Testing

Subjects were positioned with their shoulder centered within the 3-dimensional (3D) imaging volume of a biplane radiograph system in the anterior-posterior direction and approximately 30° to 40° oblique to the anterior-posterior view. The system consists of two 100-kW pulsed x-ray generators (CPX 3100CV; EMD Technologies) coupled to two 40-cm image intensifiers (AI5765HVP; Shimadzu) attached to synchronized high-speed video cameras (Phantom v9.1; Vision Research). Images were acquired at 60 Hz during an apprehension test consisting of passive external rotation with the arm at 90° of abduction, with all apprehension tests performed by 1 investigator (C.D.P.). This apprehension test began at 0° of external rotation (ie, with the forearm parallel to the ground) and continued with increasing external rotation until either the subject communicated apprehension or the joint could not be rotated further. Three trials were acquired for each control subject's dominant shoulder and instability patient's injured shoulder. The control subjects were tested at a single time point, while the instability patients were tested before surgery and at 6 months after

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One or more of the authors has declared the following potential conflict of interest or source of funding: This study was sponsored by Henry Ford Hospital, Department of Orthopaedic Surgery.

surgery. The rationale for testing patients at 6 months after surgery was because this time point is shortly after these patients have returned to full activity and should be exhibiting “normal” motion.

After testing, CT scans of the entire humerus and scapula were acquired (LightSpeed 16; GE Medical Systems). The scans had a slice thickness of 1.25 mm and an in-plane resolution of approximately 0.5 mm per pixel. The humerus and scapula were then automatically segmented from other bones and soft tissue using the same density value for each subject and reconstructed into 3D bone models with a voxel size of 0.625 mm (Mimics 10.1; Materialise).

GHJ motion during the apprehension test was assessed by tracking the 3D position of the humerus and scapula from images acquired from the biplane radiograph system. This model-based tracking technique has been shown to track 3D shoulder motion accurately to within ± 0.4 mm and $\pm 0.5°$.[6] As previously described,[4] GHJ contact patterns were estimated for each shoulder by combining joint motion measured from the biplane radiograph images with the subject-specific bone models. Briefly, the CT-based bone models were first converted into 3D surface models constructed of contiguous triangular tiles. A typical humerus or scapula model contained approximately 70,000 triangles of 0.5 mm^2 each. To avoid unnecessary calculation, 2 specific regions of interest were identified: the humeral head and the glenoid. Custom software calculated the 3D distance from every surface-triangle centroid on the humeral head to every surface-triangle centroid on the glenoid. The contact center location was then determined by calculating the centroid of the closest 200-mm^2 region of contact between the humerus and glenoid. 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 or a time series of data identifying the center of contact of the humerus on the glenoid for each trial. With use of these GHJ contact center data, the dynamic contact center location was determined by calculating the average anterior/posterior (A/P) and superior/inferior (S/I) contact center over each trial. The location of the A/P and S/I contact centers across the range of motion common to all subjects was also determined, resulting in an average contact center location at every 5° from 0° to 50° of external rotation. The length of the contact center path was also calculated by summing the change in location of the GHJ contact center in 5° increments from 0° to 50° of external rotation. Dynamic joint excursion (ie, the amount of translation of the GHJ contact center that occurred during an apprehension test) was estimated by calculating the A/P and S/I range of the contact center location over each trial as the difference between the minimum and maximum positions of the GHJ contact center from 0° to 50° of external rotation. To account for differences in subject size, we normalized all joint contact data relative to each shoulder’s glenoid height (for measurements in the S/I direction) and width (for measurements in the A/P direction) as determined from the subject-specific bone models. Measures of GHJ motion were averaged over the 3 trials for each subject.

In addition to measures of GHJ motion, shoulder strength and active ROM were measured in all subjects. As previously described,[5] isometric shoulder strength was assessed using an isokinetic dynamometer (Biodex System 2). 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 coronal-plane abduction and 0° of humeral rotation, and external rotation (ER) at 15° of coronal-plane abduction and 0° of humeral rotation. Active ROM was assessed with a goniometer for ABD, ELEV, IR and ER, with IR and ER ROM measured at 90° of abduction. For both strength and ROM measurements, 3 trials were performed at each position, and the average of 3 trials was recorded. Both shoulders were tested and testing order was randomized. To account for differences in subject size, strength measurements were then normalized to the contralateral side (eg, healthy subjects dominant to nondominant, instability patients injured to uninjured contralateral). After both testing sessions for instability patients, patient-reported clinical outcomes were assessed using the Western Ontario Shoulder Instability (WOSI) index. The WOSI index is a disease-specific quality of life subjective assessment that provides a cumulative score based on domains of physical symptoms, sports/recreation/work, lifestyle, and emotions as well as individual scores for each domain.[25]

Arthroscopic Stabilization

For all patients in this study, arthroscopic capsulolabral repair using suture anchors was performed by a single surgeon (V.M.). The goal of the surgical repair was to restore the labrum to its anatomic attachment location and reestablish the appropriate tension in the inferior glenohumeral ligament and joint capsule. To accomplish this, general anesthesia was administered and patients were placed in a lateral position with the operative arm suspended. Anterior portals were established for instrument passage, glenoid preparation, and suture management, while a posterior portal was established for the arthroscope. The glenoid, humerus, labrum, rotator cuff, and glenohumeral joint capsule were inspected to determine the extent of injury. The inferior glenohumeral ligament and joint capsule complex were elevated from the glenoid neck so that they could be shifted superiorly and laterally onto the glenoid rim. With a motorized shaver, the glenoid neck was abraded to facilitate healing of the repaired capsule and labrum. At least 3 suture anchors (PushLock; Arthrex) were placed at the articular rim from inferior to superior below the glenoid equator, with care taken to avoid penetration of the articular surface. The sutures were passed through the capsulolabral complex, and the labrum was reattached with the use of knotless anchors loaded with these sutures.

Postsurgical Rehabilitation

All patients were enrolled in a postsurgical rehabilitation program that is our institution’s standard of care. This program is based on the consensus guidelines from the

TABLE 1
Measures of Glenohumeral Joint Motion for the Control Subjects and Instability Patients[a]

Outcome Measure	Control Subjects	Instability Patients		*P* Value		
		Pre	Post	Pre vs Control	Post vs Control	Pre vs Post
A/P contact center location[b]				**.03**	.39	**.03**
% of glenoid width	–8.8 ± 5.4	–0.9 ± 9.9	–5.6 ± 11.2			
Millimeters	–2.3 ± 1.5	–0.2 ± 2.5	–1.3 ± 2.7			
S/I contact center location[b]				.88	.77	.65
% of glenoid width	7.2 ± 16.1	6.4 ± 7.3	5.6 ± 7.7			
Millimeters	2.6 ± 5.4	2.4 ± 2.8	2.1 ± 3.1			
A/P contact center range				.39	**.01**	**.01**
% of glenoid width	22.4 ± 8.6	19.4 ± 7.1	14.7 ± 3.5			
Millimeters	5.7 ± 2.3	4.7 ± 1.8	3.6 ± 1.0			
S/I contact center range				.08	.34	.11
% of glenoid width	20.1 ± 8.7	14.6 ± 4.8	17.0 ± 5.8			
Millimeters	6.7 ± 2.9	5.2 ± 1.9	6.0 ± 2.1			
Contact center path length				.50	.27	.40
% of glenoid width	22.2 ± 10.5	19.3 ± 9.5	18.0 ± 6.3			
Millimeters	7.5 ± 4.0	6.8 ± 3.3	6.3 ± 2.2			

[a]Results are reported as mean ± SD. Statistically significant differences ($P \leq .05$) are indicated in bold. A/P, anterior/posterior; Post, postsurgery; Pre, presurgery; S/I, superior/inferior.
[b]Relative to glenoid center.

American Society of Shoulder and Elbow Therapists. The postsurgical rehabilitation program consisted of 3 phases: immediate postoperative (weeks 0-6), ROM restoration (weeks 6-12), and strength training (weeks 12-24). The first phase consisted of immediate absolute immobilization for 0 to 4 weeks followed by relative immobilization in which limited ROM exercises were performed. In the second phase, passive ROM exercises and limited active ROM exercises were performed, with the goal of restoring normal ROM, increasing strength, and improving scapular stabilization. The goal of the third phase was to increase strength and endurance, resulting in full return to activities of daily living, work, and recreational activities.

Statistical Analysis

Differences in instability patients' pre- and postsurgery values regarding GHJ motion, strength, ROM, and WOSI scores were assessed with paired 2-tailed *t* tests. Differences in GHJ motion, strength, and ROM between the control subjects and instability patients both before surgery and at 6 months after surgery were assessed with unpaired *t* tests. Significance was set at $P < .05$.

RESULTS

Glenohumeral Joint Motion

Before surgery, the joint contact path followed the same general pattern for both the instability patients and control subjects. Specifically, the joint contact center began in the posterosuperior quadrant of the glenoid at the start of the apprehension test and translated primarily anteriorly on the glenoid with increasing external rotation. However, there were specific differences in the A/P contact center during the apprehension test, with the humerus of instability patients located significantly more anteriorly on the glenoid than that of the control subjects from 10° to 25° of external rotation ($P < .05$) (Figure 1). In contrast, no significant differences were detected in the S/I contact center between patients and controls at any of the 5° intervals of external rotation during the apprehension test ($P > .42$) (Figure 2). In terms of the average joint contact center position before surgery, the humerus of instability patients was located significantly more anteriorly on the glenoid than that of the control subjects ($P = .03$) (Figure 3), but no differences were detected between patients and controls in terms of the average S/I contact center ($P = .88$) (Figure 3). In addition, no differences were detected before surgery between the instability patients and control subjects in the contact path length, S/I contact center range, or the A/P contact center range ($P > .08$) (Table 1).

In comparing the pre- and postsurgical conditions of the patients, relatively few differences in GHJ motion were detected. After surgery, the contact center was located significantly more posteriorly on the glenoid from 20° to 45° of external rotation ($P < .05$) (Figure 1). The average A/P contact center was located significantly more posteriorly after surgery ($P = .03$) (Table 1 and Figure 3), and the A/P contact center range was significantly decreased after surgery as well ($P = .01$) (Table 1). However, no significant differences were detected between pre- and postsurgical time points in the average S/I contact center ($P = .65$) (Figure 3), S/I contact center range ($P = .11$) (Table 1), or contact center path length ($P = .40$) (Table 1).

After surgery, only 1 significant difference was detected in GHJ motion between the patients and controls. Specifically, the A/P contact center range was significantly decreased after surgery ($P = .01$) (Table 1). However, no differences

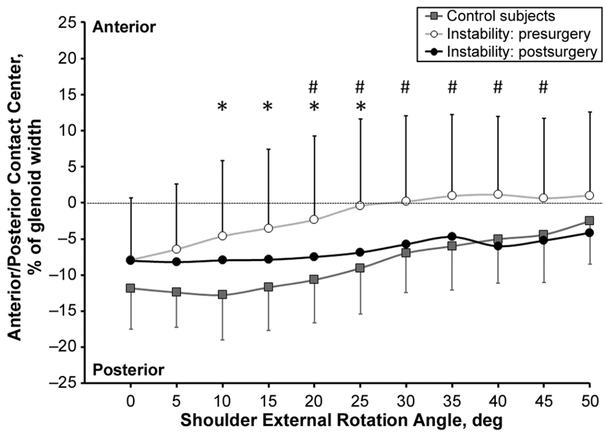

Figure 1. For the control subjects and instability patients, the joint contact center began in the posterior glenoid at the start of the apprehension test and moved anteriorly on the glenoid with increasing external rotation. The dotted horizontal line indicates the center between the anterior and posterior regions of the glenoid. *Statistically significant difference in presurgical data between the controls (■) and the patients (○). #Statistically significant difference in the presurgical (○) and postsurgical (•) data of the patients.

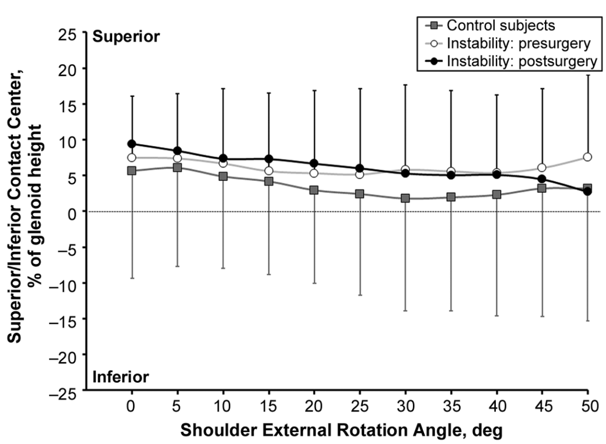

Figure 2. For the control subjects and instability patients, the joint contact center began in the superior glenoid at the start of the apprehension test and did not deviate significantly in the superior/inferior direction with increasing external rotation. The dotted horizontal line indicates the center between the superior and inferior regions of the glenoid. No significant differences in the superior/inferior joint contact center were detected.

were detected in the average A/P or S/I contact center ($P >$ .39) (Figure 3), S/I contact center range (P = .34) (Table 1), or contact center path length (P = .27) (Table 1).

Qualitatively, the contact center after surgery moved primarily posteriorly on the glenoid in 6 of the 11 patients (Figure 4A), primarily inferiorly in 3 patients (Figure 4B), and in the anterosuperior and anteroinferior directions, respectively, in 2 patients (Figure 4C).

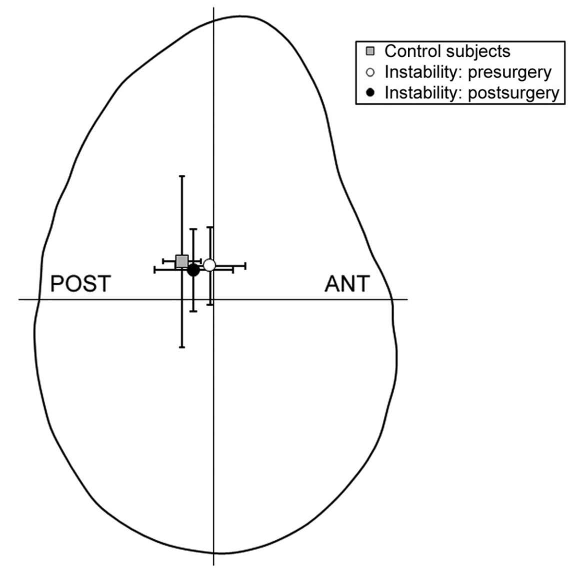

Figure 3. Before surgery, the average joint contact center in the instability patients (○) was located significantly more anteriorly on the glenoid than that of the control subjects (■) (P = .03). The average joint contact center for the patients moved significantly posteriorly on the glenoid after surgery (•) (P = .03). After surgery, no differences were detected between the controls and the patients in terms of the anterior/posterior (P = .39) or superior/inferior (P = .77) average joint contact center. ANT, anterior; POST, posterior.

Strength and Active ROM

Before surgery, the normalized ER strength (P = .05) and IR strength (P = .001) were both significantly lower in instability patients than in the control subjects (Table 2). However, no significant differences in ABD or ELEV strength were detected between the controls and the presurgical condition of the patients ($P >$ .65). In terms of active ROM, the instability patients before surgery had significantly less active ER ROM than did the controls (P $<$ .001). No significant differences were detected in active IR, ABD, or ELEV ROM between the controls and the presurgical condition of the patients ($P >$ .06) (Table 2).

In comparing the pre- and postsurgical conditions of the instability patients, IR strength was found to increase significantly after surgery (P = .001) (Table 2). However, no changes were detected after surgery in ER, ABD, or ELEV strength ($P >$ .33). In terms of ROM, there was a significant increase after surgery in ABD ROM (P = .02), with patients exhibiting full ABD ROM after surgery. However, no changes were detected after surgery in ER, IR, or ELEV ROM ($P >$ .16) (Table 2).

After surgery, no significant differences in shoulder strength were detected between the instability patients and the control subjects ($P >$ .17). Similarly, no significant differences in postsurgical condition were detected between the patients and controls in terms of IR, ABD, or ELEV ROM ($P >$ .15). However, the postsurgical ER

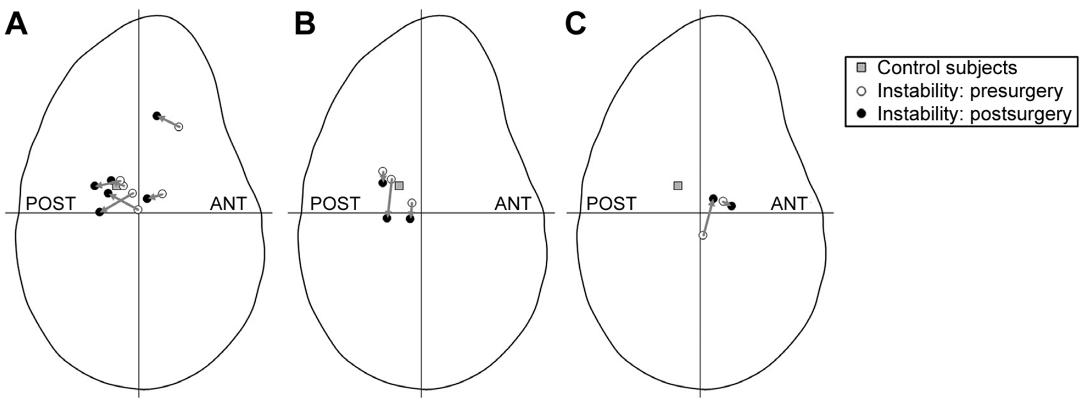

Figure 4. After surgery, (A) 6 of the 11 joint contact centers had moved posteriorly on the glenoid, (B) 3 of 11 had moved inferiorly on the glenoid, and (C) the remaining 2 had moved in anterosuperior and anteroinferior directions on the glenoid. For comparison, the average joint contact center of the control subjects is also displayed (■). ANT, anterior; POST, posterior.

TABLE 2
Shoulder Strength and Range of Motion[a]

			Instability Patients		*P* Value		
Outcome Measure	Activity	Control Subjects	Pre	Post	Pre vs Control	Post vs Control	Pre vs Post
Strength, % of contralateral shoulder	ER	100 ± 8	82 ± 27	89 ± 25	**.05**	.17	.33
	IR	108 ± 9	83 ± 20	106 ± 21	**<.01**	.82	**<.01**
	ABD	88 ± 25	88 ± 31	88 ± 17	.65	.56	.99
	ELEV	94 ± 28	91 ± 34	93 ± 19	.85	.63	.87
Range of motion, deg	ER	112 ± 9	87 ± 8	89 ± 12	**<.01**	**<.01**	.64
	IR	61 ± 20	61 ± 23	70 ± 17	.91	.29	.19
	ABD	175 ± 10	161 ± 24	180 ± 0	.06	.15	**.02**
	ELEV	177 ± 10	160 ± 41	180 ± 0	.23	.33	.16

[a]Results are reported as mean ± SD. Statistically significant differences ($P \leq .05$) are indicated in bold. ABD, frontal-plane abduction; ELEV, sagittal-plane elevation; ER, external rotation; IR, internal rotation; Post, postsurgery; Pre, presurgery.

ROM in instability patients continued to be significantly lower than that of the controls ($P < .001$) (Table 2).

Patient-Reported Outcomes

The patient-reported outcome measures in the patients increased significantly after surgery. Specifically, there were statistically significant increases in the physical symptoms (59.2 ± 20.5 [presurgery] vs 90.6 ± 9.4 [postsurgery]; $P = .0007$), sports/recreation/work (38.0 ± 12.8 [presurgery] vs 82.1 ± 25.5 [postsurgery]; $P = .0003$), lifestyle (50.0 ± 12.8 [presurgery] vs 86.1 ± 19.5 [postsurgery]; $P = .0004$), and emotions (23.5 ± 18.8 [presurgery] vs 78.0 ± 32.3 [postsurgery]; $P = .0001$) subcategories of the WOSI index. In addition, the overall composite score increased significantly from a presurgical score of 48.3 ± 13.1 (out of 100) to a postsurgical score of 86.3 ± 16.5 ($P = .0002$).

DISCUSSION

The objective of this study was to determine the effects of anterior shoulder instability and arthroscopic stabilization on in vivo GHJ motion and clinical outcomes. Briefly, the study indicated that before surgery, the humerus of the instability patients was positioned more anteriorly on the glenoid during an apprehension test compared with that of the controls. The instability patients also had lower IR strength, ER strength, and ER ROM before surgery compared with controls. At 6 months after arthroscopic stabilization, the humerus in the patients was located significantly more posteriorly on the glenoid, and there was a significant decrease in the range of the A/P joint contact center compared with presurgical values. The instability patients also demonstrated significant improvements in their WOSI score, IR strength, and ABD range of motion compared with presurgical values.

The humerus of instability patients was located more anteriorly on the glenoid before surgery compared with that of the control subjects ($P = .03$) (Figure 3), but no differences were detected between these groups in contact center range ($P = .39$) or path length ($P = .50$) (Table 1). The contact center range and path length can be interpreted as an estimate of the amount of motion that occurs at the articulating surfaces during shoulder motion, and therefore it was surprising that the study failed to detect differences in either of these variables between the presurgical instability patients and the control subjects. This suggests that apprehension (ie, the feeling that the joint may dislocate with continued external rotation) is due to the humerus being located more anteriorly on the glenoid rather than an increase in joint motion between the humerus and glenoid. This finding further suggests that although the soft tissues that act as an anterior buttress to the humerus have been damaged during traumatic shoulder dislocation, any loss in joint-stabilizing capabilities of the entire capsuloligamentous complex are perhaps too subtle to be detected during the 0° to 50° range of GHJ motion that was common to all subjects during the apprehension test.

In contrast to the lack of difference in A/P contact range between the presurgical patients and control subjects, the A/P contact range at the postsurgical time point was significantly lower than the A/P contact range of both the controls (P = .01) and the patients' presurgical time point (P = .01) (Table 1). It is possible that the A/P contact center range varies with ER ROM, and therefore this decreased A/P contact center range may simply reflect the deficits in ER ROM that were observed after surgery (P < .01) (Table 2). These findings suggest that joint motion is altered either because the surgical procedure overtightens the repair tissues or because joint stiffness occurs secondary to postoperative immobilization and/or pain. Previous research has shown that the inferior glenohumeral ligament plays an important role in resisting anterior translation[28] and external rotation[26] in the apprehension position, so it is possible that the surgical stabilization procedure may be overtightening the anterior soft tissues and limiting joint motion. However, without a practical way to measure repair tissue tension at the time of surgical repair or at postoperative time points, it is difficult to conclude that limitations in joint motion (or changes over time in joint motion) can be attributed to changes in repair tissue properties.

The results from the current study compare well with some previous studies that have also assessed GHJ translations under in vivo conditions. For example, the instability patients in the current study had an A/P contact center range of 4.7 mm before surgery. This finding is in close agreement with the 5 to 8 mm of anterior translation reported by Hawkins and colleagues.[20] The current study also reported a difference in the A/P contact center range of 1.5 mm between the patients and the controls. This finding is in excellent agreement with the findings of von Eisenhart-Rothe and colleagues,[42] who reported the GHJ translations of instability patients were 1 to 2 mm greater than subjects with healthy shoulders. These current data are reported with high confidence, particularly since the magnitude of the reported changes is greater than the ±0.5 mm uncertainty of our measurement technique,[6] but the clinical implications of these subtle changes in GHJ motion are yet unknown. However, it is well established that GHJ forces can reach or exceed 100% of body weight during activities of daily living.[3,43,44] Consequently, it is plausible that high joint forces combined with subtle changes in the location of the joint contact center (as a result of either the initial injury or surgical repair) could change the GHJ stress distribution in a way that contributes to the development of osteoarthritis.

Although the data indicated that the humerus in instability patients was positioned more anteriorly on the glenoid before surgery and then moved posteriorly on the glenoid after surgery (Figure 3), there was significant variability between patients in how surgery affected joint motion. For example, the standard deviation of the pre- and postsurgical A/P contact center locations was 9.9% and 11.2% of the glenoid width, respectively, whereas the corresponding standard deviation for the control subjects was only 5.4% of the glenoid width. In addition, while 1 instability patient displayed a more superior contact center than the others (Figure 4), this position was consistent throughout testing and remained more superior at the postoperative time point. Previous work from our laboratory has indicated that there is considerable variability in the superior/inferior location of the GHJ contact center, even among subjects with healthy shoulders.[5] Consequently, we suspect that the superior location of the contact center in this patient was simply due to patient-to-patient variability.

The pre- and postsurgical data for the individual patients (Figure 4) can likely provide some insight into details of both the injury and surgical repair. The apprehension test involves passive external rotation of the shoulder, so joint motion is likely dictated to a large extent by the passive soft tissues surrounding the GHJ (ie, the labrum, ligaments, and joint capsule). In the absence of active muscle forces, the humerus would thus be expected to translate on the glenoid to a position that minimizes the soft tissue forces applied to the humerus during this test. Thus, the change in the contact center position between pre- and postsurgical time points provides an indication of how the surgical procedure may have altered the distribution of in vivo soft tissue forces. For example, cadaveric studies (which are not an ideal comparison with in vivo studies because of inherent methodological limitations) have shown that the humerus will translate toward the direction of a labral injury and that repair of the labral lesion will recenter the humerus on the glenoid.[15] Similarly, it has been shown that repair of the anterior capsule/labrum decreases joint motion significantly and shifts the glenohumeral joint's center of rotation posteriorly and inferiorly.[2,29] However, it has also been shown that there are significant differences in joint motion and stability depending on the location and extent of the repair.[33,46] In the current study, the data suggest that for the 6 patients whose contact center moved posteriorly (Figure 4A), the surgical repair retensioned the anteroinferior soft tissues in a way that exerted a more posteriorly directed force on the humerus compared with the presurgical condition. Similarly, for the patients whose contact center moved primarily inferiorly after surgery (Figure 4B), it is plausible to suggest that the anterosuperior capsulolabral complex may have been preferentially tensioned (ie, overtightened) compared with the anteroinferior structures. Alternatively, injury to the inferior capsule may not have been fully appreciated before or during the surgical repair, and failure to stabilize the inferior capsuloligamentous region may explain why the humerus shifted inferiorly after surgical repair.

The explanation for the 2 patients whose joint contact center moved anterosuperiorly and anteroinferiorly after surgery is not clear (Figure 4C). The improvement in

WOSI scores for these 2 patients—from presurgical values of 37.5 and 38.7 to postsurgical values of 99.8 and 81.7—suggests that these patients were satisfied with their clinical outcome, but both had decreases in strength and/or ROM at the postoperative testing time point that might be associated with these unexpected changes in joint mechanics. However, it is unclear to what extent decreases in strength and/or ROM are associated with GHJ motion or if these patients' injuries were more extensive than what was observed during surgical repair. Regardless, these data suggest that some aspect of the clinical intervention (ie, surgery or rehabilitation) may have resulted in an anteriorly directed force on the humerus when the shoulder was in the apprehension position.

The improvements in patient-reported outcomes after arthroscopic stabilization are consistent with previously published studies. Specifically, the 79% increase in the WOSI score—from a presurgery value of 48.3 to a postsurgical value of 86.3—is consistent with data reported in 2 recent reviews of long-term clinical studies[17,19] and indicates that patients are satisfied with the improvements in pain and function after surgery. In terms of shoulder strength, IR was the only measure of shoulder strength to improve significantly between presurgical and postsurgical time points (Table 2). In addition, the study indicated that the instability patients exhibited an ER ROM deficit of approximately 23° after surgery compared with the controls (Table 2). These data agree well with previous research, which has shown that significant deficits in ER ROM are likely at 6 months after surgery and that small (up to 5°) deficits in ER ROM are likely to persist in the long term after arthroscopic stabilization.[17,22-24] However, it is possible that these patients may have been psychologically apprehensive and guarded during the ROM testing both before and after surgery. Determining ROM under anesthesia would likely provide more definitive insight into changes in ROM associated with instability and arthroscopic stabilization.

There are several limitations with this study. First, a separate cohort of healthy subjects was used as the control population rather than the uninjured contralateral shoulders of the patients. The rationale for selecting a separate control subject population was based on recent data from our laboratory indicating that there are significant differences in glenohumeral joint morphologic characteristics between instability patients and healthy control subjects and that these morphological differences are present in the instability patients' injured and uninjured contralateral shoulders. There is increasing evidence that joint motion is influenced appreciably by joint morphologic characteristics,[1,7,31,39,45] and therefore we used a separate cohort of control subjects because we could not be certain that the contralateral shoulders of the patients were representative of "normal" motion. Another limitation of this study is that only 1 motion was tested, even though several tests are commonly used clinically to assess shoulder instability. However, the apprehension test has been shown to have high sensitivity and specificity for assessing shoulder instability and is a strong predictor of recurrent instability.[14,32,40] Radiation exposure is also a concern, as this approach requires a CT scan and biplane radiographic imaging, but the radiation exposure for each patient in this study was at a level that is considered minimal risk by the US Food and Drug Administration. Last, the patients were tested at 6 months after surgery, which is admittedly an early postoperative time point. However, it is our intention to test these patients again at 24 months after surgery, and therefore this early postoperative time point was necessary to accurately characterize the time course of healing and return of function after arthroscopic stabilization.

In summary, this study indicated that, before surgery, patients who have been diagnosed with traumatic anterior instability have lower ER strength, IR strength, and ER ROM than do healthy control subjects. In addition, their humerus is located significantly more anteriorly on the glenoid during an apprehension test. At 6 months after arthroscopic stabilization, there are significant increases in WOSI score, IR strength, and ABD ROM, but deficits in ER ROM persist. The position of the humerus on the glenoid during an apprehension test is restored to that of the control subjects after surgery, but the A/P contact center range is lower than that of the controls, and deficits in ER ROM persist. These findings suggest that even though arthroscopic stabilization satisfactorily restores most clinical outcome measures, GHJ excursion and ER ROM remain compromised compared with healthy control subjects. The long-term implication of these findings is not yet known, but future efforts will investigate the extent to which the clinical interventions influence shoulder function and early osteoarthritis progression.

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