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# Glenohumeral translation during active external rotation with the shoulder abducted in cases with glenohumeral instability: a 4-dimensional computed tomography analysis

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**Background:** Although glenohumeral instability is common, the mechanism of instability remains unclear. The purpose of this study was to quantitatively evaluate humeral head translation during active external rotation with abduction in patients with glenohumeral instability by use of 4-dimensional computed tomography scans.
**Methods:** Ten patients with unilateral glenohumeral instability with a positive fulcrum test were prospectively included in this study. Sequential computed tomography of bilateral shoulders during active external rotation at 90° of shoulder abduction was performed for 6 seconds at 5 frames per second. The 3-dimensional positions of the humeral head center in the anteroposterior, superoinferior, and mediolateral directions were calculated at 0°, 20°, 40°, 60°, and maximum shoulder abduction–external rotation from the starting position. Translation of the humeral head center from the starting position was evaluated using Dunnett multiple-comparison tests, and the differences between the affected and intact shoulders were assessed using Wilcoxon signed rank tests.
**Results:** The humeral head center translated posteriorly, inferiorly, and medially during glenohumeral external rotation with the shoulder in the abducted position on the intact side. However, the affected humeral head showed significantly less posterior translation ($P = .028$), greater inferior translation ($P = .047$), and less medial translation ($P = .037$) than the contralateral side.
**Conclusions:** This study indicated that dysfunction of the anterior band of the inferior glenohumeral ligament causes decreased posterior, increased inferior, and decreased medial translation of the humeral head during active shoulder abduction–external rotation.
**Level of evidence:** Basic Science Study; Kinesiology


**Keywords:** Glenohumeral instability; glenohumeral dislocation; humeral head translation; glenohumeral translation; inferior glenohumeral ligament; anterior dislocation; shoulder dislocation

This study was approved by the Institutional Review Board of Keio University School of Medicine (reference study no. 20150128).

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Anterior glenohumeral instability is common in young people[37] and often disturbs patients' daily living and sports activities owing to discomfort of the shoulder and anxiety about dislocation.[12] Most patients with anterior glenohumeral instability feel pain and anxiety about dislocation in the shoulder abduction–external rotation position.[18] Abnormal translation of the humeral head is thought to occur in cases with glenohumeral instability,[5,10,13] but the details of abnormal humeral head translation remain unclear.

The amount of glenohumeral translation of normal shoulders and unstable shoulders has been evaluated using radiographs,[10,13] fluoroscopy,[19,24] magnetic resonance imaging,[4,16,34] and electromagnetic tracking devices.[9,17] Past reports showed posterior translation in the abduction–external rotation position in normal shoulders,[4,13,16] whereas anterior translation of the humeral head was reported to occur in the abduction–external rotation position in shoulders with anterior glenohumeral instability.[13,16,34] However, these studies assessed humeral head translation 2-dimensionally in the static position; thus, 3-dimensional (3D) glenohumeral translation during active shoulder motion has not been clarified. We hypothesized that the normal kinematics of the glenohumeral joint would be impaired in shoulders with glenohumeral instability and that translation of the humeral head would be different between stable and unstable shoulders during external rotation with abduction. The purpose of this study was to quantitatively evaluate humeral head translation during active external rotation with abduction in patients with glenohumeral instability by use of 4-dimensional (4D) computed tomography (CT).

## Materials and methods

### Patients

Twelve patients with glenohumeral instability before glenohumeral stabilization surgical procedures were prospectively recruited for this study. The inclusion criteria for this study were symptomatic glenohumeral instability with a positive fulcrum test, unilateral instability, and recurrent glenohumeral instability with more than 1 traumatic episode leading to dislocation or subluxation. Cases with evidence of glenohumeral arthritis on plain radiographs and with previous shoulder stabilization surgery were excluded. All patients felt anxiety about dislocation when the involved shoulder was externally rotated with the shoulder at 90° of abduction and the elbow at 90° of flexion in the supine position,[18] but the fulcrum test of the contralateral shoulder was negative. After they completely understood the details of their involvement, all candidates gave their informed consent to participate in this study. On the CT examinations, however, 2 patients showed evidence of a Hill-Sachs lesion in the asymptomatic contralateral shoulder and were excluded from this study. Thus, a total of 10 patients (mean age, 22.5 ± 3.5 years; all men) were evaluated. Of the patients, 7 had experienced recurrent subluxations whereas 3 had both subluxations and dislocations. After CT examination, arthroscopic Bankart repair was performed in all 10 patients, and all were found to have anteroinferior glenohumeral ligament–labral complex lesions without rotator cuff tears or posterior labral lesions during the stabilization surgical procedures.

### Experimental protocol

Dynamic 4D CT was performed for bilateral shoulders during active external rotation with the shoulder abducted using a 320–detector row CT system (Aquilion ONE; Canon Medical Systems, Otawara, Japan) with a maximum craniocaudal field of view of 160 mm. The patients were placed in a supine position with 90° of shoulder abduction and neutral rotation, measured by a goniometer, and they were instructed to rotate the shoulder externally from the neutrally rotated position to the maximum externally rotated position for 5 seconds in the CT gantry (Fig. 1). Sequential CT scans during active external rotation were performed, scanning with only low-dose radiation for bone analysis for 6 seconds with 5 frames per second and 0.5-mm-thick slices of CT volumetric data; thus, a total of 31 frames of 320 axial CT images were acquired for each shoulder. The intact shoulder was evaluated first, followed by the involved side. During the evaluation of the affected side, 8 patients felt discomfort whereas 2 patients did not feel any discomfort. Finally, bilateral axial CT including the whole scapula and the whole length of the humerus was performed with only low-dose radiation for bone analysis in a static supine position. The total effective dose of radiation exposure was tracked during all CT scanning and was controlled to not exceed 10 mSv. The value was close to the average effective dose of normal chest CT scans (7 mSv).[21] No patients showed any side effects from radiation exposure. All frames of dynamic and static CT scans were extracted in Digital Imaging and Communications in Medicine (DICOM) data format.

### Definition of glenoid and humeral coordinate systems

The surface models of the intact-side scapula and the bilateral humeri were separately reconstructed from the static CT data using Avizo software (version 9.0.1; Maxnet, Tokyo, Japan). First, the surface data of the left scapula and humerus were flipped horizontally to be aligned with the right shoulder coordinate system. Second, humeral motions with respect to the scapula were reconstructed for both the intact and affected shoulders. The scapula surface was matched with the scapula in all frames of the 4D CT scans using a surface registration technique with an iterative closest point (ICP) algorithm in the Visualization Toolkit program (version 6.3.0; Kitware, Clifton Park, NY, USA).[25] The humeral surface was translated by the rotation matrix that aligned the scapula in each 4D CT frame to the static scapula. Thus, humeral motion with respect to the fixed whole scapula was reconstructed. Then, the affected shoulder was aligned with the intact shoulder according to the posterior half of the affected glenoid, because a glenoid bone defect is often found in shoulders with glenohumeral instability.[20,23,31]

The dimensions of the bone defects of the glenoid and humeral head were evaluated from the CT surface data using MeshLab software (version 1.3.3; ISTI, Pisa, Italy). On the en face view of the glenoid surface, the glenoid width of both shoulders was measured as the greatest horizontal distance of the glenoid. With the intact glenoid width used as a reference, the size and ratio of

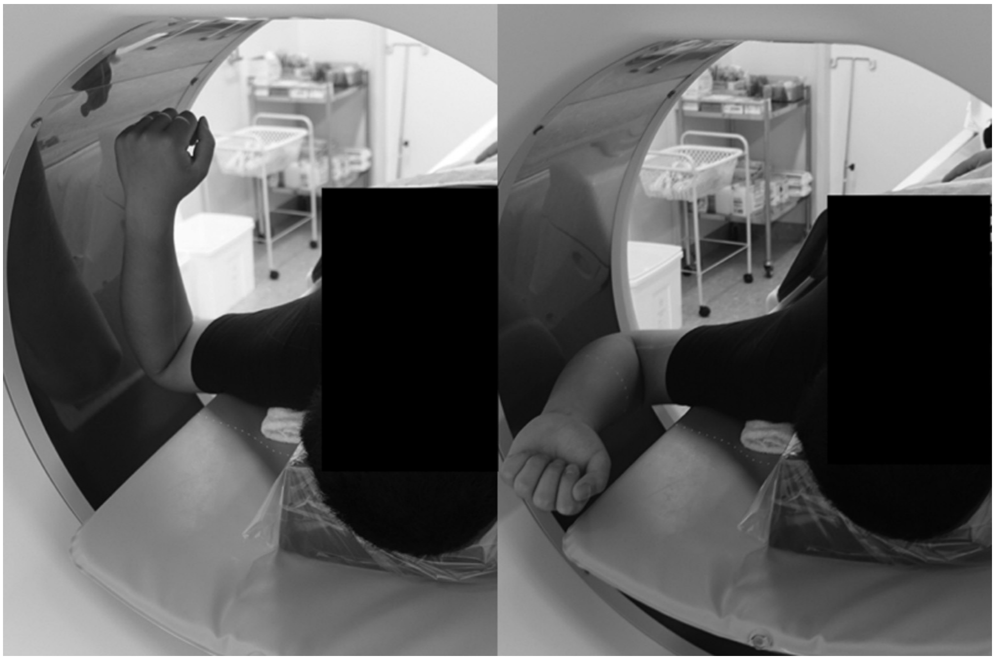

**Figure 1** Four-dimensional analysis of glenohumeral translation during active external rotation with the shoulder abducted. The patient rotates the shoulder externally from the neutrally rotated position to the maximum externally rotated position for 5 seconds in the computed tomography gantry. Sequential computed tomography scans are taken during active external rotation for 6 seconds at 5 frames per second.

the glenoid bone defect were calculated.[3] Then, the width of the Hill-Sachs lesion and the distance between the medial margin of the footprint of the rotator cuff and the medial margin of the Hill-Sachs lesion were evaluated on the posterior view of the humeral head using the humeral surface data.[3]

The local 3D coordinate systems of the glenoid and humerus were defined using the individual bony landmarks. The glenoid coordinate system was defined in the intact scapula. The glenoid plane was defined as the best-fitting plane of the glenoid surface, which was reconstructed from all points on the manually extracted glenoid articular surface.[22] The superior pole of the glenoid was set as the supraglenoid tubercle of the ovoid glenoid surface, where the long head of the biceps tendon is thought to originate, and the inferior pole was set as the farthest point from the superior pole on the glenoid surface. The z-axis was defined as the line normal to the glenoid plane, pointing laterally. The x-axis was defined as the line perpendicular to the z-axis and the glenoid longitudinal axis, which connects the superior and inferior poles of the glenoid, pointing forward. The y-axis was defined as the common line perpendicular to the glenoid x- and z-axes, pointing superiorly (Fig. 2, *A*). The origin of the glenoid coordinate system was set at the center of gravity of the glenoid surface.[22,34]

The humeral coordinate system was independently defined in the intact shoulder, followed by the affected shoulder, using the humeral head center, lateral epicondyle, and medial epicondyle according to the International Society of Biomechanics recommendation.[35] The humeral head articular surface was approximated as a sphere using the software, and the humeral head center was defined as the center of the best-fitting sphere of the humeral head articular surface. The x-axis was defined as the line perpendicular to the plane formed by 3 humeral landmarks, pointing forward, and the y-axis was defined as the line connecting the humeral head center and the midpoint of the medial and lateral epicondyles, pointing to the humeral head center. The z-axis was defined as the common line perpendicular to the x- and y-axes, pointing laterally (Fig. 2, *B*).

## Three-dimensional analysis of humeral head translation

The rotation of the humeral coordinate system was calculated with respect to the glenoid coordinate system using the Euler-Cardan angles (in $y_1$-x-$y_2$ order),[35] and the rotation around $y_2$ represents external or internal rotation of the glenohumeral joint. Humeral head translation was evaluated by tracking the 3D position of the humeral head center on the glenoid coordinate system (Fig. 3).[34] The starting position of shoulder abduction–external rotation was defined as 0° of glenohumeral external rotation, and the humeral head center position with respect to the origin of the glenoid coordinate system was interpolated in 20° increments of the glenohumeral external rotation angle from the starting position to external rotation of 60°, as all patients achieved the range. Translation was approximated with the closest 2 values with an assumption of linear change during the intervals of glenohumeral external rotation.

## Statistical analysis

SPSS Statistics software (version 25.0.0.0; IBM, Armonk, NY, USA) was used for the statistical analyses. The 3D positions of the humeral head center were calculated at 0° (starting position), 20°, 40°, 60°, and maximum shoulder abduction–external rotation from the starting position. The humeral head center position at each externally rotated position in the anteroposterior (x-axis), superoinferior (y-axis), and mediolateral (z-axis) directions was

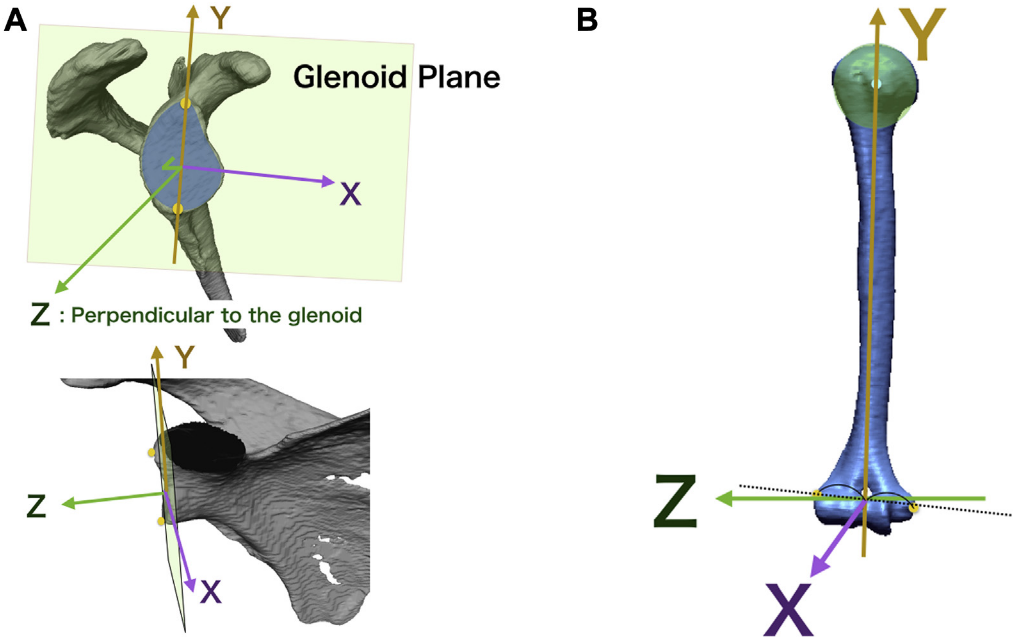


**Figure 2** (**A**) The glenoid coordinate system is defined from the scapular model of the intact shoulder. The origin of the glenoid coordinate system is set at the center of gravity of the glenoid surface. (**B**) The humeral coordinate system is independently defined in both shoulders using the humeral head center, lateral epicondyle, and medial epicondyle.

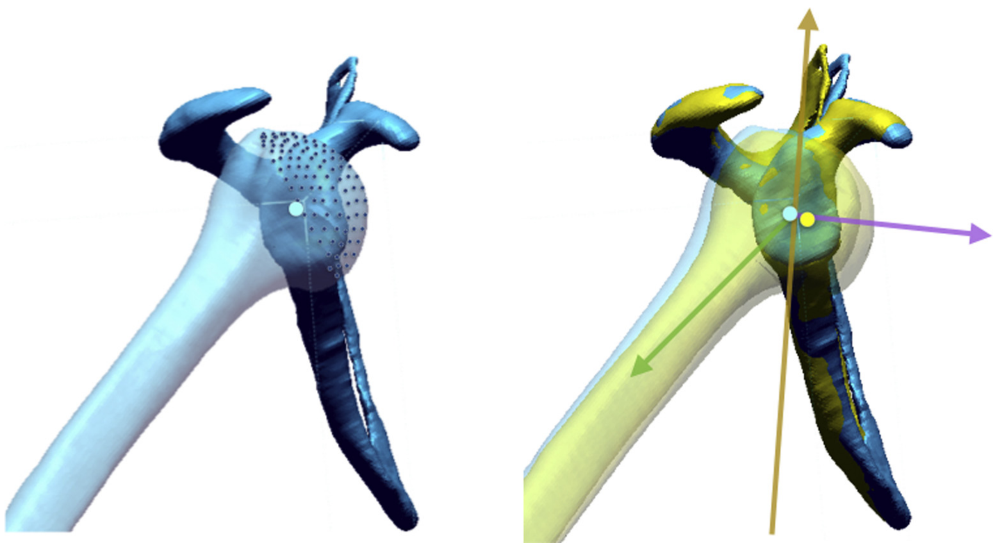

**Figure 3** Humeral head translation is evaluated by tracking the 3-dimensional position of the humeral head center on the glenoid coordinate system. The reconstructed surfaces of the scapula and humerus from static computed tomography data are matched onto the reconstructed surfaces of the glenoid and proximal humerus, respectively, from dynamic 4-dimensional computed tomography data (*blue*, surface models of intact shoulder; *yellow*, surface models of affected shoulder). *Purple arrow*, X axis; *yellow arrow*, Y axis; *green arrow*, Z axis.

compared with the humeral head center position at 0° of shoulder abduction–external rotation (starting position) in both the affected and intact shoulders using Dunnett multiple-comparison tests after the values were revised with respect to the starting position. To assess glenohumeral translation between the intact and affected sides, Wilcoxon signed rank tests were used to evaluate the differences in glenohumeral translation distance in the anteroposterior, superoinferior, and mediolateral directions at 0°, 20°, 40°, 60°, and the maximum externally rotated position between the affected and intact shoulders. The significance level was set at .05 in all analyses.

## Results

Glenoid bone defects were present in 8 patients, whereas 9 patients had Hill-Sachs lesions. The average glenoid width of the intact shoulder was 28.2 ± 1.1 mm (range, 27.4-30.9 mm). The average glenoid bone defect measured 3.2 ± 1.8 mm (range, 0-5.6 mm), and the average ratio of glenoid bone defects was 11.4% ± 6.4% (range, 0%-18.1%). The average width of the Hill-Sachs lesion was 10.6 ± 6.2 mm (range, 0-20.4 mm), and the average distance between the medial margin of the footprint of the rotator cuff and the medial margin of the Hill-Sachs lesion was 13.3 ± 6.7 mm (range, 0-23.5 mm). With the calculation of the glenoid track width,[36] 1 shoulder was determined to have an off-track Hill-Sachs lesion whereas the other 9 patients had an on-track Hill-Sachs lesion.[3]

The average glenohumeral rotation at the starting position was 44° ± 5° (range, 39°-53°) of abduction, 46° ± 9° (range, 28°-52°) of extension, and 10° ± 8° (range, –3° to 18°) of external rotation. The mean arc of glenohumeral external rotation in the abducted shoulder position was 70° ± 8° (range, 60°-85°) in the intact shoulders and 72° ± 8° (range, 62°-87°) in the affected shoulders. At the starting position of 0° of shoulder abduction–external rotation, the humeral head center was located an average of 0.6 ± 1.7 mm posterior, 0.1 ± 1.2 mm superior, and 24.0 ± 1.5 mm lateral to the origin of the glenoid coordinate system in the intact shoulders, whereas it was located an average of 0.4 ± 1.8 mm anterior, 0.6 ± 1.7 mm inferior, and 24.7 ± 1.7 mm lateral to the glenoid origin in the affected shoulders.

On the intact side, the humeral head center translated posteriorly, inferiorly, and medially during glenohumeral external rotation with the shoulder in the abducted position. Posterior translation was significant at 40° (2.1 mm posterior, $P = .008$), 60° (2.8 mm posterior, $P < .001$), and maximum external rotation (3.4 mm posterior, $P < .001$). Inferior translation was significant at 60° (1.2 mm inferior, $P < .001$) and maximum external rotation (1.7 mm inferior, $P < .001$), and significant medial translation was shown at 40° (23.4 mm lateral, $P = .005$), 60° (23.1 mm lateral, $P < .001$), and maximum external rotation (22.9 mm lateral, $P < .001$). On the other hand, the affected shoulder showed significant inferior translation of the humeral head at 60° (1.7 mm inferior, $P < .001$) and maximum external rotation (2.1 mm inferior, $P < .001$) but not in the anteroposterior and mediolateral directions.

At the starting position, the 3D position of the humeral head center was not different between intact and affected shoulders in 3 directions. Compared with the contralateral side, however, the affected shoulder showed significantly less posterior translation (1.4 mm with $P = .028$ at 20°, 2.0 mm with $P = .009$ at 40°, 2.1 mm with $P = .017$ at 60°, and 2.6 mm with $P = .013$ at maximum external rotation) (Fig. 4), greater inferior translation (0.8 mm with $P = .037$ at 20°, 0.6 mm with $P = .047$ at 40°, and 0.4 mm with $P = .047$ at maximum external rotation) (Fig. 5), and less medial translation (0.7 mm with $P = .037$ at 20°, 1.2 mm with $P = .009$ at 40°, 1.1 mm with $P = .013$ at 60°, and 1.2 mm with $P = .007$ at maximum external rotation) (Fig. 6) of the humeral head during shoulder abduction–external rotation.

## Discussion

This study quantitatively evaluated 3D translation of the humeral head during active shoulder abduction and external rotation using 4D CT. The findings showed that the humeral head center normally translated posteriorly, inferiorly, and medially during active abduction–external rotation and that shoulders with glenohumeral instability showed decreased posterior, increased inferior, and decreased medial translation of the humeral head compared with the intact side. Patients with anterior glenohumeral instability felt discomfort and anxiety about dislocation with the shoulder in the abducted–externally rotated position.[18] These kinematic changes of the glenohumeral joint might cause the instability felt by the patients.

Because past studies of glenohumeral translation were 2-dimensional analyses with the glenohumeral joint in a static position,[4,10,13,16,19,24,34] 3D glenohumeral kinematics has not been clarified. Recently developed multidetector CT scanners with wide CT gantries can take multiple scans in 1 second, enabling 4D CT analyses of joint motion. Several studies have used 4D CT to assess the sternoclavicular joint,[11] acromioclavicular joint,[1] scapulothoracic joint,[2] wrist,[6] and knee.[7] Using this technology, our study quantitatively evaluated 3D translation of the humeral head during active external rotation with the shoulder abducted in cases with and without glenohumeral instability. In our intact shoulders, the humeral head translated posteriorly during active abduction–external rotation, and our results were consistent with those of past 2-dimensional analyses.[4,13,16] The humeral head translated posteriorly even in shoulders with anterior glenohumeral instability, but its posterior translation was significantly smaller than that on the intact side, similarly to past reports.[13,34] In addition to posterior translation, this 3D study showed that abnormal translation of the humeral head occurs in the superoinferior and mediolateral directions in unstable shoulders.

The inferior glenohumeral ligament, which originates from the inferior margin of the articular surface and around the anatomic neck of the humerus[29] and inserts into the anteroinferior and posteroinferior portions of the glenoid,[14] restrains anterior and inferior translation of the humeral headin abduction and external rotation.[28,33] Most cases with glenohumeral instability are related to dysfunction of the inferior glenohumeral ligament, and lesions in the anteroinferior labral complex and dysfunction of the inferior glenohumeral ligament were found in all 10 patients in our study. In these cases, medial translation, in addition to posterior translation, of the humeral head was significantly smaller in the affected shoulder than in the intact shoulder. Our results indicate that the inferior glenohumeral ligament and anteroinferior labrum hold the humeral head posteriorly and superiorly and that they pull the head medially to prevent anterior dislocation of the shoulder when tightened in the externally rotated position. Thus, prevention of anterior, inferior, and lateral displacement of the humeral head would be needed for the treatment of recurrent glenohumeral instability.

This study had several limitations. The frequency of the 4D CT analysis was 5 frames per second. Although 4D

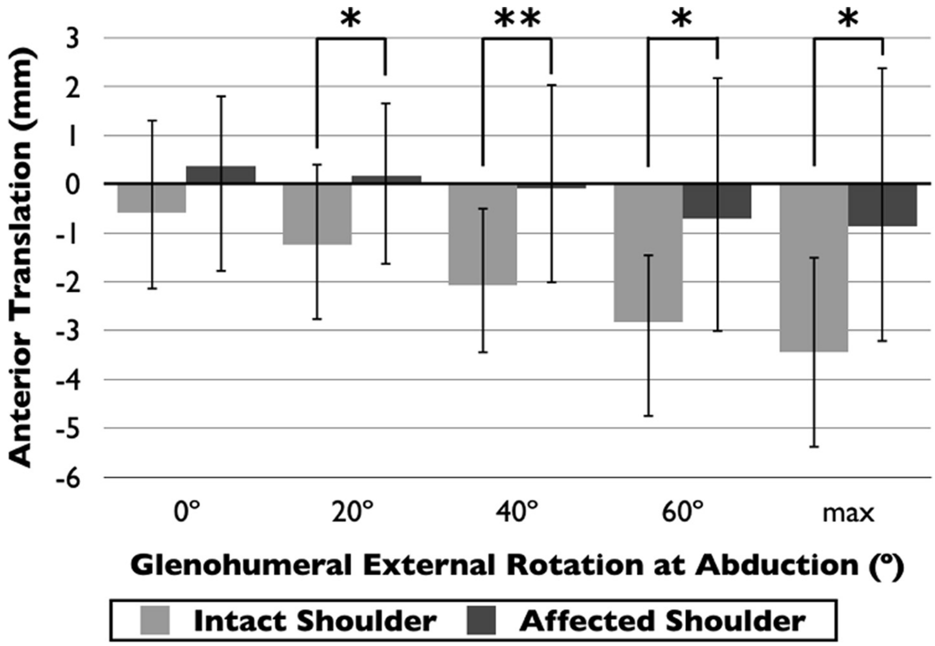


**Figure 4** Anterior translation of humeral head during glenohumeral external rotation with shoulder abducted in cases with unilateral glenohumeral instability. The affected shoulder shows significantly less posterior translation at 20° ($P = .028$), 40° ($P = .009$), 60° ($P = .017$), and maximum (*max*) glenohumeral external rotation ($P = .013$). *$P < .05$. **$P < .01$.

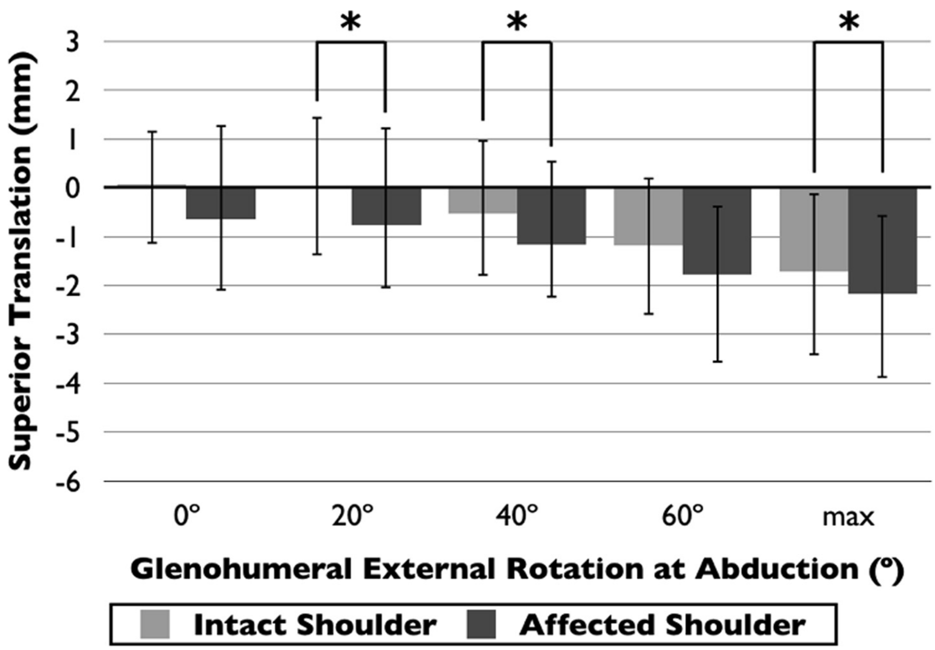


**Figure 5** Superior translation of humeral head during glenohumeral external rotation with shoulder abducted in cases with unilateral glenohumeral instability. The affected shoulder shows significantly greater inferior translation at 20° ($P = .037$), 40° ($P = .047$), and maximum (*max*) glenohumeral external rotation ($P = .047$). *$P < .05$.

CT analysis can directly evaluate joint kinematics during active motion, the frame frequency is lower than in past kinematic studies using an optical or electromagnetic tracking system.[9,15,17] Analysis using a surface registration technique is another possible limitation of this study. To reduce the difference in defining the glenoid and humeral coordinate systems between frames of the dynamic 4D CT scans and to exclude the influence of a glenoid bone defect, which is often found in shoulders with glenohumeral instability,[20,23,31] a surface-matching technique was used for the analysis. Although bilateral shoulders are reported to be highly symmetrical in shape and size[8,27,30] and CT surface matching is a reliable technique that has been used to evaluate deformities of the

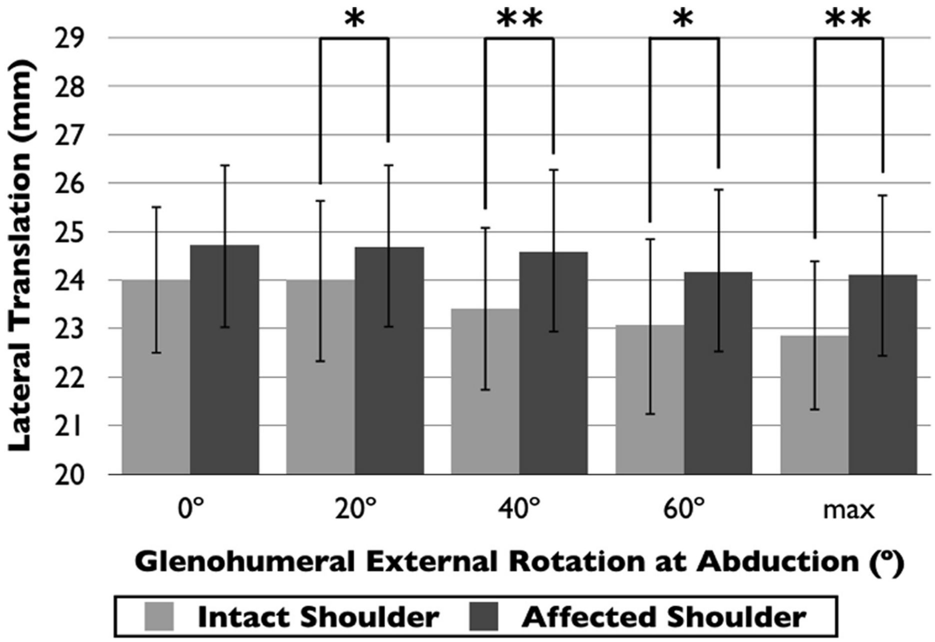


**Figure 6** Lateral translation of humeral head during glenohumeral external rotation with shoulder abducted in cases with unilateral glenohumeral instability. The affected shoulder shows significantly less medial translation at 20° ($P = .037$), 40° ($P = .009$), 60° ($P = .013$), and maximum (*max*) glenohumeral external rotation ($P = .007$). *$P < .05$. **$P < .01$.

upper extremity,[20,26,32] side-to-side differences in the glenoid shape and errors in surface matching might have affected the results of this study. Furthermore, the combination of dynamic 4D CT scans and CT surface matching is used to evaluate active joint motion,[25] but the technique has not been validated. Additional limitations were related to exposure to radiation. To reduce the patients' radiation exposure, each examination consisted of a single trial of shoulder abduction and external rotation for each shoulder, and the sample size was small (10 male patients). Although the differences in translation between the affected and intact sides were small, the values were comparable to those in past studies.[13,16,34] Fortunately, the shoulders consistently showed a characteristic pattern of glenohumeral kinematic changes, and these results appear to successfully represent glenohumeral kinematics of normal and unstable shoulders.

## Conclusion

Using 4D CT, we evaluated 3D translation of the humeral head in cases with unilateral glenohumeral instability. This study showed that the humeral head center translates posteriorly, inferiorly, and medially during active shoulder abduction–external rotation and that shoulders with glenohumeral instability showed decreased posterior, increased inferior, and decreased medial translation of the humeral head compared with the intact side.

## Disclaimer

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