■ SHOULDER & ELBOW

Glenohumeral joint kinematics during apprehension-relocation test in patients with anterior shoulder instability and glenoid bone loss

A RADIOSTEREOMETRIC ANALYSIS STUDY ON 20 PATIENTS

J. Olsen Kipp,
E. T. Petersen,
T. Falstie-Jensen,
J. Frost Teilmann,
A. Zejden,
R. Jellesen Åberg,
S. de Raedt,
T. M. Thillemann,
M. Stilling

From Aarhus University Hospital, Aarhus, Denmark

Aims

This study aimed to quantify the shoulder kinematics during an apprehension-relocation test in patients with anterior shoulder instability (ASI) and glenoid bone loss using the radiostereometric analysis (RSA) method. Kinematics were compared with the patient's contralateral healthy shoulder.

Methods

A total of 20 patients with ASI and > 10% glenoid bone loss and a healthy contralateral shoulder were included. RSA imaging of the patient's shoulders was performed during a repeated apprehension-relocation test. Bone volume models were generated from CT scans, marked with anatomical coordinate systems, and aligned with the digitally reconstructed bone projections on the RSA images. The glenohumeral joint (GHJ) kinematics were evaluated in the anteroposterior and superoinferior direction of: the humeral head centre location relative to the glenoid centre; and the humeral head contact point location on the glenoid.

Results

During the apprehension test, the centre of the humeral head was 1.0 mm (95% CI 0.0 to 2.0) more inferior on the glenoid for the ASI shoulder compared with the healthy shoulder. Furthermore, the contact point of the ASI shoulder was 1.4 mm (95% CI 0.3 to 2.5) more anterior and 2.0 mm (95% CI 0.8 to 3.1) more inferior on the glenoid compared with the healthy shoulder. The contact point of the ASI shoulder was 1.2 mm (95% CI 0.2 to 2.6) more anterior during the apprehension test compared to the relocation test.

Conclusion

The humeral head centre was located more inferior, and the GHJ contact point was located both more anterior and inferior during the apprehension test for the ASI shoulders than the healthy shoulders. Furthermore, the contact point displacement between the apprehension and relocation test revealed increased joint laxity for the ASI shoulder than the healthy shoulders. These results contribute to existing knowledge that ASI shoulders with glenoid bone loss may also suffer from inferior shoulder instability.

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Correspondence should be sent to J. Olsen Kipp; email: Josephine.olsen@clin.au.dk

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Introduction

Patients with anterior shoulder instability (ASI) typically feel apprehension or re-dislocate the shoulder during a forced abduction and external rotation of the humerus.[1] Anterior-directed stress to the humerus can further aggravate this. The apprehension feeling can typically be reproduced with an apprehension test of patients during which the shoulder is abducted, externally rotated, and stimulated with a posterior-to-anterior directed force on the proximal humerus.[1] The combination of abduction, external rotation, and anterior or posterior stress, as in the apprehension-relocation test, has only been examined in one study on patients after first-time dislocation.[2] Surprisingly, the authors found a posterior humeral head movement during the apprehension test for both the injured and the healthy shoulder.

Up to 50% of patients with ASI have glenoid bone loss, which has been shown to alter the glenohumeral joint (GHJ) kinematics in experimental studies.[3-5] However, to our knowledge, the GHJ kinematics in patients with ASI and glenoid bone loss have not been examined yet. Understanding the GHJ kinematics in patients with ASI and glenoid bone loss is a prerequisite for optimizing the surgical reconstruction and may be useful for identifying other risk factors for surgical failure and their effect on the GHJ with bone or soft-tissue procedures.[6]

Radiostereometric analysis (RSA) is a high-precision model-based method for measuring joint kinematics in six degrees of freedom.[7] RSA has previously been applied to the GHJ joint to evaluate impingement and rotator cuff lesions, but has also shown value in the assessment of joint stability in the knee and wrist during clinical stability tests.[8-11]

The aim of this study was to examine the GHJ kinematics using RSA during an apprehension-relocation test in patients with ASI and anterior glenoid bone loss, in comparison with the patient's healthy contralateral shoulder.

Methods

Patients aged between 18 and 40 years who were scheduled for an open Latarjet procedure due to ASI between February 2022 and February 2023 were included in this study. Indications for the Latarjet procedure were: CT of the glenoid showed > 10% glenoid width anterior bone loss using a best-fit circle method; and/or recurrent dislocations despite previous Bankart repair.[12] Exclusion criteria were patients with bilateral or multidirectional shoulder instability or alcohol/drug abuse.

The Danish Protection Agency (Journal no. 1-16-02-344-21, issued October 2021) and the Central Denmark Region Committees on Health Research Ethics (Journal no. 1-10-72-298-21, issued October 2021) approved the study. The study was carried out in accordance with the Declaration of Helsinki,[13] and written patient consent was obtained.

Sample size estimate. The sample size calculation in this study was based on a study by Mehl et al.[14] Under the assumption of finding a mean anterior humeral head translation difference between the intact and the injured shoulder of 3.6 mm, a SD of 3.9 mm, using a power of 0.8 and an α of 0.05 an estimated sample size of 14 patients was calculated. The sample size was increased to 20 patients to account for technical problems.

Patient characteristics. Patient demographics, including age, sex, arm dominance, side of the ASI shoulder, number of dislocations, and previous Bankart repair, were obtained at the time of inclusion. The patients were asked to complete the Western Ontario Shoulder Instability Index (WOSI) questionnaire, where 0 is the best and 2100 is the worst possible score.[15]

The cohort consisted of 20 patients. Table I presents patients' characteristics, mean glenoid bone loss, previous Bankart repair, and the WOSI score.

Test setup and image acquisition. An experienced shoulder surgeon performed an apprehension-relocation test twice on both the ASI and the healthy shoulder (Figure 1).[1] Static RSA images were captured at the end-range position of both tests.

Table I. Patient characteristics.

Characteristic	Total
Sex, n (%)	
Male	17 (85)
Female	3 (15)
Median age, yrs (IQR)	29 (25 to 37)
Shoulder, n (%)	
Left	12 (60)
Right	8 (40)
Dominant shoulder, n (%)	
Yes	9 (45)
Not	11 (55)
Mean glenoid bone loss, % (SD)	17.5 (5.3)
Previous Bankart repair, n (%)	16 (80)
Mean dislocations, n (95% CI)	11.1 (7.4 to 14.8)
Mean WOSI score (95% CI)	1,145 (1,026 to 1,265)

*2,100 is the worst possible score.
ASI, anterior shoulder instability; WOSI, Western Ontario Shoulder Instability Index.

The RSA recordings were performed with the digital Adora RSA system (NRT X-ray, Denmark), which has two ceiling-mounted x-ray tubes angled 40° on one another. The two digital Canon CXDI-70C image detectors (Canon, Japan) were positioned behind a carbon calibration box (Carbon box 24; Medis Specials, Netherlands). The exposure settings for the RSA recordings were 75 kV and 630 mA. The resolution of the images was 2,800 × 3,408 pixels (0.125 × 0.125 mm/pixel).

The patients' shoulders and elbows were CT scanned (SOMATOM Definition Flash; Siemens Healthcare, Germany). The exposure settings were 120 kV, 260 mAs, slice thickness 0.3, and pixel spacing 0.49 × 0.49 mm.

CT analysis. Patient-specific bone volume models were extracted from the CT scans by automated graph cut segmentation.[16,17] Glenoid bone loss can be evaluated with several methods; however, in this study, it was evaluated by applying a best-fit circle to the inferior part of the glenoid in the 2D CT images (Enterprise Imaging v. 8.1.2 SP7.10; Agfa-Gevaert NV, Belgium).[18] The bone loss was calculated as the percentage of the glenoid diameter in which bone was missing.

RSA. Model-based RSA (RSAcore, Netherlands) was used for calibration of the RSA recordings. Analysis of the recordings was performed using AutoRSA software (AutoRSA Research Group, Orthopaedic Research Unit, Denmark) utilizing a robust optimization scheme.[7] First, the CT-based bone volume models were manually initialized and subsequently matched to the recorded images in half resolution utilizing a global optimizer (controlled random search algorithm with local mutations) followed by a local optimizer (Nelder-Mead Simplex). Second, a refined local optimization in full resolution, excluding the models' surroundings, was performed.

Anatomical coordinate systems. Standardized anatomical coordinate systems were applied to the patient-specific bone models of the humerus and scapula by defining anatomical landmarks on the surface of the bone models (Figure 2). The anatomical landmarks on the humerus were applied as defined by the International Society of Biomechanics.[19] The humeral head centre was defined as the centre of a sphere fitted to the

a

b

Fig. 1

Test setup of the apprehension-relocation test. a) During the apprehension test, the shoulder is abducted and externally rotated, while a posterior-to-anterior directed force is applied to the proximal humerus. b) In the relocation test, an anterior-to-posterior pressure is applied to the proximal humerus. The test is positive if the patient feels apprehension during the apprehension test, followed by relief of the symptoms during the relocation test.

articulating part of the humeral head. On the scapula, a glenoid-oriented coordinate system was applied as described by Kolz et al[20] due to the more intuitive clinical interpretation.

Glenohumeral joint kinematics. The GHJ kinematics in six degrees of freedom were calculated by use of Cardan angles in the rotation sequence abduction-flexion-external rotation, to estimate the position and orientation of the humerus relative to the glenoid during the apprehension-relocation test. The three rotations evaluated were: abduction(+)/adduction(-); flexion(+)/extension(-); and external rotation(+)/internal rotation(-). The two translations evaluated were: anterior(+)/posterior(-); and superior(+)/inferior(-) (Figure 2).

The GHJ kinematics were measured for each recording with two different methods to evaluate the relative GHJ bone movement (centre method) and contact (contact point method). The first was the centre method, which involved calculating the translation of the humeral head centre relative to the glenoid centre in the anteroposterior and superoinferior directions. The humeral head centre and glenoid centre were defined as described in the local coordinate systems (Figure 3a). The second was the contact point method, which involved estimating the contact point using the weighted mean proximity of the humeral head surface and the glenoid surface (Figure 3b). Each glenoid surface mesh point within a 10 mm distance to the surface of the humerus was weighted based on its distance.[21] The distance was grouped in 1 mm increments, and for each increase, the weight factor was quadrupled; hence, the shorter the distance to the scapula, the greater the weight.

Statistical analysis. Descriptive analyses of patient demographics were performed (Stata v17.0; StataCorp, USA). Histograms and QQ-plots were used to check for the normal distribution of data. The repeatability of the kinematic RSA outcomes from the apprehension-relocation test was calculated to approximate the precision as the mean difference with SD and 95% limits of agreement (LoA). The mean value of the two recordings in each position was calculated and used in the kinematic outcomes. A paired *t*-test was used to compare the mean kinematic outcomes. The level of significance was set at $p < 0.05$ in all analyses.

Results

Repeatability of the apprehension-relocation test. The precise position of the GHJ was evaluated for healthy and ASI shoulders to compare the range of motion during the apprehension-relocation test. During the apprehension test, the healthy shoulder was a mean 10.4° (95% CI 3.6° to 17.2°) more abducted, 11.5° (95% CI 5.5° to 17.4°) more extended, and 6.0° (95% CI 0.6° to 11.3°) more externally rotated than the ASI shoulder. During the relocation test, the same pattern was seen; the healthy shoulder was a mean 8.0° (95% CI -0.4° to 16.3°) more abducted, 4.8° more extended (95% CI -0.1° to 9.8°), and 3.8° more externally rotated (95% CI -2.7° to 10.2°) compared to the ASI shoulder.

The repeatability estimates of the GHJ centre method showed mean (SD; 95% LoA) differences of 0.0 mm (1.0; -2.1 to 2.1) in the anteroposterior direction and 0.0 mm (0.5; -1.1 to 1.0) in the superoinferior direction. For the contact point method, the repeatability showed mean (SD, 95% LoA) differences of -0.1 mm (0.8; -1.8 to 1.6) in the anteroposterior direction and 0.0 mm (0.8; -1.7 to 1.7) in the superoinferior direction.

Apprehension-relocation test GHJ kinematics. Data on anteroposterior humeral head position are presented in Table II and Figure 4.

No statistically significant differences were found during the apprehension test, the relocation test, or between the

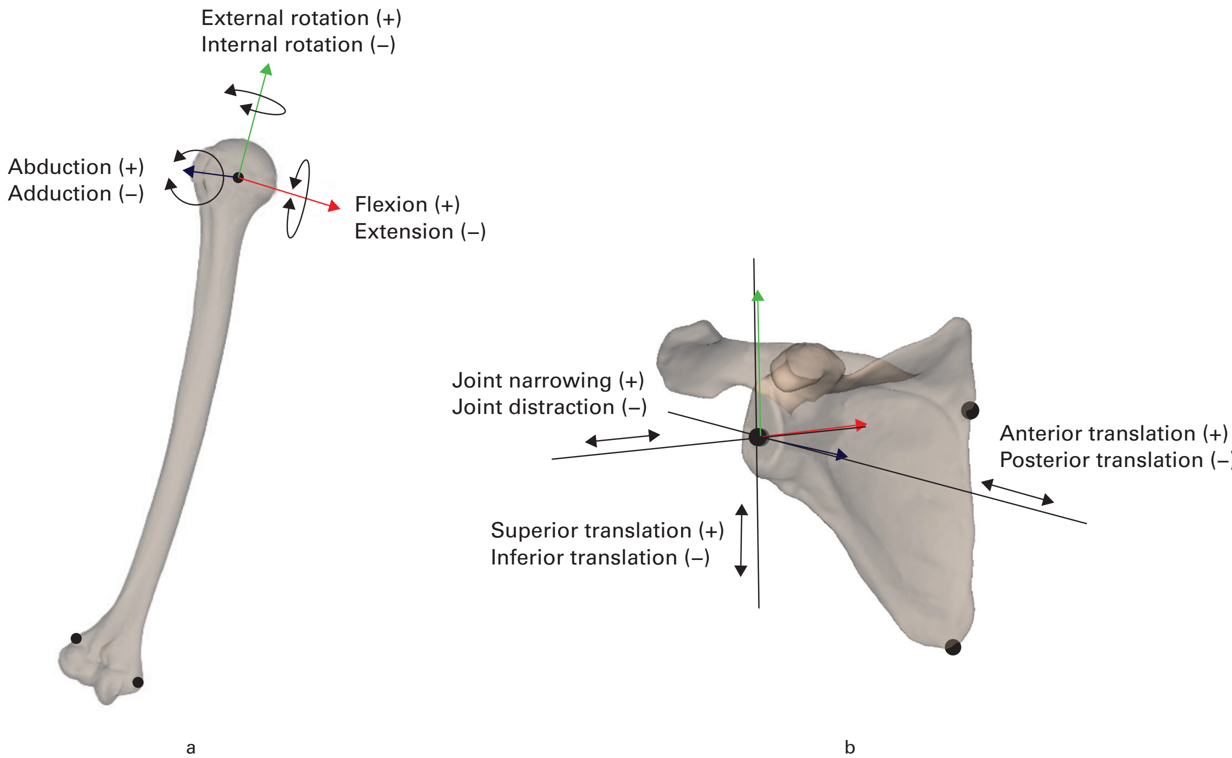

Fig. 2

Anatomical landmarks and anatomical coordinate systems with kinematics in six degrees of freedom. a) The superoinferior axis (green arrow) was defined by a line between the humeral centre and the midpoint between the medial and the lateral epicondyle. The medial-lateral axis (blue arrow) was defined by an orthogonal projection from the superoinferior axis towards the medial epicondyle. The anteroposterior (red arrow) axis was defined by the cross-product of the superoinferior axis, and the medial-lateral axis. b) The medial-lateral axis (red arrow) was defined as the line between the trigonum spinae and the glenoid centre, which was defined by a best-fit circle to the inferior part of the glenoid. The superoinferior axis (green arrow) was defined by an orthogonal projection from the medial-lateral axis towards the inferior angle of the scapula. The anteroposterior axis (blue arrow) was defined by the cross-product of the medial-lateral axis and superoinferior axis.

apprehension and relocation tests for the healthy and injured shoulder using the centre method.

Comparing the apprehension tests, the contact point of the ASI shoulder was located 1.4 mm (95% CI 0.3 to 2.5) more anterior than the healthy shoulder using the contact point method. The contact point of the ASI shoulder was 1.2 mm (95% CI 0.2 to 2.6) more anterior during the apprehension test than the ASI shoulder during the relocation test.

Data on the superoinferior humeral head position are presented in Table III and Figure 4.

Comparing the apprehension tests, the humeral head centre of the ASI shoulder was located 1.0 mm (95% CI 0.0 to 2.0) more inferior than that of the healthy shoulder using the centre method. No difference was found between the humeral head centre for the relocation tests of the healthy and injured shoulders or when comparing the humeral head centre during the apprehension and relocation test for the healthy and injured shoulders, respectively.

Comparing the apprehension tests, the contact point for the ASI shoulder was located 2.0 mm (95% CI 0.8 to 3.1) more inferior than that of the healthy shoulder using the contact point method. No difference was found between the contact point for the relocation tests of the healthy and injured shoulders or when comparing the contact point during the apprehension and relocation tests for the healthy and injured shoulders, respectively.

Discussion

This study is the first to describe the GHJ kinematics in patients with ASI and glenoid bone loss during an apprehension-relocation test. During the apprehension test, the humeral head centre was located more inferior, and the contact point was located more anterior and inferior for the ASI shoulder compared to the healthy shoulder. Only the ASI shoulder displayed an increased joint laxity with a contact point difference between the apprehension and relocation tests.

The humeral head translation calculated by the centre method in the anteroposterior direction during a modified apprehension test, with a static 3-pound load to the hand, has previously been examined by dynamic RSA in patients following a primary GHJ dislocation.[2] The humeral head centre exhibited a non-significant posterior movement at 0.246 mm (SD 0.206) for the injured shoulder and 0.270 mm (SD 0.429) for the healthy shoulder during the apprehension test relative to the glenoid centre. In the present study, the centre method likewise resulted in a posterior location of the humeral head during the apprehension test. However, we found that the translation of the

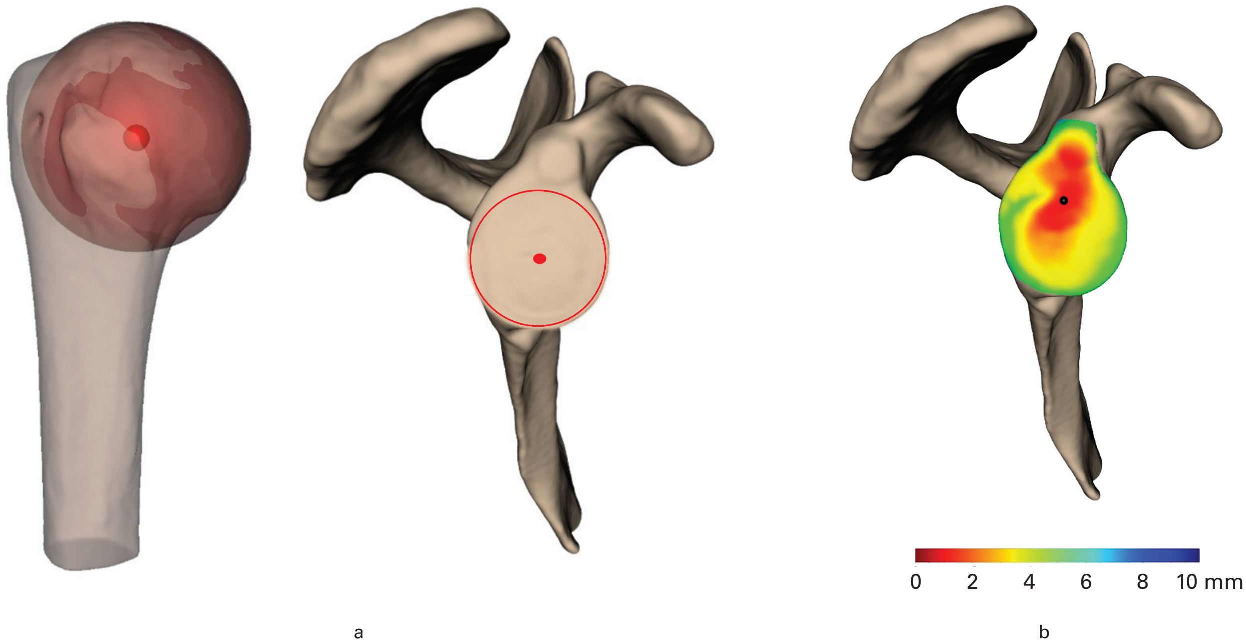

Fig. 3

Glenohumeral joint kinematic outcomes. a) The centre method defined by the best-fit sphere on the humerus and the best-fit circle on the glenoid. b) The contact point defined by the weighted average proximity of the humeral head surface and the glenoid surface (black dot).

humeral head centre from the relocation position to the apprehension position was anteriorly directed for the ASI shoulders and posteriorly directed for the healthy shoulders. Differences in study populations may explain this difference in our findings. Kim et al[2] evaluated patients after a first-time dislocation, who most likely had no glenoid bone loss compared to our cohort with a glenoid bone loss above 10%, which has previously been shown to increase the humeral head translation.[4,5] von Eisenhart-Rothe et al[22] used the humeral head centre method to assess the humeral head translation in an open MRI scanner on patients with ASI, and found a mean posterior humeral head translation of 0.6 mm (SD 1.3) at 30° of abduction. However, with the shoulder abducted to 90°, the humeral head exhibited a mean anterior humeral translation of 2.3 mm (SD 1.6) in neutral rotation and 2.8 mm (SD 1.8) in 90° external rotation. A possible explanation for the posterior location of the humeral head with ASI in all studies could be that the centre of the humeral head does not correspond to its actual rotational centre, or that the rotational centre is not fixed at variable abduction and rotation angles. Thus, due to some asymmetry of the humeral head, the humeral translation may be interfered with by the humeral orientation during abduction and external rotation.

Ultrasound has also been described as a method for evaluating anteroposterior humeral head translation, where the anterior part of the humeral head was used as a landmark.[23,24] Both studies found an increased anterior humeral head translation at 4.9 mm (SD 0.6) and 5.3 mm (SD 3.1) with the arm in a neutral position and a 90 N and 40 N anterior-directed load, respectively. The anterior humeral head translation increased with increasing abduction angles to 8.9 mm (SD 5.2) at 45° of abduction and 9.5 mm (SD 4.4) at 90° of abduction.[24] Compared to our results, these larger translations may be explained by the large 90 N anterior-directed load used in the study by Krarup et al,[23] and in the study by Inoue et al[24] due to examination of the patients under general anaesthesia and interscalene nerve block. Patients in general anaesthesia have previously been shown to have an increased humeral head translation compared to an awake state, which has been ascribed to a reflective muscle contraction of the rotator cuff to protect the shoulder from dislocating.[25] The challenge with the interference between humeral rotations and translations remains with the ultrasound method, since the humeral head is not symmetric. Furthermore, this method adds uncertainty by the difficulty of locating the same landmarks before and after loading and at follow-ups.

Another method is the contact point method, which can supplement the evaluation of the GHJ kinematics. This method has advantages by avoiding the interference between translations and rotations, since it describes the contact of the humerus on the glenoid. The contact point during an external shoulder rotation has only been examined in one other study, by Peltz et al,[26] of patients with ASI and minimal-to-no bone loss compared with healthy controls using RSA. Like our study, they found that the contact point of the ASI shoulder was more anteriorly located compared to the position in the healthy controls. Yet, they did not find statistically significant differences in anteroposterior translation range, superoinferior translation range, or superoinferior translation for the ASI and healthy patients. In our study, statistically significant differences in both the anteroposterior and the superoinferior contact points were found. Previous experimental studies have shown that the GHJ translations in both anterior and inferior directions in shoulders with significant bone loss (> 10%) are larger than those without

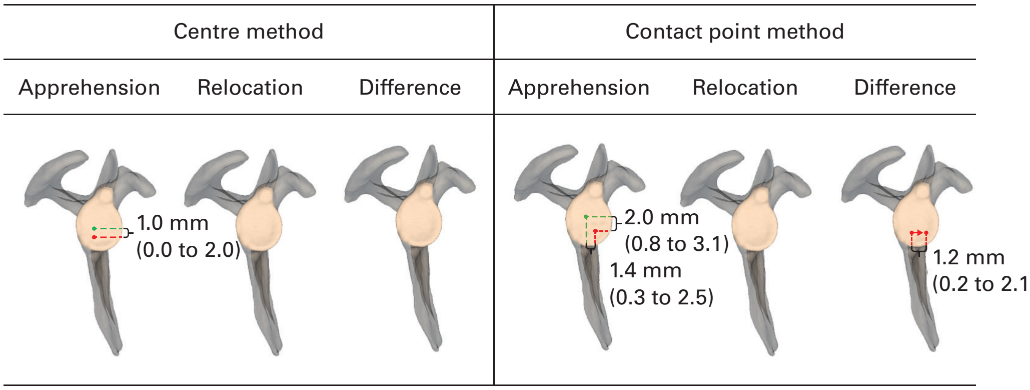

Fig. 4

Illustration of the significant kinematic outcomes measured with the centre and contact point methods in the anteroposterior and superoinferior directions. The red dot represents the location of the anterior shoulder instability shoulder, and the green dot represents the location of the healthy shoulder when significant differences are found. "Difference" represents the difference between the locations in the apprehension-relocation test.

Table II. Anteroposterior location of the humeral head centre and the contact point. Mean location of the centre of the humeral head and contact point in mm (95% CI) of the humeral head in the anterior(+)-posterior(-) direction relative to the centre of the glenoid.

Group	Centre method				Contact point method			
	Apprehension	Relocation	Difference	p-value*	Apprehension	Relocation	Difference	p-value*
ASI	-5.1 (-6.2 to -3.9)	-5.3 (-6.6 to -3.9)	0.2 (-0.5 to 1.0)	0.556	0.3 (-0.5 to 1.1)	-0.9 (-1.9 to 0.1)	1.2 (0.2 to 2.1)	0.017
Healthy	-5.5 (-6.7 to -4.3)	-4.8 (-6.1 to -3.5)	-0.7 (-1.8 to 0.5)	0.238	-1.1 (-2.0 to -0.2)	-1.1 (-1.9 to -0.3)	0.1 (-0.9 to 1.0)	0.899
Difference	-0.4 (-1.8 to 0.9)	0.4 (-1.4 to 2.3)	N/A		1.4 (0.3 to 2.5)	0.2 (-0.9 to 1.4)	N/A	
p-value*	0.510	0.612			0.018	0.667		

*Paired *t*-test.
ASI, anterior shoulder instability; N/A, not applicable.

Table III. Superoinferior location of the humeral head centre and the contact point. Mean location of the centre of the humeral head and contact point in mm (95% CI) of the humeral head in the superior(+)-inferior(-) direction relative to the centre of the glenoid.

Group	Centre method				Contact point method			
	Apprehension	Relocation	Difference	p-value*	Apprehension	Relocation	Difference	p-value*
ASI	6.7 (5.6 to 7.8)	7.0 (5.8 to 8.2)	0.2 (-0.5 to 1.0)	0.081	4.4 (2.8 to 6.0)	4.7 (3.1 to 6.3)	-0.3 (-1.0 to 0.3)	0.326
Healthy	7.7 (6.6 to 8.8)	7.8 (6.7 to 9.0)	0.7 (-1.8 to 0.5)	0.474	6.3 (4.8 to 7.9)	5.9 (4.7 to 7.1)	0.4 (-0.5 to 1.3)	0.335
Difference	1.0 (0.0 to 2.0)	0.8 (-0.3 to 1.9)	N/A		2.0 (0.8 to 3.1)	1.2 (-0.2 to 2.6)	N/A	
p-value*	0.045	0.133			0.002	0.082		

*Paired *t*-test.
ASI, anterior shoulder instability; N/A, not applicable.

glenoid bone loss.[4,5] The present study indicates that a glenoid bone loss affects the superoinferior contact point of the GHJ, and the absence of a glenoid bone loss in the study by Peltz et al[26] may explain the difference between our results. However, in the present study, we found no correlation between the size of the glenoid bone lesion and the translation length. This inferior translation in patients with ASI may, therefore, be just as important a component of ASI as the anterior translation, which may necessitate a higher focus in the future surgical treatment of patients with ASI.

The main strength of the present study is the precision of the RSA method for the evaluation of joint kinematics in six degrees of freedom.[27] Thus, we were able to evaluate the translation in both the anteroposterior and superoinferior directions and, at the same time, control the rotation of the humerus to ensure the GHJ orientation. The GHJ kinematics have been evaluated by two different kinematics methods, providing a more nuanced description of the GHJ. Furthermore, with this method, we were able to perform the apprehension-relocation test by applying stress to the proximal part of the humerus until each patient felt apprehension or relief, which is a more clinical approach than using a static standard load. The sample size calculation for this study was performed with an 80% power and 3.6 mm mean difference, yet we were able to identify significant differences that are much lower, underlining the certainty of differences in the present study. However, this study was not without limitations. We have used the patient's contralateral shoulder as a healthy control. This was done because we expected some interindividual differences of the GHJ, and by using the contralateral shoulder as a control, this was sought to be limited.[28] Another limitation of this study was the lack of cartilage on the bone model for the calculation of the GHJ contact point. However, Schleich et al[29] have shown a homogenous cartilage distribution of the humerus and glenoid, and therefore we assumed that the addition of the cartilage would not change the contact point critically. In this study, we investigated GHJ kinematics during an observer-applied apprehension-relocation test on awake patients using static RSA, and reflectory muscle guarding of the GHJ may have limited the measured translations. Furthermore, the slight delay in our recordings from when the observer reached the endpoint of apprehension to the completion of the RSA recording (approximately one second) may have affected the humeral head position on the RSA recordings, thus potentially decreasing the difference between the healthy and ASI shoulders. A dynamic recording and evaluation of the apprehension-relocation test could be warranted in the future to describe this potential mechanism.

In conclusion, with RSA as an objective and highly precise method, we have identified that the humeral head centre was located more inferiorly, and the GHJ contact point was located both more anterior and inferior during the apprehension test for the ASI shoulders compared to the patients' healthy contralateral shoulders. Furthermore, the contact point displacement between the apprehension and the relocation test revealed increased joint laxity for the ASI shoulder compared to the patients' healthy contralateral shoulders. An increased focus on inferior instability in addition to anterior instability in patients with > 10% bone loss after shoulder dislocation and ASI may improve future surgical treatments.

Take home message

- Patients with anterior shoulder instability and glenoid bone loss display an inferior displacement of the humeral head centre, and an anterior and inferior humeral head displacement of the contact point during the apprehension test.
- Our findings suggest that a comprehensive approach, focusing on both anterior and inferior instability, may enhance the effectiveness of future surgical treatments for patients with > 10% bone loss after shoulder dislocation and anterior shoulder instability.

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Author information:
J. Olsen Kipp, MD, Medical Doctor, Researcher, AutoRSA Research Group, Orthopaedic Research Unit, Aarhus University Hospital, Aarhus, Denmark; Department of Clinical Medicine, Aarhus University, Aarhus, Denmark.

E. T. Petersen, MSc, PhD, Researcher, Assistant Professor
M. Stilling, MD, PhD, Professor, Orthopedic Surgeon
AutoRSA Research Group, Orthopaedic Research Unit, Aarhus University Hospital, Aarhus, Denmark; Department of Clinical Medicine, Aarhus University, Aarhus, Denmark; Department of Orthopedic Surgery, Aarhus University Hospital, Aarhus, Denmark.

T. Falstie-Jensen, MD, PhD, Orthopaedic Surgeon, Department of Orthopedic Surgery, Aarhus University Hospital, Aarhus, Denmark.

J. Frost Teilmann, BSc, Medical Student, Researcher
S. de Raedt, MSc, PhD, Researcher
AutoRSA Research Group, Orthopaedic Research Unit, Aarhus University Hospital, Aarhus, Denmark.

A. Zejden, MD, Radiologist
R. Jellesen Åberg, MD, Radiologist
Department of Radiology, Aarhus University Hospital, Aarhus, Denmark.

T. M. Thillemann, MD, PhD, Orthopaedic Surgeon, Department of Clinical Medicine, Aarhus University, Aarhus, Denmark; Department of Orthopedic Surgery, Aarhus University Hospital, Aarhus, Denmark.

Author contributions:
J. Olsen Kipp: Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Writing – original draft.
E. T. Petersen: Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Writing – review & editing.
T. Falstie-Jensen: Data curation, Investigation, Resources, Writing – review & editing.
J. Frost Teilmann: Data curation, Investigation, Writing – review & editing.
A. Zejden: Investigation, Resources, Writing – review & editing.
R. Jellesen Åberg: Investigation, Resources, Writing – review & editing.
S. de Raedt: Methodology, Software.
T. M. Thillemann: Conceptualization, Data curation, Investigation, Resources, Supervision, Writing – review & editing.
M. Stilling: Conceptualization, Data curation, Funding acquisition, Methodology, Resources, Supervision, Validation, Writing – review & editing.

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