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Posterior shoulder stability depends on acromial anatomy: a cadaveric, biomechanical study

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Background: Failure rates in the management of recurrent posterior shoulder instability remain a concern. Cadaveric studies have established that posterior capsulolabral tears, glenoid retroversion, and posterior glenoid bone loss result in increased posterior humeral head translation in the setting of a posteriorly directed force. A high and flat acromion has recently been associated with posterior instability. Therefore, the purpose of this study was to evaluate a potential stabilizing effect of the acromion against posterior humeral head displacement.

Methods: Eight fresh-frozen human cadaveric shoulders were biomechanically tested in a shoulder simulator in the load-and-shift and Jerk test positions. Prior to testing, computed tomography scans were performed to measure native glenoid width, glenoid retroversion, posterior acromial coverage (PAC), sagittal acromial tilt (SAT), and posterior acromial height (PAH). Each specimen underwent 4 testing conditions using preplanned and 3D printed cutting and reduction guides: (1) Intact joint, native acromion; (2) Intact joint, *severe* acromial malalignment (SAT 69°, PAC 47°, PAH 26 mm); (3) Intact joint, *moderate* acromial malalignment (SAT 59°, PAC 57°, PAH 20 mm); (4) Intact joint, *corrected* acromial alignment (SAT 48°, PAC 70°, PAH 11 mm). The degree of acromial malalignment and acromial reorientation was chosen based on a previous study that defined acromial anatomy in patients with posterior instability. The humeral head was translated posteriorly until reaching either (1) a peak force of 150N or (2) a maximum posterior displacement of 50% of the glenoid width. Forces (N), displacement (mm), and acromiohumeral contact pressures (kPA) were simultaneously recorded.

Results: The force needed to displace the humeral head by 50% of the glenoid width decreased between 23% and 60% in moderate to severe acromial malalignment (high and flat acromion) and increased up to 122% following surgical correction of acromial alignment (low and steep acromion) when compared to the native condition. Correction of acromial alignment significantly increased stability compared to all other scenarios after ≥5% of displacement ($P < .05$ for all comparisons). Furthermore, it increased acromiohumeral contact pressures compared with severe malalignment in 30° flexion and with moderate and severe acromial malalignment in 60° flexion ($P < .05$ for all comparisons).

Investigation performed at the Department of Biomedical Engineering, University of Melbourne.
The University of Melbourne Office of Research Ethics and Integrity approved this study (ref # 2023-28236-47675-3).

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Conclusion: The acromion acts as a mechanical buttress to posterior humeral head displacement. Surgical correction of acromial malalignment cannot only effectively restore but increase glenohumeral joint stability. Future studies are needed to define the quantitative relevance of the different factors contributing to posterior shoulder instability and assist in defining the optimal amount of correction needed in an individual situation.

Level of evidence: Basic Science Study; Biomechanics

Keywords: Shoulder; instability; posterior instability; glenohumeral instability; acromion; acromial morphology

Posterior shoulder instability is becoming a better understood and increasingly recognized cause of shoulder pain and dysfunction.[20,28,33,41,42] Posterior capsulolabral tears, glenoid retroversion, and posterior glenoid bone loss are clinically and biomechanically proven factors that decrease resistance to humeral head displacement in response to a posteriorly directed force.[4,6,8,22,23,26,27] If conservative measures fail, surgical options include open or arthroscopic capsulolabral repair, glenoid osteotomies (±J-Graft) and posterior glenoid bone augmentation or combinations thereof. However, failure rates for these procedures are up to 35% for capsulolabral repairs,[3,9,15,30,39] up to 73% for open posterior bone block procedures[5,34] and up to 33% for glenoid osteotomies[14,18,35] at long-term follow-up.

Acromial morphology has recently been shown to be associated with posterior instability[1,24,25] and posterior glenoid bone loss.[21] In these shoulders, the acromion was situated high and oriented almost horizontally, implying poor posterior coverage of the humeral head. This concept has been tested in an experimental study of three-dimensionally (3D) printed surface models,[16] with the major limitation of lacking the stabilizing effect of the surrounding capsulolabral tissue and rotator cuff. There are, however, no *cadaveric* studies evaluating the relevance of the acromion as a restraint against posterior humeral head displacement.

It was therefore the purpose to assess (1) the stabilizing effect of the acromion and (2) acromiohumeral contact patterns under posterior humeral head displacement. It was hypothesized that acromial malalignment (ie a high and flat acromion) significantly reduces (1) resistance forces to posterior humeral head displacement and (2) acromiohumeral contact pressure and (3) that surgically corrected acromial alignment would restore stability.

Materials and methods

Ethical approval was obtained for this controlled laboratory study. A priori power analysis was conducted using G*Power (version 3.1.9.6; Erdfelder, Faul, & Buchner, 1996) for sample size estimation, based on data from a pilot study (n = 2). The effect size in the pilot study was 2,39 and considered to be small using Cohen's criteria. With a significance criterion of $\alpha = .05$ and power = .80, the minimum sample size needed with this effect size was 8 for a 2-way repeated-measures analysis of variance (ANOVA). Eight fresh-frozen cadaveric shoulders without any evidence of glenohumeral arthritis, rotator cuff tears, previous injuries or surgeries as determined by computed tomography (CT) and visual inspection were obtained from the University of Melbourne body donor program. The mean age of the specimens was 77.8 years (range: 68-94 years; 4 male and 4 female).

Further CT scan evaluation included native glenoid width, glenoid retroversion, posterior acromial coverage (PAC), sagittal acromial tilt (SAT), and posterior acromial height (PAH) (Fig. 1).

Testing conditions and planning of acromial malalignment

The definition of moderate or severe acromial malalignment was based on a previous study which defined acromial anatomy in patients with posterior instability on 3D surface models of segmented CT scans.[1] Moderate acromial malalignment was matched to mean values of SAT (59°), PAC (57°), and PAH (20 mm) which have been observed in patients with dynamic posterior instability,[1] while severe acromial malalignment was defined as the mean values plus one standard deviation (SD) of SAT (69°), PAC (47°), and PAH (26 mm), which is still within the observed range of these patients. For a corrected acromial alignment, the mean values minus one SD of SAT (48°), PAC (70°), and PAH (11 mm) of healthy controls without shoulder instability were chosen (Fig. 2).

Each of the specimens underwent the following testing in chronological order:

1. Intact joint, native acromion (mean (SD); SAT 58.6° (10.2), PAC 63.6° (7.3), PAH 18.9 mm (5.2), Table I).
2. Intact joint, *severe* acromial malalignment (SAT 69°, PAC 47°, PAH 26 mm)
3. Intact joint, *moderate* acromial malalignment (SAT 59°, PAC 57°, PAH 20 mm)
4. Intact joint, *corrected* acromial alignment (SAT 48°, PAC 70°, PAH 11 mm)

Semi-automatic segmentation was performed with 3D Slicer (version 5.6.0, https://www.slicer.org/) and segmented CT scans were imported into CASPA (Computer Assisted Surgery Planning Software; Balgrist Campus, Zurich, Switzerland) for the measurement of all values and planning of acromial osteotomies and orientation for the above-described scenarios (B.S.). A vertical acromial osteotomy was simulated 10 mm medial to the glenoid. The acromion of each specimen was converted into a moderate and severe malalignment and a corrected alignment scenario based on the predefined SAT, PAC, and PAH values for each condition. Cutting and reduction guides were planned with CASPA and manufactured using a 3D printer (Selective Laser Sintering;

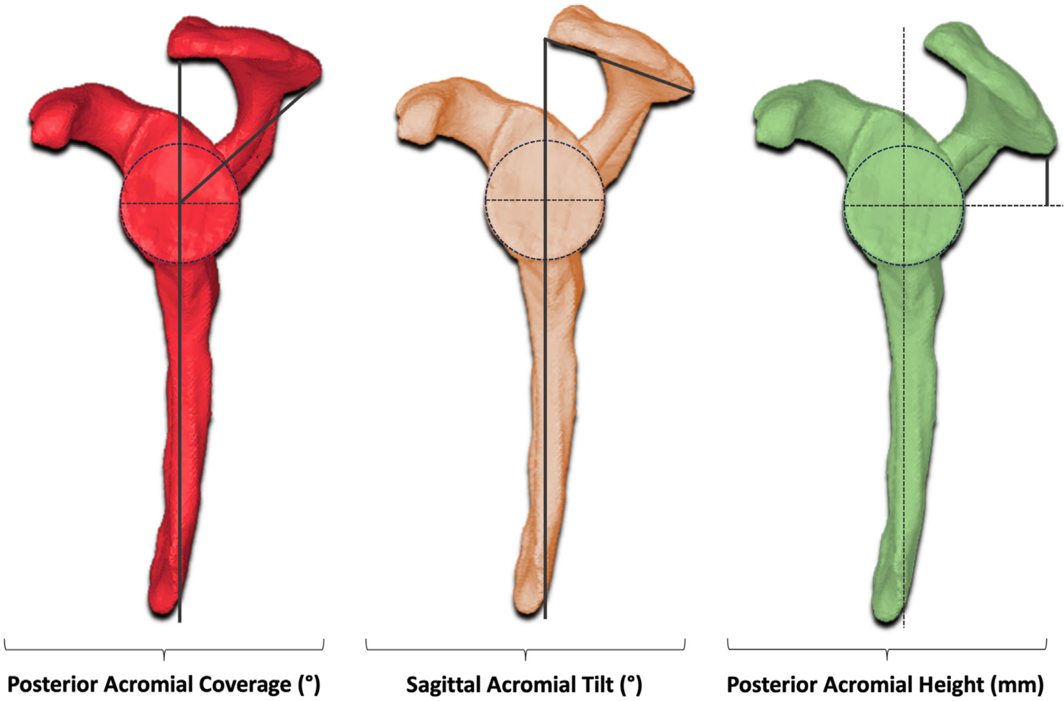

Figure 1 Shows how acromial alignment was measured on segmented 3D models. The vertical *dark gray lines* correspond to the scapular plane. *Bold lines* correspond to specific measurements. *3D*, three-dimensional.

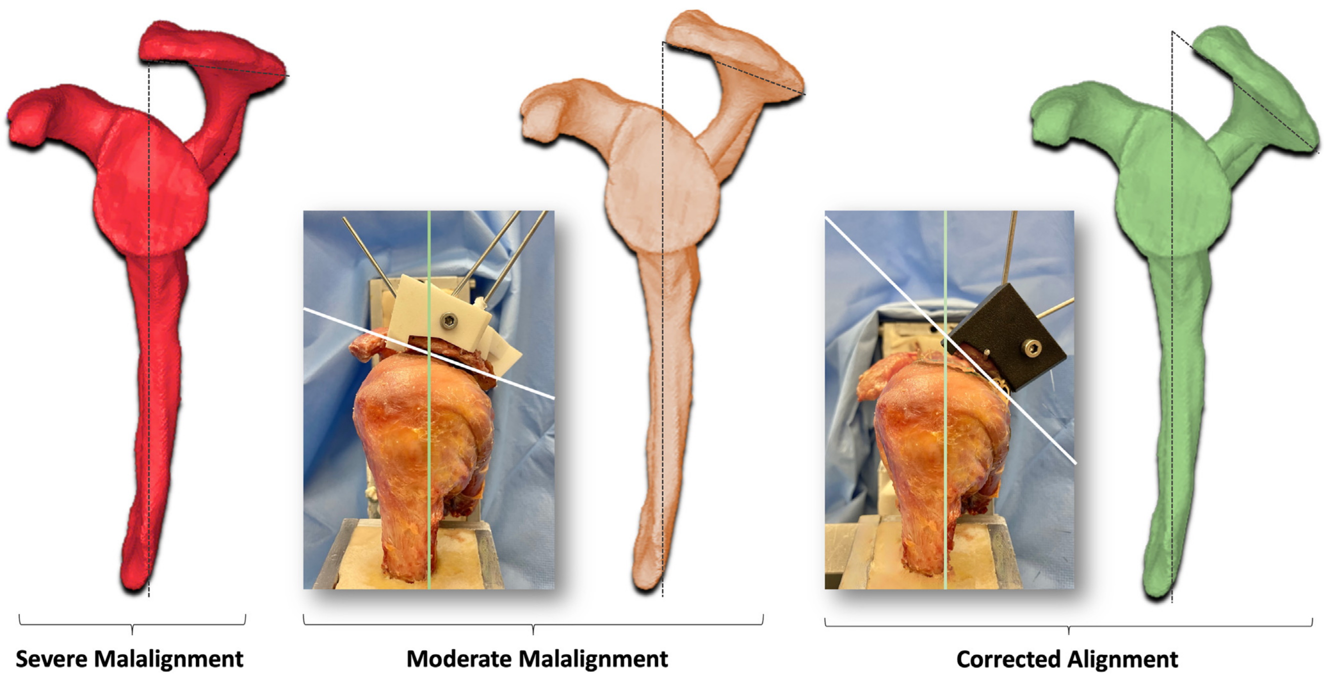

Figure 2 Illustration of the anatomical differences among the 3 surgically achieved conditions. The *black dotted lines*, superimposed on the 3D models, show the orientation of the scapula and the undersurface of the acromion. In the 2 photos, the *green line* indicates the orientation of the scapula, whereas the *white line* indicates the undersurface of the acromion. *3D*, three-dimensional.

Table I Specimen characteristics

Specimen	Gender	Age	Glenoid version (°)	Glenoid width (mm)	PAC (°)	PAH (°)	SAT (°)
1	M	94	−3,0	23	61.0	19.9	53.8
2	M	68	−2,7	31	61.0	**24.5**	**69.0**
3	F	68	−2,8	24	57.1	**22.8**	**69.1**
4	F	74	−2,2	21	63.1	16.9	50.5
5	F	79	−1,4	25	77.6	8.5	41.1
6	M	78	−5,2	30	69.2	18.3	54.3
7	M	79	−1,3	24	65.2	16.7	58.2
8	F	82	−5,8	25	**54.4**	**23.5**	**72.6**

PAC, posterior acromial coverage; *SAT*, sagittal acromial tilt; *PAH*, posterior acromial height; *SD*, standard deviation; *CT*, computed tomography. Bold values were considered malaligned as they do not lie within the mean ± SD of the healthy control cohort based on a previous study that defined acromial anatomy in patients with posterior instability on 3D surface models of segmented CT scans.[1]

FORMIGA P 110 VelocisEOS GmbH, Krailling, Germany) with Fine Polyamide (Nylon) 12 PA2200.

Specimen preparation and setup

All specimens were thawed for 24 hours at room temperature prior to testing. Specimens were kept moist with phosphate-buffered saline to prevent dehydration during specimen preparation and testing. One fellowship-trained shoulder surgeon performed all surgeries (B.H.). Scapula and humerus were dissected free from surrounding soft tissue, including the clavicle. The scapular spine was exposed by elevating the supraspinatus and infraspinatus muscles. The rotator cuff muscles, and their tendinous attachments were preserved, so was the capsuloligamentous complex of the glenohumeral joint. The rotator interval was vented. The humeral shafts were osteotomized 15 cm distal to the most superior portion of the humeral head (Fig. 3, *A*). Both, the scapulae and humeri were potted with polymethylmethacrylate in custom fixtures. Prior to potting, the exposed bony ends were transfixed with multiple bicortical screws to increase rotational stability at the bone-potting interface. The scapula was potted in a box shaped fixture. The scapular plane was aligned parallel to the lateral borders of the fixture and the glenoid face parallel to the floor of the fixture (ie 0° of glenoid version)[6,40] (Fig. 3, *B* and *C*). This was reliably achieved through the placement of a 3D-printed *cutting* guide on the scapular spine. K-wires that indicated the scapular and glenoid plane were placed through pre-defined holes through that guide. The same guide was also used to osteotomize each scapular spine after testing of the native specimen in the predefined planes using a 1-mm thick and 20-mm wide sawblade.

Creation of acromial malalignment and correction

After the osteotomy, the *reduction* guides were placed on the specimen (Figs. 2 and 3, *D*). Those consisted of an anterolateral and posteromedial part, which were the same for every scenario. The third and middle part was interchangeable and different for each surgical condition. It consisted of (1) a moderate malalignment block, (2) a severe malalignment block, and (3) a corrected alignment block (Fig. 3, *D*). The reduction guides were used to reduce and hold the lateral acromial fragment in the predefined position during testing which ensured rigid fixation of the acromion following osteotomy (Fig. 3, *D*). The guide blocks were designed to hook onto the bone at specific points, interlock with each other, and be compressed with a screw and nut. Additional stabilization was performed with K-wires (Figs. 2 and 3, *D*).

Stability testing

The specimens were mounted onto a custom-built shoulder-testing system (Figs. 4 and 5, *B*). The scapular box was fixed on a horizontal linear bearing translator and lever arm system on top of 2 translation plates. These plates permitted mediolateral and superoinferior translations. The humerus was mounted to the upper crosshead of the Instron testing machine (8874; Instron Corp., Norwood, MA, USA) equipped with a 6-axis force-torque sensor (K6D68, ME-Meßsysteme GmbH, Hennigsdorf, Germany). Tests were performed in 2 different positions to simulate (1) the posterior load-and-shift test and (2) the Jerk test. The load-and-shift test was defined as neutral adduction, 30° of glenohumeral flexion and 45° of internal rotation and is a position in which most of the stability is being provided by the glenohumeral articulation rather than ligamentous and tendinous structures.[26,27] The Jerk test is a position which is classically understood to produce posterior instability and was defined as neutral adduction, 60° of glenohumeral flexion, and, to simplify the setup, 45° of internal rotation instead of the typically described 60° of internal rotation.[19,38] A compressive load of 50N was applied perpendicular to the glenoid through the horizontal linear bearing translator, which allowed the humeral head to preliminarily self-center within the glenoid concavity.[6,36,40] Definitive positioning within the center of the glenoid concavity was defined as the position in which the anteroposterior forces recorded by the Instron summed to 0 N[27]. This position was defined as the reference-neutral position[6,26,29] and represented the starting point for each of the testing conditions. After defining the starting position, superoinferior translation of the scapula was restricted by blocking the respective translation plate. The humeral head was then translated in the posterior direction at a rate of 10 mm/min.[10] Two endpoints were defined, at which each of the testing cycles were stopped: (1) a peak force of 150N or (2) a maximum posterior displacement of 50% of the glenoid width. These endpoints were defined based on preliminary testing and to prevent dislocation of the joint, which could have resulted in capsulolabral damage. Forces (N) and displacement (mm) observed during testing were recorded.

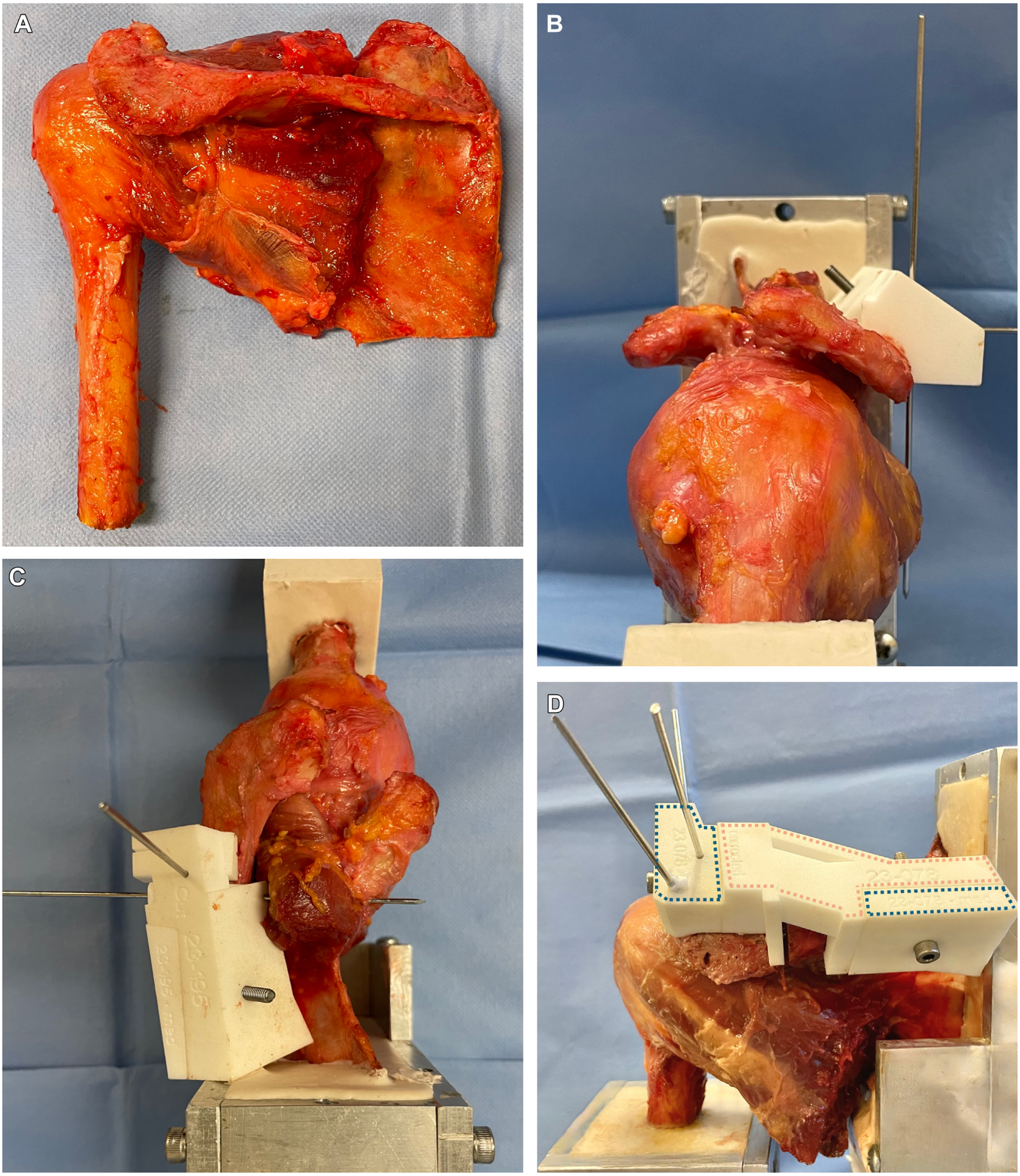

Figure 3 Illustration of the surgical steps. (**A**) Preparation of the specimen. (**B** and **C**) Application of personalized, 3D printed, *cutting guide* with K-wires that indicate scapular (**B**) and glenoid (**C**) orientation to facilitate reliable and reproducible potting in the desired position. Alignment of the scapula and the glenoid during potting was verified via the alignment between the 2 K-wires and the customized fixture. (**D**) Application of reduction guide. The posteromedial (*dotted blue lines*) and anterolateral parts (*dotted blue lines*) were the same for every scenario. The middle part (*dotted orange lines*) was interchangeable. With the connection of the anterolateral and posteromedial parts, the desired position of the acromion was achieved, and the osteotomy was held in place. *3D*, three-dimensional.

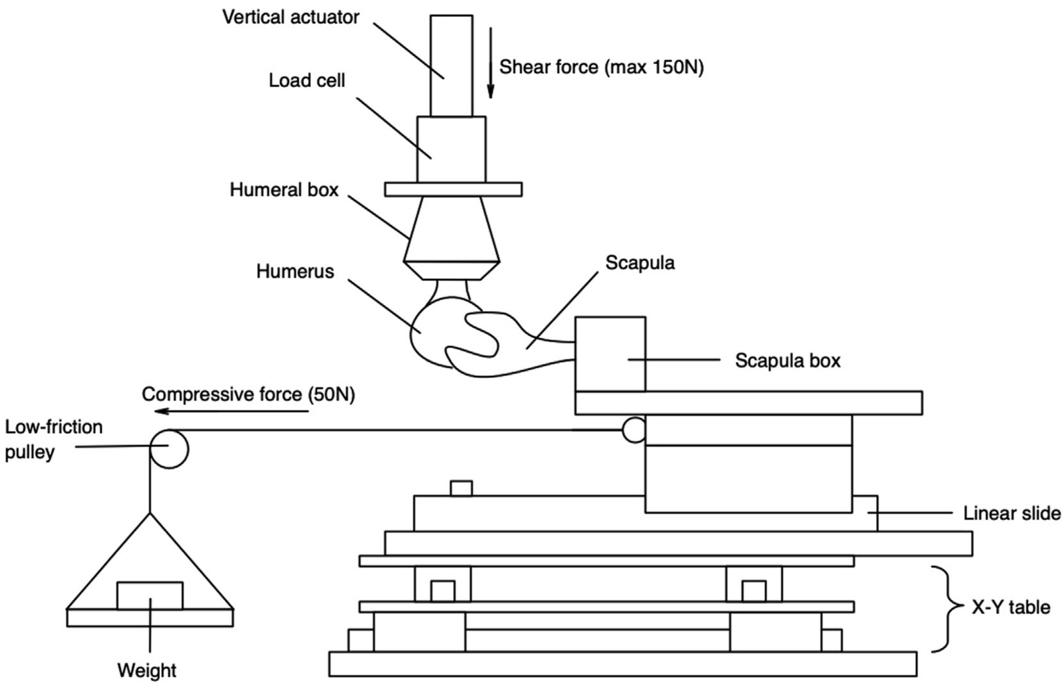

Figure 4 Illustration of the custom-made shoulder simulator. Arrows point into the direction of posterior directed force (max. 150N) and compressive force (50N) generated by a static weight via a lever arm. Anteroposterior displacement was generated by the vertical actuator. The linear slide allowed for mediolateral translation whereas the XY table allowed for superoinferior translation.

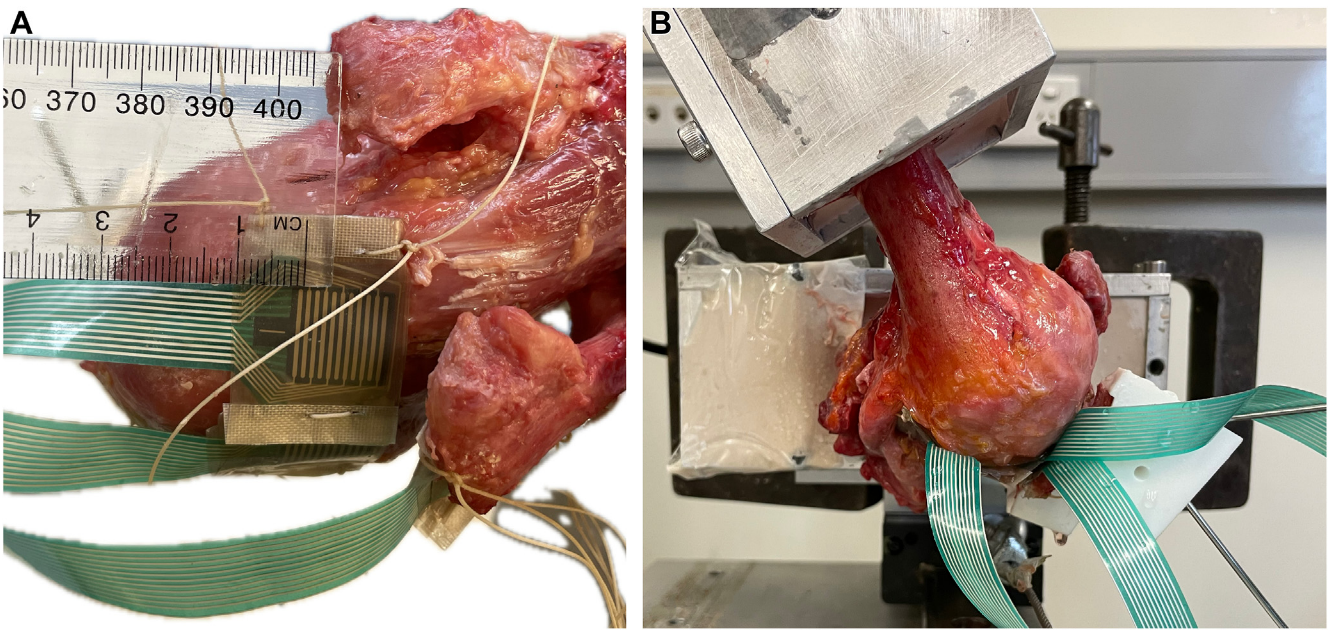

Figure 5 (**A**) Position of the 3 Tekscan sensors and fixation technique. (**B**) Mounted specimen in the testing apparatus.

Acromiohumeral contact patterns and average contact pressure

During testing, acromiohumeral contact patterns and average contact pressure were simultaneously measured using dynamic pressure-sensitive pads that were 0.102 mm thick with a 14 × 14–mm sensel matrix and a resolution density of 62 sensels/cm^2 (Sensor No. 6900; Tekscan). Each sensor was precalibrated according to the manufacturer's guidelines. One sensor was positioned on the undersurface of the acromion aligned with the posterolateral edge, a second sensor was placed just superior to the junction of supraspinatus and infraspinatus on top of supraspinatus tendon, 3 cm medial to the insertion, and a third sensor was placed just inferior to that junction on top of the infraspinatus tendon (Fig. 5, *A*). Positions of sensors were marked and secured with sutures to ensure correct positioning throughout testing.[6,13,29] The same force-controlled protocol with a posteriorly directed force of 150N was used for analyzing average acromiohumeral contact pressures (kPA).

To normalize data to specimen size, and specifically account for differences in glenoid size, displacement (mm) was reported as a percentage of individual glenoid width. All tests were performed in the 2 positions and for each of the 4 testing conditions described above. Testing was repeated 3 times per condition and mean values were used for analysis. After all testing conditions had been completed, the rotator cuff of each specimen was reflected and the capsule incised at its lateral insertion to inspect the posterior labrum and verify its integrity. In none of the specimens was any macroscopic damage to the labrum or capsuloligamentous attachments observed.

Scapular anatomy of native specimens

Mean native glenoid width was 25.4 mm (21-31 mm), glenoid retroversion was 3.1° (1.3-5.8°), SAT was 58.6° (41.1-72.6°), PAC was 63.6° (54.4-77.6°), and PAH was 18.9 mm (8.5-24.5 mm). Three shoulders had ≥2 acromial parameters outside of one SD of the mean of healthy shoulders.[1] Their acromial anatomy resembled that of the moderate malalignment condition chosen for this study. The remaining 5 shoulders had no acromial malalignment (Table I). Differences between the 5 "normal" native and 3 "moderately malaligned" native specimens were further analyzed descriptively in the results section (*printed in cursive*, Fig. 8). The entire remaining data contain the data of all 8 native shoulders.

Statistical analysis

Data normality was assessed with the Shapiro–Wilk test. Statistical analysis of force-displacement data was performed using a 2-way repeated measures ANOVA. Analysis of acromiohumeral contact patterns was performed using a one-way repeated ANOVA. Since the assumption of sphericity was not met, the Greenhouse-Geisser correction was applied to adjust the degrees of freedom for the F-tests accordingly. Posthoc Tukey's Test was performed to adjust for multiple comparisons.

For each condition in every specimen, a polynomial curve was fitted through all measurements up to the maximum force of 150N. Since in certain cases posterior displacement had to be stopped before reaching 50% of glenoid width (because the maximum of 150N was reached and to avoid destruction of soft tissue and/or fracture of the acromion), the dataset was inhomogeneous. To prevent bias associated with ignoring missing datapoints and to be able to statistically compare conditions that reached the maximum force with conditions that reached the maximum displacement, curve extrapolation was performed to complete the dataset.

Absolute values (mean ± SD) for all measurements as well as mean differences and 95% confidence intervals for comparisons can be found in Supplementary Tables S1-S4 in the Appendix. All statistical tests were conducted using an alpha level of 0.05. Data analysis was performed with GraphPad Prism (version 10.0.3; GraphPad Software, Inc, La Jolla, CA, USA).

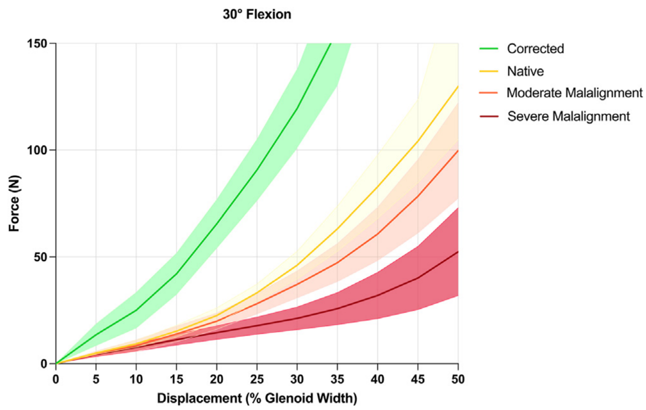

Figure 6 Force-displacement curves for all tested conditions in 30° of glenohumeral flexion. Whereas the corrected condition reached the force limit of 150N after approximately 34% of displacement, the 3 other conditions reached 50% of displacement at varying lower levels of force.

Results

Stability testing

In 30° and 60° of glenohumeral flexion, stability decreased significantly with increasing acromial malalignment compared to the native condition after ≥30% of posterior humeral head displacement (Figs. 6-10 and Supplementary Tables S1 and S2). Correction of acromial alignment significantly increased stability compared to all other scenarios after ≥5% of displacement.

In 30° of flexion, on average, the native, moderate, and severe malalignment condition reached 50% of humeral displacement before 150N of shear force (native: 129.9 N ± 59; moderate: 99.8 N ± 52.9; severe: 52.4 N ± 48.7, $P < .05$ for all comparisons) (Figs. 6 and 7). *While the native specimens considered as* "normal" reached 147.6 N ± 56.7 at 50% displacement, the native specimens considered as "malaligned" reached 100.3 N ± 53.1 (Fig. 8). In contrast, the corrected acromial alignment condition reached the force limit at approximately 34% of posterior humeral head displacement and would have reached 288.3 N ± 149 at 50% displacement.

In 60° of flexion, the force limit was reached before 50% of displacement in all conditions (Fig. 9). A significantly

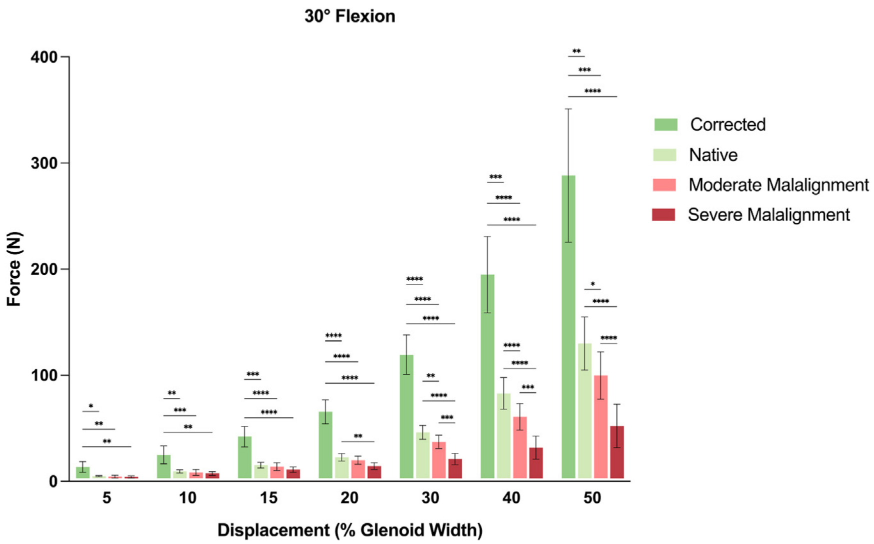

Figure 7 Statistical comparison of the force (N) that was reached, and would have been reached, per condition at different magnitudes of displacement (% glenoid width) at 30° of glenohumeral flexion. $*P < .05$; $**P < .01$; $***P < .001$; $****P < .0001$.

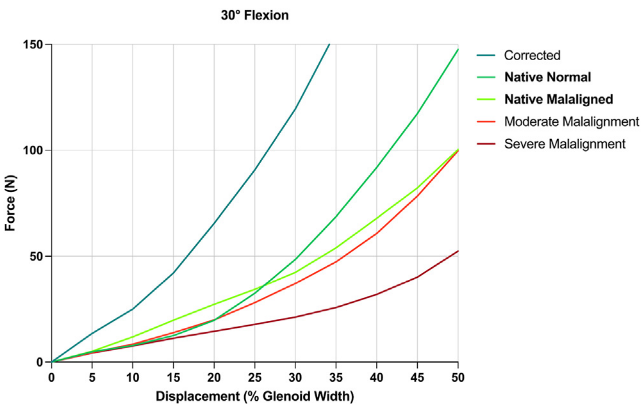

Figure 8 Differences in the mean force-displacement curves between native specimens that were considered normal (n = 5) and the ones that were considered malaligned (n = 3). The anatomy as well as the force-displacement curves of the 3 malaligned native shoulders were comparable with the surgically moderately malaligned condition.

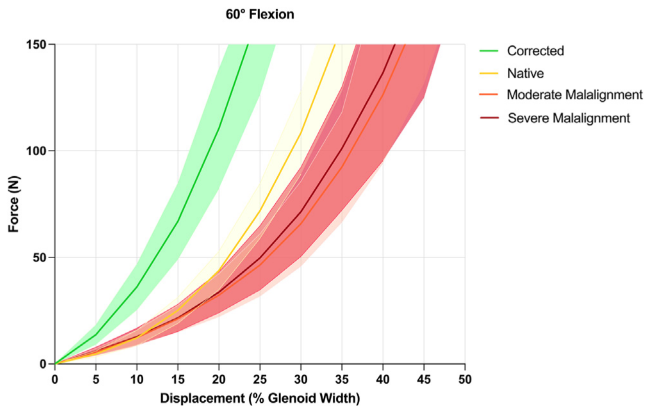

Figure 9 Force-displacement curves for all tested conditions in 60° of glenohumeral flexion. All conditions reached the force limit of 150N.

higher force was needed to translate the humeral head 30% of the glenoid width in the native condition (108.4 N ± 46.0) compared to the moderate (65.9 N ± 47.1, $P < .001$) and severe malalignment condition (71.3 N ± 49.6, $P < .05$) (Fig. 10). Similarly, significantly higher forces would have been needed in the corrected condition compared to all other conditions (234.3 N ± 129.1; $P < .001$ for all comparisons).

Acromiohumeral average contact pressure

At 30° of flexion, average contact pressure (Fig. 11, Supplementary Tables S3 and S4) on the infraspinatus was significantly higher for the corrected condition (173.2 kPa ± 177.8) compared to the moderate (39.5 kPa ± 62.0, $P < .01$) and severe malalignment (11.3 kPa ± 26.4, $P < .01$), whereas average contact pressure on the supraspinatus was comparable between the corrected condition (379.7 kPa ± 341.1) and the moderate malalignment (420.8 ± 334.7) but significantly higher in both conditions compared to the severe malalignment (150.5 kPa ± 148.5, $P < .05$ and $P < .01$, respectively). Similarly, average contact pressure on the undersurface of the acromion was comparable between the corrected condition (158.0 kPa ± 116) and the moderate malalignment (130.7 kPa ± 110.8) but significantly higher in both conditions compared to the severe malalignment (77.1 kPa ± 63.3; $P < .01$ and $P < .05$). Combined acromiohumeral contact pressures (rotator cuff + acromion) were significantly higher in the corrected (710.9 kPa ± 352.2) and moderate malalignment (591.1 kPa ± 360.6) condition than in the severe

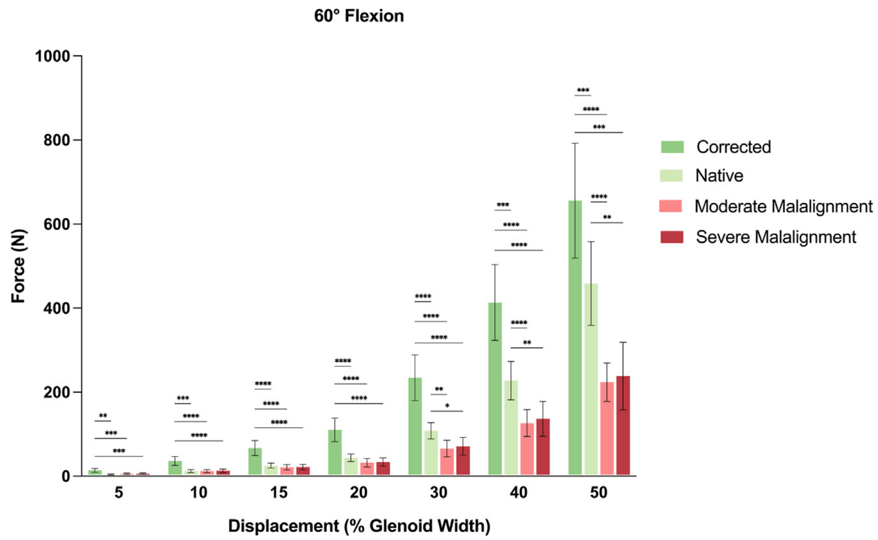

Figure 10 Statistical comparison of the force (N) that was reached, and would have been reached, per condition at different magnitudes of displacement (% glenoid width) at 60° of glenohumeral flexion. $*P < .05$; $**P < .01$; $***P < .001$; $****P < .0001$.

malalignment condition (238.9 kPa ± 168.3; $P < .0001$ and $P < .0001$).

At 60° of flexion, average contact pressure (Fig. 11, Supplementary Tables S3 and S4) on the infraspinatus was negligible throughout conditions whereas pressure on the supraspinatus was significantly higher for the corrected condition (256 kPa ± 147.1) compared to the moderate (148.3 kPa ± 169.2, $P < .001$) and severe malalignment (103.6 kPa ± 170.0 $P < .001$). Combined acromiohumeral average contact pressure was significantly higher for the corrected condition (404.8 kPa ± 276.0) compared to the moderate (303.0 kPa ± 265.7, $P < .01$) and severe malalignment (265.1 kPa ± 201.8, $P < .05$).

Discussion

The most important finding of this study is that the acromion is a relevant stabilizer against posterior displacement of the humeral head. Depending on its three-dimensional anatomic relationship with the glenoid, the force needed to displace the humeral head by 50% of the glenoid width decreased between 23% and 60% in moderate to severe acromial malalignment (high and flat acromion) and increased up to 122% following surgical correction of acromial alignment (low and steep acromion) when compared to the native condition. Surgical correction of acromial malalignment consistently improved posterior glenohumeral stability compared to all other conditions throughout the tested range of motion. Furthermore, acromiohumeral contact patterns differed in terms of pressure distribution between locations but also in terms of pressure intensity. A steeper acromion, providing more posterior humeral head coverage, exerted more pressure on the infraspinatus, especially in 30° of flexion, and combined acromiohumeral average contact pressures were lower, the flatter the acromion. In otherwise comparable and normal shoulders regarding glenoid morphology and posterior capsulolabral tissue, these results provide the first biomechanical evidence for the stabilizing role of the acromion and a possible and plausible explanation for the previously described association between a high and flat acromion and posterior shoulder instability.[1,24]

Understanding risk factors for primary as well as recurrent posterior shoulder instability is crucial, given that posterior shoulder instability is an increasingly recognized cause of shoulder pain that accounts for up to 18% of primary glenohumeral instability events[20] and up to 24% of surgical stabilizations[33] and that the failure rates for commonly used surgical treatment options lie between up to 35 and 73%[30,34] at long-term follow-up. These high failure rates might be explained by the fact, that acromion morphology has so far not been recognized as a relevant stabilizing element of the shoulder. Abnormal acromial anatomy, however, is a documented feature of shoulders with posterior instability: significant and consistent differences between the acromion of anteriorly unstable[24] as well as stable[1] shoulders and those with posterior instability have been identified. The acromion of the latter group is characterized by a high and flat acromial roof with less posterolateral coverage of the humeral head. Our data confirm that acromial anatomy is not only a descriptive factor of posterior shoulder instability but a relevant, mechanical buttress to posterior humeral head displacement.

The acromion appears to have a stabilizing effect after as little as 5% of posterior humeral head displacement. This effect increases exponentially with increasing displacement, so that, at least in our study design with a maximum of 150N posterior directed force, a subluxation of more than 35% in 30° flexion and more than 25% in 60° flexion

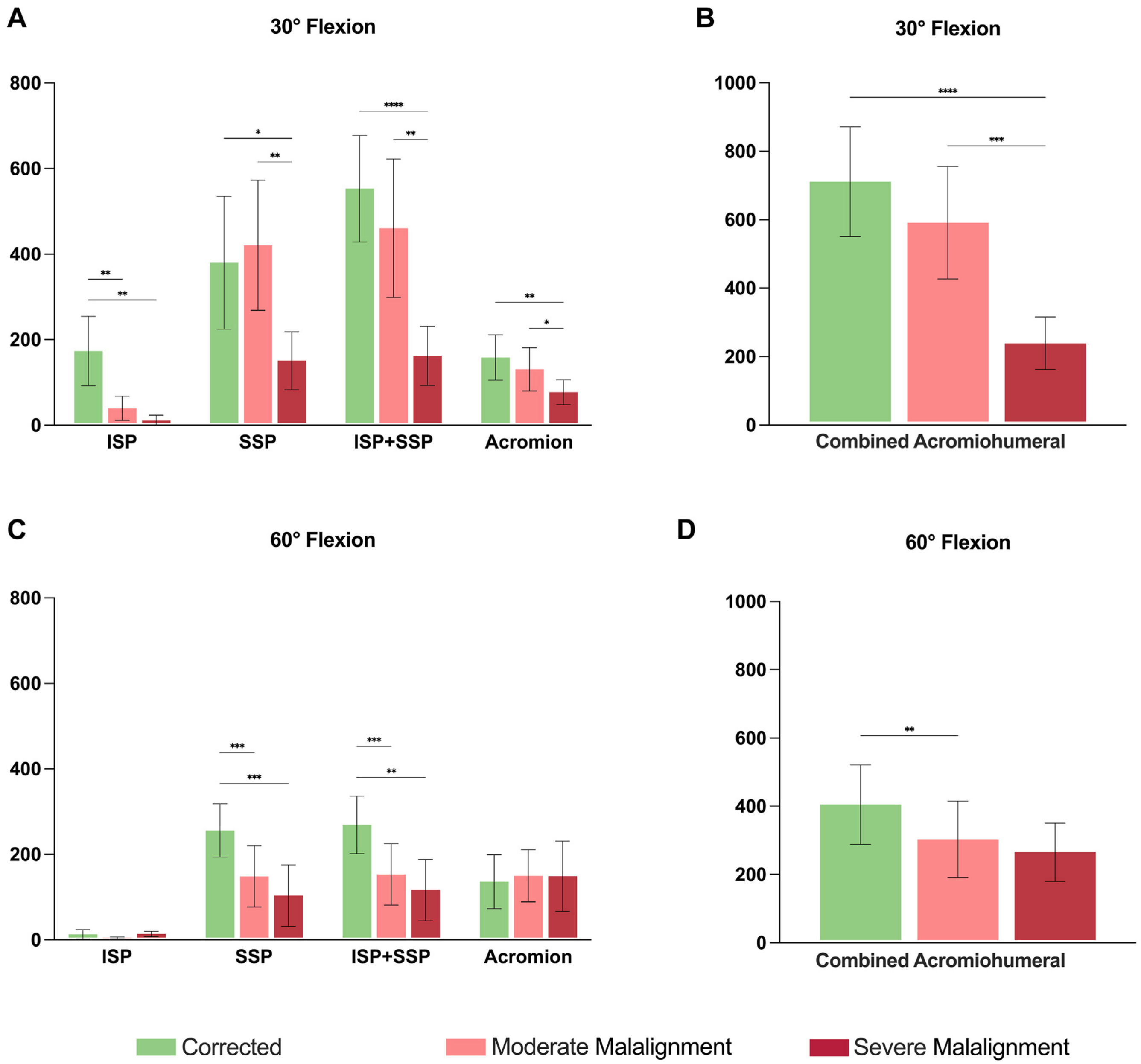

Figure 11 Isolated and combined acromiohumeral average contact pressures. Contact pressures (**A**) per Tekscan location and (**B**) combined acromiohumeral pressures (infraspinatus (ISP) + supraspinatus (SSP) + acromion) in 30° of glenohumeral flexion. Contact pressures (**C**) per Tekscan location and (**D**) combined acromiohumeral pressures in 60° of glenohumeral flexion. $*P < .05$; $**P < .01$; $***P < .001$; $****P < .0001$.

did not occur in the surgically corrected state to a theoretically ideal, three-dimensional position of the acromion.[1,16] While the full 50% of displacement of the humeral head was observed in all other conditions at 30° flexion, this was not the case at 60° flexion. We assume that this is because the posteroinferior capsulolabral complex is tense in this position and offers more stability than in 30° flexion. In the presence of a posterior capsulolabral lesion and associated insufficient soft tissue stabilization, the acromial morphology could therefore play an even more important role in 60°, the classic position of posterior instability, than suggested by the presented data.

Since the purpose of our study was to fundamentally investigate the effect of the acromion on posterior shoulder stability, other factors, with previously identified and undeniable relevance, such as the posterior soft tissue,[2,23,37,38] glenoid morphology[6-8,17] and bone loss,[4,6,8,17,22,26,36] were not investigated. Therefore, this study was executed with normal glenoid orientation without bone loss and an intact capsulolabral complex and represents the situation of a posterior instability with either a normal glenoid or a glenoid which is corrected in terms of version, inclination, and integrity. With the results of a previous study,[16] it cannot be assumed that correction of the acromion alone will have the same effects described in this study in situations of malalignment of the glenoid. Especially as the stability mediated by the acromion appears to be a continuum and varies depending on the individual anatomy. Although there are significant anatomical differences between healthy and unstable cohorts, individual cases of healthy shoulders can be close to the unstable values and vice versa, as the standard deviations of the 2 groups overlap slightly. The ideal amount of acromial correction is currently unknown. For this study, a slight amount of ‘‘overcorrection’’ was chosen based on our experience with other shoulder stabilization procedures (anterior and posterior bony augmentation, glenoid corrective osteotomies, etc.). The findings of the corrected alignment group invite to study whether correcting the acromion toward this anatomy might allow to compensate for minor malalignments of the glenoid. Obviously, the same question would then arise if a slight overcorrection of marked glenoid deformity would allow renouncing to surgery on the acromion.

Acromiohumeral contact pressures decreased with increasing malalignment. Similarly, this finding was more pronounced in 30° compared to 60° of flexion. This in turn can be explained by the fact that in 60° flexion more force was absorbed by the ligamentous stabilizers and the force limit was reached after less displacement, resulting in less contact between the rotator cuff and acromion. One might raise the concern that higher degrees of humeral head coverage and consecutively increased acromiohumeral contact pressures might be associated with non-physiological loading of the humeral head and infraspinatus and might even induce osteoarthritis or damage to the rotator cuff by virtue of imposing abnormal movement patterns and notably the physiological dorsocranial translation of the center of rotation during active movement. While we believe that the soft tissue ‘‘buffer’’ provided by the infraspinatus between the humeral head and the acromion mitigates potential issues with increased cartilage contact pressure of the humeral head, further research will be necessary to confirm this and exclude relevant impingement of the posterosuperior cuff. Another aspect that needs further research is potential changes in alignment, joint kinematics, and contact pressures within the acromioclavicular and sternoclavicular joint.

The data reported in the present study are in general agreement with a previous biomechanical study using 3D printed scapular models of healthy shoulders and shoulders that presented with static posterior subluxation, showing that a low and steep acromion is a relevant stabilizer against posterior displacement of the humeral head.[16] However, the transition from a clinical finding[1,24] and experimental conceptual validation[16] to clinical application is yet to be established. Although there are preliminary treatment proposals for acromial malalignment, the clinical relevance of this study is to increase awareness of the acromion in relation to posterior shoulder instability and ultimately to develop solutions to reduce the risk of treatment failure for posterior shoulder instability. In 1973, Scapinelli[31] proposed bone grafting of the posterolateral acromion and reported long term results in 2006 in 10 patients with posterior instability and reported no recurrence of instability with a mean follow-up of 9.6 years.[32] Gerber et al[11] described a surgical technique for restoring normal scapular anatomy to correct static, dynamic, and/or mixed posterior instabilities using 3D planned acromial and glenoid osteotomies. In this case report, static posterior instability was addressed to prevent development of early osteoarthritis in a relatively young patient. At 2 years, recentering of the humeral head in the glenoid is documented with a promising clinical outcome. Furthermore, encouraging preliminary results on the treatment of dynamic instabilities were presented recently.[12]

This study is not without limitations. Static and dynamic stabilizing factors cannot be fully replicated in a cadaveric study. Bone and soft tissue quality of the specimens used may differ from in vivo conditions, and the number of different testing conditions and testing cycles applied per specimen may have had a cumulative effect on tissue quality. Hence, a testing sequence was chosen in which the most malaligned acromion morphology was tested after the native condition, before all other surgical interventions, to ensure the most stable soft tissue situation and allow for more soft tissue laxity in the corrected acromion condition to minimize this bias. Furthermore, there were no exclusion criteria for this study regarding acromion morphology of the native specimens. For this reason, 3 cadavers had anatomies very similar to the moderate malalignment condition. This should be considered when interpreting the results. However, as the values for SAT, PAC, and PAH were within 2 SD of the mean of healthy shoulders, those specimens can still be considered normal which again highlights the concept of a ‘‘continuously mediated stability.’’ The anatomy for the corrected condition was deliberately chosen to be relatively steep in this study to ensure that any potential effect could be detected. A homogeneous, native cohort with acromial anatomy close to the mean values of a healthy cohort and a corrected condition that closely resembles native anatomy would be desirable for future studies. This would allow for a better comparison of those 2 conditions, especially in terms of restoration of stability and acromiohumeral contact pressures. Displacement data were collected by the Instron in a posterior direction only; possible superior or inferior displacement due to bending forces along the humerus when abutting the acromion were not collected and can therefore not be interpreted with the present setup. The Tekscan foils chosen for this study were small and neither covered the whole rotator cuff nor the entire undersurface of the acromion. Depending on the tested condition, the rotator cuff came into contact with the acromion at different points. The steeper the acromion, the more anterior the initial contact. Accordingly, the acromiohumeral pressures, especially the combined and acromion-specific pressures, as well as the pressure distribution, may have been underestimated by our study design, mainly regarding the corrected condition. Furthermore, planar Tekscan sensors are not ideally suited for measuring pressure between concave/convex surfaces, such as the humeral head and acromion undersurface, resulting in sensor kinking. To minimize this kinking phenomenon, phosphate-buffered saline was applied in between sensors before each test and to prevent sensor damage, sensors were replaced after a full testing cycle of each specimen. A final limitation concerns the extrapolation of data beyond the force limit of 150N. Extrapolation relies on the assumption that the patterns observed in the existing data set will continue beyond the known range. The data over 150N should therefore be viewed as a prediction only and interpreted cautiously.

Conclusion

The results of our study demonstrate that the acromion acts as a mechanical buttress to posterior humeral head displacement. Surgical correction of acromial malalignment cannot only effectively restore but increase posterior glenohumeral stability beyond that of the native shoulder. Future studies are needed to define the quantitative relevance of the different factors contributing to posterior shoulder instability and assist in defining the optimal amount of correction needed in an individual situation.

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Supplementary Data

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References

1. Beeler S, Leoty L, Hochreiter B, Carrillo F, Götschi T, Fischer T, et al. Similar scapular morphology in patients with dynamic and static posterior shoulder instability. JSES Int 2021;5:181-9. https://doi.org/10.1016/j.jseint.2020.11.003
2. Blasier RB, Soslowsky LJ, Malicky DM, Palmer ML. Posterior glenohumeral subluxation: active and passive stabilization in a biomechanical model. J Bone Joint Surg Am 1997;79:433-40.
3. Bradley JP, Baker CL, Kline AJ, Armfield DR, Chhabra A. Arthroscopic capsulolabral reconstruction for posterior instability of the shoulder. Am J Sports Med 2006;34:1061-71. https://doi.org/10.1177/0363546505285585
4. Bryce CD, Davison AC, Okita N, Lewis GS, Sharkey NA, Armstrong AD. A biomechanical study of posterior glenoid bone loss and humeral head translation. J Shoulder Elbow Surg 2010;19:994-1002. https://doi.org/10.1016/j.jse.2010.04.010
5. Cognetti DJ, Hughes JD, Kay J, Chasteen J, Fox MA, Hartzler RU, et al. Bone block augmentation of the posterior glenoid for recurrent posterior shoulder instability is associated with high rates of clinical failure: a systematic review. Arthroscopy 2022;38:551-63.e5. https://doi.org/10.1016/j.arthro.2021.07.018
6. Ernstbrunner L, Borbas P, Ker AM, Imhoff FB, Bachmann E, Snedeker JG, et al. Biomechanical analysis of posterior open-wedge osteotomy and glenoid concavity reconstruction using an implant-free, J-shaped iliac crest bone graft. Am J Sports Med 2022;50:3889-96. https://doi.org/10.1177/03635465221128918
7. Ernstbrunner L, Häller T, Waltenspül M, Wieser K, Gerber C. Posterior open-wedge osteotomy and glenoid concavity reconstruction using an implant-free, J-shaped iliac crest bone graft in atraumatic posterior instability with pathologic glenoid retroversion and dysplasia: a preliminary report. Clin Orthop Relat Res 2021;479:1995-2005. https://doi.org/10.1097/corr.0000000000001757
8. Ernstbrunner L, Loucas R, Ker A, Borbas P, Imhoff F, Hofstede S, et al. Biomechanics of posterior glenoid bone block procedures for posterior instability with and without correction of glenoid retroversion. J Shoulder Elbow Surg 2021;30:e444. https://doi.org/10.1016/j.jse.2021.03.065
9. Fuchs B, Jost B, Gerber C. Posterior-inferior capsular shift for the treatment of recurrent, voluntary posterior subluxation of the shoulder. J Bone Joint Surg Am 2000;82:16-25.
10. Galbraith JG, Huntington LS, Borbas P, Ackland DC, Tham SK, Ek ET. Biomechanical comparison of intramedullary screw fixation, dorsal plating and K-wire fixation for stable metacarpal shaft fractures. J Hand Surg Eur 2022;47:172-8. https://doi.org/10.1177/17531934211017705
11. Gerber C, Sigrist B, Hochreiter B. Correction of static posterior shoulder subluxation by restoring normal scapular anatomy using acromion and glenoid osteotomies: a case report. JBJS Case Connect 2023;13:e23.00060. https://doi.org/10.2106/jbjs.cc.23.00060
12. Gerber C, Sigrist B, Hochreiter B. EFORT 2024. The role of acromial anatomy and its correction for restoration of recalcitrant posterior shoulder instability. 2024. Available at: https://scientific.efort.org/site/programme/?1=1&sessiondetail=4773501&abstractdetail=152864&a=efort2024&trackid=0&i=. Accessed June 25, 2024.
13. Ghodadra N, Gupta A, Romeo AA, Bach BR, Verma N, Shewman E, et al. Normalization of glenohumeral articular contact pressures after Latarjet or iliac crest bone-grafting. J Bone Joint Surg Am 2010;92:1478-89. https://doi.org/10.2106/jbjs.i.00220
14. Hawkins RH. Glenoid osteotomy for recurrent posterior subluxation of the shoulder: assessment by computed axial tomography. J Shoulder Elbow Surg 1996;5:393-400.
15. Hines A, Cook JB, Shaha JS, Krul K, Shaha SH, Johnson J, et al. Glenoid bone loss in posterior shoulder instability: prevalence and outcomes in arthroscopic treatment. Am J Sports Med 2018;46:1053-7. https://doi.org/10.1177/0363546517750628
16. Hochreiter B, Beeler S, Hofstede S, Sigrist B, Snedeker JG, Gerber C. Posterior stability of the shoulder depends on acromial anatomy: a biomechanical study of 3D surface models. J Exp Orthop 2023;10:59. https://doi.org/10.1186/s40634-023-00623-x
17. Imhoff FB, Camenzind RS, Obopilwe E, Cote MP, Mehl J, Beitzel K, et al. Glenoid retroversion is an important factor for humeral head centration and the biomechanics of posterior shoulder stability. Knee Surg Sports Traumatol Arthrosc 2019;27:3952-61. https://doi.org/10.1007/s00167-019-05573-5

18. Inui H, Nobuhara K. Glenoid osteotomy for atraumatic posteroinferior shoulder instability associated with glenoid dysplasia. Bone Joint J 2018; 100-B:331-7. https://doi.org/10.1302/0301-620x.100b3.bjj-2017-1039.r1
19. Kim SH, Park JC, Park JS, Oh I. Painful Jerk test. Am J Sports Med 2004;32:1849-55. https://doi.org/10.1177/0363546504265263
20. Lanzi JT, Chandler PJ, Cameron KL, Bader JM, Owens BD. Epidemiology of posterior glenohumeral instability in a young athletic population. Am J Sports Med 2017;45:3315-21. https://doi.org/10.1177/0363546517725067
21. Livesey MG, Bedrin MD, Baird MD, Tran A, Weir TB, Hasan SA, et al. Acromion morphology is associated with glenoid bone loss in posterior glenohumeral instability. J Shoulder Elbow Surg 2023;32: 1850-6. https://doi.org/10.1016/j.jse.2023.03.005
22. Marcaccio SE, O'Donnel RM, Schilkowsky R, Owens MBD, Bokshan SL. Posterior glenoid osteotomy with capsulolabral repair improves resistance forces in a critical glenoid bone loss model. Orthop J Sports Med 2022;10:23259671221083580. https://doi.org/10.1177/23259671221083579
23. Mayer SW, Kraszewski AP, Skelton A, Kontaxis A, Warren R. What are the effects of capsular plication on translational laxity of the glenohumeral joint. Clin Orthop Relat Res 2018;476:1526-36. https://doi.org/10.1097/01.blo.0000534681.21276.14
24. Meyer DC, Ernstbrunner L, Boyce G, Imam MA, Nashar RE, Gerber C. Posterior acromial morphology is significantly associated with posterior shoulder instability. J Bone Joint Surg Am 2019;101: 1253-60. https://doi.org/10.2106/jbjs.18.00541
25. Meyer DC, Riedo S, Eckers F, Carpeggiani G, Jentzsch T, Gerber C. Small anteroposterior inclination of the acromion is a predictor for posterior glenohumeral erosion (B2 or C). J Shoulder Elbow Surg 2019;28:22-7. https://doi.org/10.1016/j.jse.2018.05.041
26. Nacca C, Gil JA, Badida R, Crisco JJ, Owens BD. Critical glenoid bone loss in posterior shoulder instability. Am J Sports Med 2018;46: 1058-63. https://doi.org/10.1177/0363546518758015
27. Nacca C, Gil JA, DeFroda SF, Badida R, Owens BD. Comparison of a distal tibial allograft and scapular spinal autograft for posterior shoulder instability with glenoid bone loss. Orthop J Sports Med 2018; 6:2325967118786697. https://doi.org/10.1177/2325967118786697
28. Owens BD, Duffey ML, Nelson BJ, DeBerardino TM, Taylor DC, Mountcastle SB. The incidence and characteristics of shoulder instability at the United States military academy. Am J Sports Med 2007; 35:1168-73. https://doi.org/10.1177/0363546506295179
29. Pauzenberger L, Dyrna F, Obopilwe E, Heuberer PR, Arciero RA, Anderl W, et al. Biomechanical evaluation of glenoid reconstruction with an implant-free J-bone graft for anterior glenoid bone loss. Am J Sports Med 2017;45:2849-57. https://doi.org/10.1177/0363546517716927
30. Rothrauff BB, Arner JW, Talentino SE, Bradley JP. Minimum 10-year clinical outcomes after arthroscopic capsulolabral repair for isolated posterior shoulder instability. Am J Sports Med 2023;51:1571-80. https://doi.org/10.1177/03635465231162271
31. Scapinelli R. [Surgical treatment of habitual posterior shoulder luxation]. Clin Ortop 1973;24:234-40. [Article in Italian].
32. Scapinelli R. Posterior addition acromioplasty in the treatment of recurrent posterior instability of the shoulder. J Shoulder Elbow Surg 2006;15:424-31. https://doi.org/10.1016/j.jse.2005.10.012
33. Song DJ, Cook JB, Krul KP, Bottoni CR, Rowles DJ, Shaha SH, et al. High frequency of posterior and combined shoulder instability in young active patients. J Shoulder Elbow Surg 2015;24:186-90. https://doi.org/10.1016/j.jse.2014.06.053
34. Villefort C, Stern C, Gerber C, Wyss S, Ernstbrunner L, Wieser K. Mid-term to long-term results of open posterior bone block grafting in recurrent posterior shoulder instability: a clinical and CT-based analysis. JSES Int 2023;7:211-7. https://doi.org/10.1016/j.jseint.2022.12.008
35. Waltenspül M, Häller T, Ernstbrunner L, Wyss S, Wieser K, Gerber C. Long-term results after posterior open glenoid wedge osteotomy for posterior shoulder instability associated with excessive glenoid retroversion. J Shoulder Elbow Surg 2022;31:81-9. https://doi.org/10.1016/j.jse.2021.05.028
36. Waltz RA, Brown J, Brady AW, Bartolomei C, Dornan GJ, Miles JW, et al. Biomechanical evaluation of posterior shoulder instability with a clinically relevant posterior glenoid bone loss model. Am J Sports Med 2023;51:2443-53. https://doi.org/10.1177/03635465231177957
37. Wellmann M, Blasig H, Bobrowitsch E, Kobbe P, Windhagen H, Petersen W, et al. The biomechanical effect of specific labral and capsular lesions on posterior shoulder instability. Arch Orthop Trauma Surg 2011;131:421-7. https://doi.org/10.1007/s00402-010-1232-y
38. Wellmann M, Bobrowitsch E, Khan N, Patzer T, Windhagen H, Petersen W, et al. Biomechanical effectiveness of an arthroscopic posterior Bankart repair versus an open bone block procedure for posterior shoulder instability. Am J Sports Med 2010;39:796-803. https://doi.org/10.1177/0363546510389991
39. Wolfe JA, Elsenbeck M, Nappo K, Christensen D, Waltz R, LeClere L, et al. Effect of posterior glenoid bone loss and retroversion on arthroscopic posterior glenohumeral stabilization. Am J Sports Med 2020;48:2621-7. https://doi.org/10.1177/0363546520946101
40. Yamamoto A, Massimini DF, DiStefano J, Higgins LD. Glenohumeral contact pressure with simulated anterior labral and osseous defects in cadaveric shoulders before and after soft tissue repair. Am J Sports Med 2014;42:1947-54. https://doi.org/10.1177/0363546514531905
41. Yow BG, Wade SM, Bedrin MD, Rue J-PH, LeClere LE. The incidence of posterior and combined AP shoulder instability treatment with surgical stabilization is higher in an active military population than in the general population: findings from the US naval academy. Clin Orthop Relat Res 2020;479:704-8. https://doi.org/10.1097/corr.0000000000001530
42. Zacchilli MA, Owens BD. Epidemiology of shoulder dislocations presenting to emergency departments in the United States. J Bone Joint Surg Am 2010;92:542-9. https://doi.org/10.2106/jbjs.i.00450