

Glenohumeral stability from concavity-compression: A quantitative analysis

Steven B. Lippitt, MD, J. Eric Vanderhooft, MD, Scott L. Harris, MS, John A. Sidles, PhD, Douglas T. Harryman II, MD, and Frederick A. Matsen III, MD, Seattle, Wash.

The purpose of this research was to determine the degree to which compression of the humeral head into the glenoid concavity stabilizes it against translating forces. Ten normal fresh-frozen cadaver glenohumeral joints in which the labrum was preserved were used. A compressive load of 50 N was applied to the humeral head in a direction perpendicular to the glenoid surface. Increasing tangential forces were then applied until the head dislocated over the glenoid lip. The tangential force at dislocation was examined for eight different directions, 45° apart around the glenoid. Concavity-compression stability was then examined for an increased compressive load of 100 N. Finally, the protocol with 50 and 100 N of compressive load was repeated after the glenoid labrum was excised. Concavity-compression of the humeral head into the glenoid is a most efficient stabilizing mechanism. With the labrum intact the humeral head resisted tangential forces of up to 60% of the compressive load. The degree of compression stabilization varied around the circumference of the glenoid with the greatest magnitude superiorly and inferiorly. This may be attributed to the greater glenoid depth in these directions. Resection of the glenoid labrum reduced the effectiveness of compression stabilization by approximately 20%. These results indicate that concavity-compression may be an important mechanism for providing stability in the mid-range of glenohumeral motion where the capsule and ligaments are lax. The effectiveness is enhanced by the presence of an intact glenoid labrum. (J SHOULDER ELBOW SURG 1993;2:27-35.)

The mechanisms by which the glenohumeral joint is stabilized in the mid-range of motion have not been well-defined. Traditionally, glenohumeral stability is thought to be provided by the ligaments and capsule. Although these structures are under tension at the extremes of motion, in the mid-range they are lax and cannot exert major stabilizing effects.

Among the possible mechanisms for providing stability in the mid-range of glenohumeral

motion, one of the more important may be the compression of the convex humeral head into the concave glenoid fossa. The specialized anatomy of the rotator cuff is ideally situated to provide a compressive load throughout the range of motion of the glenohumeral joint. The potential effectiveness of the concavity-compression mechanism is limited by the strength of the rotator cuff and other compressing muscles, as well as by the relatively small size of the glenoid fossa, which is only one fourth the size of the articular surface of the humeral head.

The purpose of this research was to determine the degree to which concavity compression can stabilize the humeral head against translating forces. Recognizing that the anatomy of the glenoid fossa changes around its circumference, we compared the effectiveness of concavity

From the Department of Orthopaedics, University of Washington, Seattle.

Reprint requests. Steven B. Lippitt, MD, Department of Orthopaedics, RK-10, University of Washington, Seattle, WA 98195.

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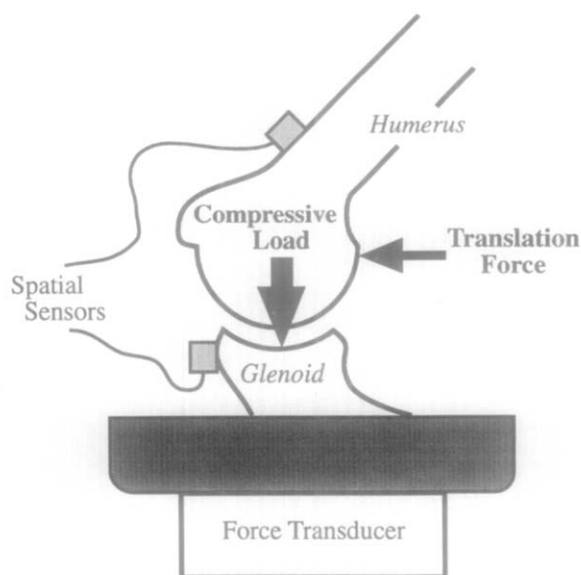


Figure 1 Progressively larger translating forces were applied manually to humeral head as it was compressed into glenoid concavity until humeral head dislocated. Magnitude and direction of these translating forces were measured by force transducer and spatial sensors.

compression for different directions of translating force.³ Finally, realizing that the glenoid labrum appears to contribute to the depth of the glenoid concavity, we compared the effectiveness of concavity compression before and after resection of the labrum.¹²

METHODS

We studied 10 normal fresh-frozen cadaver glenohumeral joints. The average age of the patients at death was 73 years (range 55 to 89 years). All included shoulder specimens had intact articular cartilage of the glenoid and humeral head and were free from tearing or gross degenerative changes in the glenoid labrum.

The specimens were prepared by sectioning the scapula from the thorax and dividing the humerus at mid-shaft. The muscles and tendons of the rotator cuff, biceps, and deltoid were resected. The glenohumeral joint capsule was dissected from its humeral insertion and was then resected just lateral to the glenoid labrum. The labral attachment to the glenoid rim was preserved.

The vertebral border of each scapula was

potted in a plastic container with plaster of Paris. This container was fixed rigidly to a vertically mounted force transducer (Astek Model, FS160A-600, Barry Wright Corporation, Watertown, Mass.) that had 6° of freedom so that the glenoid fossa was facing upward, parallel to the floor. Once calibrated, the Astek transducer allowed measurement of both the magnitude and direction of manually applied forces. By convention the superior aspect of the glenoid was designated as 0° and the anterior aspect as 90°.

To maximize the congruity of the glenohumeral joint, the center of the humeral head articular surface was aligned symmetrically to the center of the glenoid fossa. This roughly corresponded to placing the humerus in neutral flexion with 45° of abduction and 35° of external rotation. A 5/8 inch wooden dowel was placed transversely through the humeral head (above the articular surface) to establish an antero-posterior alignment guide. Weights were attached to this dowel to compress the humeral head into the glenoid fossa. Two additional 1/4 inch dowels were placed at right angles into the humeral head to establish superoinferior and medial-lateral alignment guides. The starting position of the humeral head in the glenoid for each experiment was achieved by compressing the head into the glenoid and then aligning the dowel guides to the superior, anterior, and vertical axes of the glenoid. The sensors of a spatial digitizer (Polhemus, Navigational Sciences, Colchester, Vt.) with 6° of freedom were attached to the humeral shaft and scapula to allow measurement of the translation and rotation of the humeral head with respect to the glenoid fossa. This system has been shown to be accurate to within 1 mm of translation and 1° of angular motion.⁹⁻¹¹ Data were recorded during the trials by computer (Orthokine software, University of Washington, Seattle, Wash.).

With essentially no load applied, the humeral head was translated along the 0° axis from the center of the glenoid to the superior glenoid edge and was next translated along the 180° axis from the center to the inferior glenoid edge. The process was then repeated in the 45° to 225° plane, the 90° to 270° plane, and the 135° to 315° plane. The effective concavity of the glenoid fossa was demonstrated by measuring the

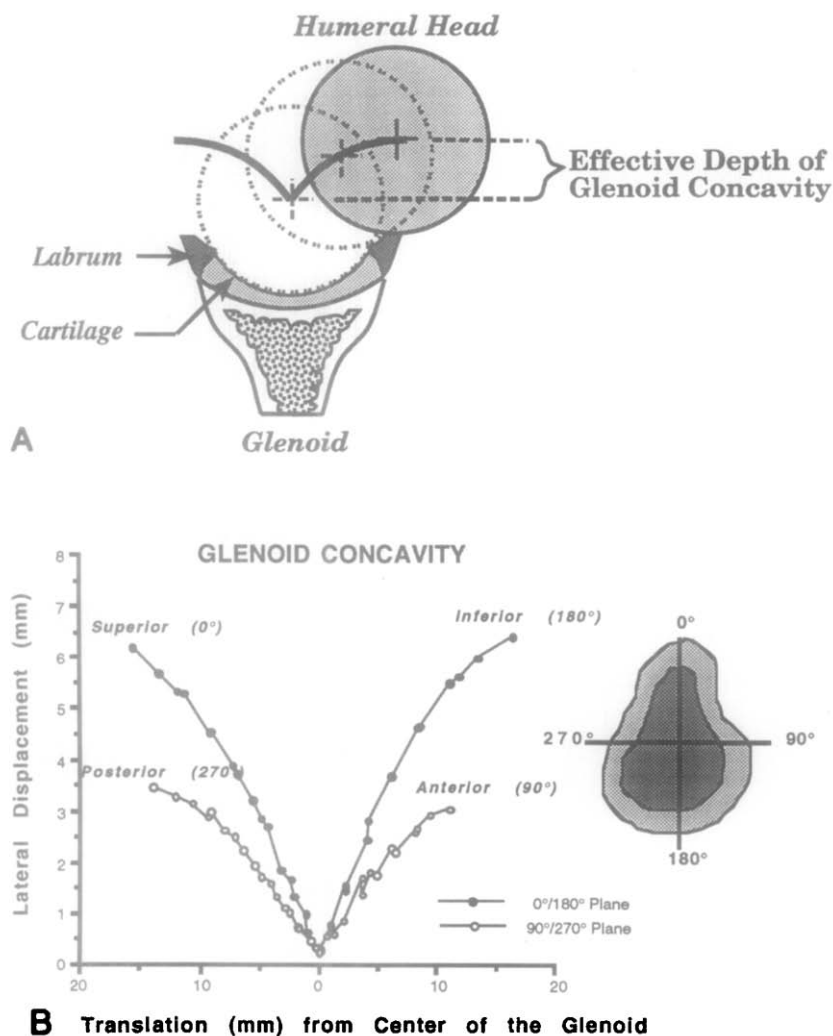


Figure 2 **A** Path of center of head as it is translated away from glenoid center is shown by "V"-shaped graph. Effective depth of glenoid concavity in specified direction of translation is defined by maximum lateral displacement of humeral head at glenoid edge relative to its starting point centered in glenoid fossa. **B.** Effective depth of glenoid in superoinferior direction and anteroposterior direction for typical specimen.

lateral displacement of the humeral head as it was translated up the contour of the glenoid surface.

Next, a compressive load of 50 N was applied to the humeral head in a direction perpendicular to the glenoid surface. To determine the stability of the head against a defined direction of translation, progressively larger translating forces were applied manually to the humeral head while the magnitude and direction of these forces were measured by the force transducer and spatial sensors (Fig. 1). The

forces were applied tangential to the glenoid surface until the head dislocated over the glenoid rim. This dislocation occurred abruptly so that the maximal force before dislocation was easily discernible. The translation force at dislocation was recorded for eight different directions at 45° intervals (superior: 0°, anterosuperior: 45°, anterior: 90°, etc.). To determine the effect of the magnitude of the compressive load on concavity compression stability, the sequence was repeated with a 100 N compressive load (in this sequence the 0°, 90°, 180°, and 270°

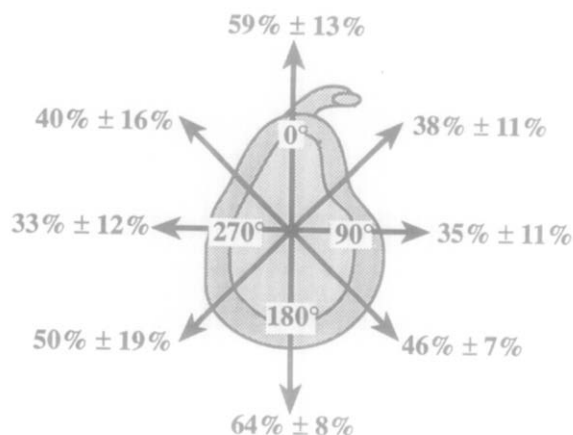


Figure 3 Stability ratio for 10 glenohumeral joints with labrum intact and 50 N compressive load (average \pm 1 SD). Stability ratio is given as percentage by defined equation: stability ratio (%) = translating force at dislocation/compressive load \times 100.

directions were examined). Finally the entire protocol was repeated after the glenoid labrum was excised to the level of the articular cartilage.

In an attempt to prevent desiccation and to maintain constant friction between the glenoid and the humeral head, the articular surfaces were kept moist by periodic irrigation with normal saline solution.

Because the same specimens were tested many times under different conditions (groups: 50 N versus 100 N compressive load, with and without labrum), the repeated-measures analysis of variance (ANOVA) was used for statistical analysis. Intragroup comparisons of the stability for the different directions of translation force (0°, 45°, 90°, etc.) were analyzed with the Dunnett *t* test. Statistical significance was set at the $p < 0.05$ level.

RESULTS

Glenoid concavity and effective glenoid depth. The effective depth of a glenoid in a specified direction was determined by plotting the lateral displacement of the humeral head as it was translated in the specified direction from the glenoid center up the surface of the glenoid concavity. This plot created a "V"-shaped graph (Fig. 2A and B), which represents the changing slope of the glenoid concavity in contact with the humeral head. The effective depth of the concavity is the maximum

Table I Translating force resisted for compressive loads

Degree	Compressive load (N)	Translating force (N)
0	50	29 \pm 7
	100	51 \pm 9
90	50	17 \pm 6
	100	29 \pm 5
180	50	32 \pm 4
	100	56 \pm 12
270	50	17 \pm 6
	100	30 \pm 12

lateral translation of the humeral head at the glenoid edge compared with the starting point at the glenoid center (Fig. 2A).

In this group of shoulders the average effective glenoid depths varied around the perimeter of the glenoid as shown for a typical shoulder in Fig. 2B. For all of the shoulders the average glenoid depths were greater superiorly (4.8 mm) and inferiorly (4.9 mm) than anteriorly (2.2 mm) and posteriorly (2.1 mm).

Stability from concavity compression.

The following data show that the effectiveness of concavity compression was affected by the magnitude of the compressive load, the direction of the translating force, the presence of the glenoid labrum, and the effective depth of the glenoid concavity.

Magnitude of the compressive load

Fifty N compressive loads stabilized the humeral head against translating forces up to 32 N, depending on the direction of the translating force (see following). Increasing the compressive load to 100 N increased humeral head stability against even greater translating forces measuring of up to 56 N (See Table I).

To facilitate the analysis of the effectiveness of concavity compression under different conditions, a "stability ratio" was calculated as suggested by Fukuda et al.⁸ For convenience this ratio was expressed as a percentage instead of a decimal by the following equation: stability ratio (%) = translating force at dislocation/compressive load \times 100.

Directional effect of the translating force. The stability ratio varied around the perimeter of the glenoid (Fig. 3). For all preparations the stability ratios were significantly greater ($p < 0.05$) superiorly (0°) and inferiorly

Table II Change in the stability ratio with removal of the labrum

Degree	Stability ratio at 50 N compressive load			Stability ratio at 100 N compressive load		
	Labrum intact (%)	Labrum excised (%)	p Value	Stability ratio (%)	Labrum excised (%)	p Value
0	59 ± 13	47 ± 8	0.012	51 ± 9	45 ± 7	0.028
45	38 ± 11	30 ± 10	0.032			
90	35 ± 11	28 ± 6	0.062	29 ± 5	26 ± 5	0.021
135	46 ± 6	39 ± 8	0.008			
180	64 ± 8	41 ± 13	0.0001	56 ± 12	40 ± 13	0.0002
225	50 ± 19	30 ± 10	0.001			
270	33 ± 12	25 ± 11	0.017	30 ± 12	23 ± 9	0.01
315	40 ± 16	32 ± 14	0.032			

Data reported as average ($n = 10$) ± 1 standard deviation.
Statistical significance $p < 0.05$.

(180°) than anteriorly (90°) or posteriorly (270°). In contrast, there was no significant difference in the stability ratio ($p < 0.05$) between the superior and the inferior directions nor between the anterior and the posterior directions.

The effect of excision of the glenoid labrum. Excision of the glenoid labrum decreased the effectiveness of concavity compression as indicated by diminished stability ratios (Table II). This was true for all directions of displacement and for both magnitudes of compressive loading.

The percentage of labral contribution to the stability ratio (SR) for a given direction of displacement was calculated by the formula: labral contribution (%) = (SR labrum intact) – (SR labrum excised) / SR labrum intact. This labral contribution to stability through concavity-compression was variable, averaging 20%, and did not differ for the different directions of translation at the 95% confidence level. However, there was a trend toward greater contribution of the labrum to the stability ratio in the inferior and posteroinferior directions (average 37%) as compared with all other directions on the glenoid (average 18%).

Relationship between stability ratio and effective glenoid depth. As discussed previously, the effective depth of the glenoid concavity was greater in the superoinferior than it was in the anteroposterior plane. The increased stability ratios in the superoinferior directions correlated with the increased effective depth of the glenoid concavity in this plane. Indeed, both the depth and stability in the superoinferior direction were approximately

twice the respective values in the anteroposterior direction. This relationship of depth to concavity-compression stability was also demonstrated by comparing the stability ratios after resection of the glenoid labrum, which decreased the effective depth of the glenoid concavity. This relationship between effective depth and stability ratio appeared to be linear (Fig. 4).

DISCUSSION

The glenohumeral joint provides the greatest range of motion of any joint in the body but also is one of the most susceptible to instability.^{15, 21} Because the glenohumeral ligaments and capsule must have sufficient laxity to allow the immense range, they can provide stability only when they become tight at the extremes of glenohumeral motion.^{16, 24, 26, 27} Other factors must contribute to glenohumeral stability in mid-range glenohumeral positions, where the arm is most commonly positioned.

The glenoid articular geometry may seem too shallow to provide a significant stabilizing role for the humeral head. Though the glenoid fossa is only one fourth the size of the articular surface of the humeral head, it is not flat. Radiographs are misleading because they show only the bony contour of the glenoid in relation to the humeral head. Flatow et al.⁷ demonstrated that although the subchondral bone of the glenoid is relatively flat, the cartilage surface is thicker peripherally than in the center, producing a radius of curvature that matches the humeral head very closely.

Radiographic studies by Howell et al.¹³ and

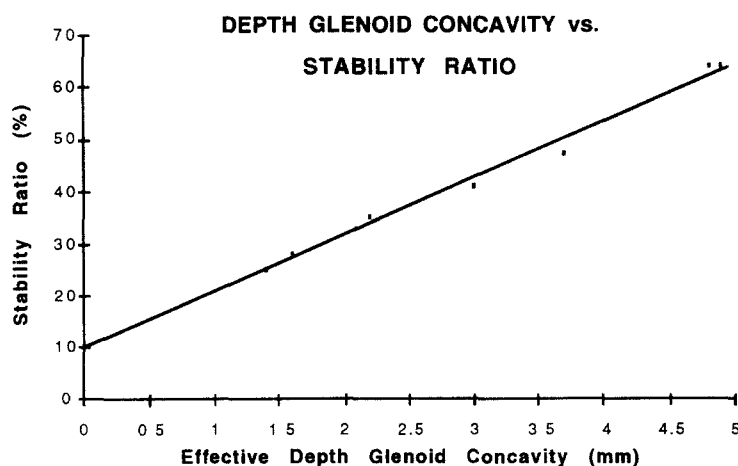


Figure 4 Average data for labrum-intact and labrum-excised specimens with 50 N compressive load for superior, inferior, anterior, and posterior directions. Linear regression by least-squares method provides formula: stability ratio (%) = 10.3 (effective depth glenoid concavity in mm) + 9.7.

by Poppen and Walker¹⁸ demonstrate that the humeral head essentially remains centered on the glenoid throughout active motion in the frontal and horizontal planes, respectively. These studies support a "ball and socket" kinematic model of the humeral head rotating in a congruent glenoid concavity during active motion.

In our study we demonstrated the effective glenoid depth of the concavity by observing the lateral displacement of the humeral head as it was translated from the glenoid center to the glenoid rim in various directions. The depth of the concavity was the greatest in the superior and inferior directions. This is consistent with the results of Howell and Galinat,¹² who identified the glenoid fossa as deeper in the superoinferior direction, averaging approximately 9 mm as compared with the anteroposterior direction, which averages 5 mm. This may be explained by understanding the pear-shaped anatomy of the glenoid fossa. Because the superoinferior dimension is wider than the anteroinferior direction, the glenoid fossa must be deeper in this direction, given that the glenoid radius of curvature has minimal deviation from sphericity (Fig. 5).⁷

The functional importance of this concavity was demonstrated in the present study by compressing the humeral head into the glenoid fossa and applying a tangential translation force until dislocation occurred. The maximum stability ratio (translation force divided by the

compressive load) ranged from 33% to as much as 64% for the labrum-intact glenoid specimens. The greater stability ratio for the superior and inferior directions (64%) as compared with the anterior and posterior directions (33% to 35%) was related to the greater effective depth in this plane (approximately 4.8 mm versus 2.2 mm). In fact, an almost linear relationship existed between the effective glenoid depth and its stability ratio for any given direction.

The role of the glenoid labrum as a stabilizer of the glenohumeral joint was popularized by Bankart.¹ The labrum is not only a significant site of attachment of the glenohumeral ligaments but also provides a fibrous extension to the glenoid rim, which further enhances the depth of the fossa.^{5, 6, 16} Howell et al.^{12, 14} presented the concept of the "glenoid-labral" socket, in which the circular, pliable, fibrous labrum contributed approximately 50% to the total depth of the glenoid. In our study the stability ratio was significantly less after the glenoid labrum was excised for each direction tested. On the average, the labrum contributed approximately 20% to the concavity-compression stabilization of the glenohumeral joint.

Cooper et al.³ investigated the anatomy of the glenoid labrum in cadaver shoulders and found distinct morphologic differences around the glenoid rim. The superior and anterosuperior labrum appeared meniscal with a loose attachment to the glenoid, at times allowing the la-

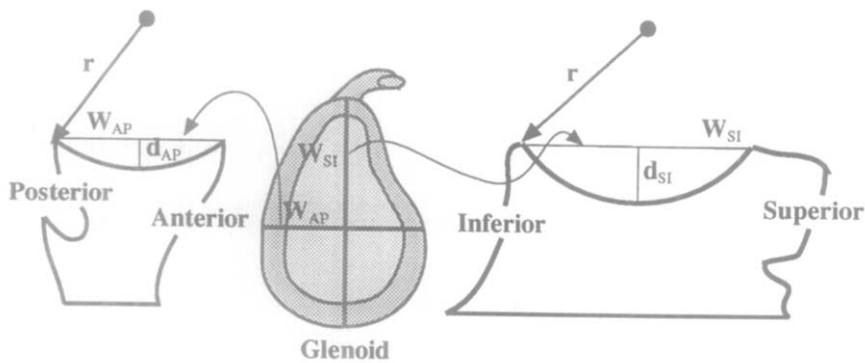


Figure 5 Width of glenoid in superoinferior direction (W_{SI}) is greater than width of glenoid in anteroposterior direction (W_{AP}). For given radius of curvature (r), increase in width results in increase in depth. Thus depth of glenoid in superoinferior direction (d_{SI}) is greater than depth of glenoid in anteroposterior direction (d_{AP}).

brum to be quite mobile. In contrast, the inferior portion of the labrum represented an immobile, intimately attached fibrous extension of the articular cartilage. They concluded that this firm attachment of the inferior labrum to the glenoid rim provided evidence of its role as a stabilizing bumper against translation of the humeral head. Our results are consistent with this concept, showing a highly suggestive trend toward greater contribution of the labrum to inferior and posterior inferior stability than that of other directions on the glenoid.

The quality and size of the labrum may vary among shoulders. DePalma et al.⁵ reported the attritional changes that occur in the glenoid labrum with increasing age, such as detachment and fraying. Our experiment used older shoulder specimens, ranging from 55 to 89 years of age, though we included only those without gross evidence of degenerative causes. It is possible that in younger shoulders with more robust labra, the labra may demonstrate an even greater effect on glenohumeral stability.

Clinical support exists for the concept of concavity-compression as a stabilizing mechanism for the glenohumeral joint. Glenoid rim fractures involving significant loss of the articular surface (glenoid concavity) can be associated with glenohumeral instability.²³ Repair of glenoid labrum and glenohumeral ligament detachment (Bankart lesion) back to the glenoid rim has been documented as an effective treatment for traumatic anterior instability.^{20, 25} An anatomic glenohumeral ligament repair not only allows firm attachment of the ligaments but

also helps restore the concavity to the glenoid fossa.

Fukuda et al.⁸ demonstrated the principle of concavity-compression in various designs of glenohumeral joint prosthetic replacement. Their study reported the amount of force required to cause subluxation and dislocation of the prosthetic glenohumeral joint under known axial load. Among the designs, the glenoid components with the largest curvature had the highest resistance to subluxation of the corresponding humeral head component. In all cases, the anteroposterior subluxation forces were lower than the corresponding superoinferior subluxation forces. This was attributed to the variation of constraining wall height provided by the glenoid surface. They related the presence of an axial force as the most important factor in maintaining joint stability.

The magnitude and direction of the normal compressive forces acting at the glenohumeral joint have been estimated by various authors.^{2, 4, 14, 17-19, 23, 28} Walker and Poppen^{19, 28} showed the resultant joint contact force increased linearly with progressive arm abduction to a maximum of 0.89 times body weight at 90° abduction. The great majority of the compressive forces are provided by the rotator cuff muscles: subscapularis, supraspinatus, infraspinatus, and teres minor, and by the long head of the biceps and the deltoid and pectoral muscles in certain positions.

The importance of concavity compression as a stabilizing mechanism for the glenohumeral joint may be demonstrated in the normal indi-

vidual. When the subject is completely relaxed, an examiner can easily translate the humeral head anteriorly or posteriorly with respect to the glenoid. If the subject then contracts the shoulder muscles (e.g., by slightly abducting the shoulder), this anteroposterior excursion is virtually eliminated.

CLINICAL RELEVANCE

Our study investigated the stabilizing effect of concavity-compression in the glenohumeral joint in vitro. The results indicate that compression of the humeral head into the concave glenoid fossa can stabilize the articulation effectively. This mechanism can act throughout the range of motion, including in the mid-range, where the capsule and ligaments are lax. Concavity-compression stabilization is increased with increasing compressive loads and in directions with greater effective glenoid depth (superior and inferior). This mechanism is significantly compromised by the absence of an intact glenoid labrum.

These results may be relevant to clinical traumatic instability. They suggest that detachment or surgical resection of the glenoid labrum may decrease shoulder stability, giving rise to subluxation or dislocations. They suggest that reestablishment of the effective glenoid depth through anatomic repair may be an important element of the surgical repair for recurrent glenohumeral instability.

These results may also be relevant to clinical atraumatic multidirectional instability, where the joint is characteristically unstable in the mid-range of motion. Flatness of the glenoid articular surface could predispose a joint to this type of instability, allowing relatively easy translation in multiple directions as a result of a lack of effective glenoid depth. They also suggested that rotator-cuff strengthening may enhance stability by providing for increased compressive loads.

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