Bucholz, Robert W., Heckman, James D.
Rockwood & Green's Fractures in Adults, 5th Edition

BIOMECHANICS

Part of "28 - SUBLUXATIONS AND DISLOCATIONS ABOUT THE GLENOHUMERAL JOINT"

Factors in Glenohumeral Stability

The glenohumeral joint is suited for mobility (293). The large spherical head of the humerus articulates with the small, shallow glenoid fossa of the scapula. The glenoid provides little coverage of the head, particularly when the shoulder is (a) adducted, flexed, and internally rotated, (b) abducted and elevated, or (c) adducted at the side with the scapula rotated downward (264). Despite this lack of coverage, the normal shoulder precisely constrains the humeral head to within 1 mm of the center of the glenoid cavity throughout most of the arc of movement (198). It is amazing that this seemingly unstable joint is able to provide this precise centering, resist the gravitational pull on the arm hanging at the side for long periods, allow for the lifting of large loads, permit throwing a baseball at speeds approaching 100 miles an hour, and hold together during the application of an almost infinite variety of forces of differing magnitude, direction, duration, and abruptness. Rather than asking why the shoulder dislocates in some patients, perhaps we should ask how it can be so stable in most individuals. We suggest that glenohumeral stability results from a hierarchy of mechanisms, including those that do not require the expenditure of energy by muscles ("passive" mechanisms) and those that do ("active" mechanisms). In

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this way, nature conserves energy while reserving the ability to call up muscular reinforcement as needed.

Passive Mechanisms

It is apparent that muscle activity is not required to hold the shoulder together. The intact shoulder of a fresh anatomic specimen is quite stable. The anesthetized and paralyzed shoulder does not fall apart in the operating room. Basmajian and Bazant (17) used electromyography of the deltoid, supraspinatus, infraspinatus, biceps, and triceps in a series of young men to show that none of these muscles is active when the arm hangs quietly at the side. In cadaver studies, Kumar and Balasubramaniam (138) found the position of the humeral head was maintained without muscle activity (with the entire arm hanging down) in 18 of 24 cadaver shoulders. Thus, it is appropriate to discuss "passive" stabilizing mechanisms of the glenohumeral joint, which include joint conformity, finite joint volume, adhesion/cohesion, ligamentous and capsular restraints, and the glenoid labrum.

Joint Conformity

Saha (228) demonstrated that there is considerable variation in the radii of the curvature of the glenoid fossa. The contour may be almost flat or slightly curved or may have a definite socket-like appearance. The stability of the glenohumeral joint is affected by the size, shape, and tilt of the glenoid fossa.

Cyprien and co-workers (51) studied the humeral retrotorsion and glenohumeral relationship in normal patients and in patients with recurrent anterior dislocation and found essentially no difference. However, when they studied the affected and unaffected shoulders in the group of patients with recurrent dislocation, they found that the diameter of the glenoid and the contact index were smaller in the dislocated shoulders than in the normal shoulders. Whether these changes were the cause or the effect of the instability is unclear. Brewer and associates (28) measured the “retroversion” of the glenoid in ten adolescents with 17 posteriorly unstable shoulders. They concluded that “excessive retroversion is a developmental deformity and is considered the primary etiology of posterior instability of the shoulder.” However, their data are also consistent with the hypothesis that the deformity is a result (rather than a cause) of the instability: a major right–left difference in glenoid tilt (>10 degrees) was found only when one shoulder had experienced numerous dislocations and the other none. Perhaps even more important is the fact that the apparent tilt of the glenoid surface on the axillary view varies with the angle at which the radiograph is obtained (Fig. 28-77).

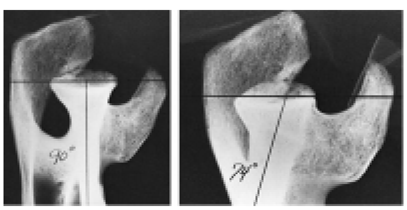

FIGURE 28-77. Two radiographs of the same cadaver scapula showing the variation in apparent glenoid retroversion depending on the radiographic projection. (From Matsen FA III, Thomas SC, Rockwood CA Jr. Glenohumeral instability. In: Rockwood CA, Matsen FA III, eds. *The shoulder*. Philadelphia: WB Saunders, 1990:611–689.)

Randelli and Gambrioli (199) used CT to perform glenohumeral osteometry. They found no significant developmental differences in glenohumeral index, glenoid AP orientation, and humeral retrotorsion between 50 normal subjects and 40 patients with recurrent anterior dislocations. They concluded that erosions and fractures may affect the apparent orientation and AP diameter of the glenoid.

The depth of the bony glenoid is enhanced by the contributions of the articular cartilage and the glenoid labrum, which, by virtue of their relative compliance, provide an element of plasticity that can enhance the quality of the glenohumeral fit (similar to the “feathered” edge of a contact lens) (Fig. 28-78). The concavity and the fit of the glenoid to the humeral head provide stability to the joint, which is enhanced by forces pressing the ball into the socket (see Active Mechanisms, below).

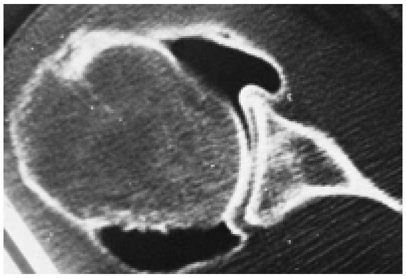

FIGURE 28-78. CT arthrogram of glenohumeral joint. The depth of the bony glenoid is enhanced by contributions of the articular cartilage and the glenoid labrum. This further increases the stability of the glenohumeral joint. (From Matsen FA III, Thomas SC, Rockwood CA Jr. Glenohumeral instability. In: Rockwood CA, Matsen FA III, eds. *The shoulder*. Philadelphia: WB Saunders, 1990:611–689.)

Finite Joint Volume

When one pulls on the plunger of a plugged syringe, a relative vacuum is created that resists displacement of the plunger. Anatomic studies, surgical findings, attempts at aspiration, and MRI

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all confirm that there is minimal (<1 mL) free fluid in the normal shoulder joint. The normal shoulder is sealed by the capsule so that outside fluid cannot enter it. Thus, like the syringe, the shoulder joint is stabilized by its limited joint volume. As long as the joint is a closed space containing minimal free fluid, the joint surfaces cannot be easily distracted or subluxated. Small translations of the humerus on the glenoid can be balanced by fluid flow in the opposite direction, allowing a nonuniform gap to open in the joint space. This gap can increase until all available fluid has been mobilized, at which point further motion of the joint is resisted by negative fluid pressure in the joint. This negative pressure pulls the capsule inward toward the joint space, putting its fibers “on the stretch.” Individuals with more stretchy capsules (see the discussion of the AMBRI syndrome, Table 23-3) will allow greater translation than those with stiff joint capsules.

This mechanism is aided by the fact that intraarticular pressure is normally slightly negative. This negative intraarticular pressure is likely to be the result of the high osmotic pressure in interstitial tissues, which draws water from the joint. For example, if the colloid osmotic pressure of normal synovial fluid is 10 mm Hg and that of the synovial interstitium is 14 mm Hg, the equilibrium pressure in the joint fluid will be more than 4 mm Hg (243). This negative intraarticular pressure adds a small amount of resistance to distraction (about 1 ounce per square inch) to the limited joint volume effect. The greater importance of these osmotic effects lies in the fact that they provide a mechanism by which free fluid is scavenged from the joint space.

Adhesion/Cohesion

The stabilization mechanism changes when the gap between the articular surfaces becomes very small. Viscous and intermolecular forces begin to dominate, preventing ready fluid motion and providing a cohesive bond between the glenoid and humerus. We term this the “adhesion/cohesion mechanism.” A familiar example is provided by two wet microscope slides pressed together. Water is held to their surfaces by adhesion. They can readily slide on each other but cannot be pulled apart easily by forces applied at right angles to their flat surfaces—the water holds them together by cohesion. Joint surfaces also are wet with joint fluid that holds them together by adhesion/cohesion. This joint fluid interface has the highly desirable properties of (a) having high tensile strength (difficult to pull apart) and (b) having little shear strength (allows sliding of the two joint surfaces on each other with low resistance) (243). An important distinction is that the adhesion/cohesion mechanism does not put the capsular fibers on the stretch, because viscous forces suffice to prevent fluid from entering the joint space. Thus, stability is provided entirely by forces exerted by and on the articular surfaces. It is also noteworthy that adhesion/cohesion forces do not stabilize a prosthetic shoulder replacement, because metal and polyethylene are insufficiently compliant to provide the necessary near-perfect congruence and because water does not adhere to their surfaces.

Both the limited joint volume effect and the effect of adhesion/cohesion would be reduced or eliminated by the addition of excess fluid (gas or liquid) to the joint. This phenomenon was well described by Humphrey (116) in 1858:

> In many joints—the ball and socket joints for instance—though the ligaments assist, as just mentioned, in preventing dislocation, it is quite clear that the articular surfaces cannot, under ordinary circumstances, be directly held in apposition by them, inasmuch as they must be loose in the whole circumference to permit the movements of the joint in every direction. If the ligament were sufficiently tight at any one part to hold the bones together, it must of necessity prevent the movement in one direction, which we know is not the case. The experiments of Weber upon the hip-joint were, I believe, the first to prove the fact that atmospheric pressure is the real power by which the head of the femur is held in the acetabulum when the muscles are at rest. One convincing experiment is easily repeated; hold up a side of the pelvis, with its appended lower extremity, the joint not having been opened, and then bore a hole through the acetabulum, so as to admit air into the hip-joint. The weight of the limb causes it to drop from half an inch to an inch, the head of the thigh-bone is pulled out of the acetabulum, as soon as the air is permitted to pass between the articular surfaces. In the unopened
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> state of the joint, therefore, the weight of the limb is entirely borne by atmospheric pressure, so that both ligaments and muscles, the latter especially, are relieved in a corresponding manner. The same fact may be shown with regard to the shoulder and other joints, in a greater or less degree, though obviously the illustration is easiest in the hip and shoulder. The advantages of this construction, and the facilities it affords for easy movement by leaving all the muscles free to act upon the joint, need no demonstration. We have only to remember that this power is in continual operation to appreciate the amount of animal force that is economized by it.

The contribution of atmospheric pressure to shoulder stability is also described in *Gray's Anatomy* (second edition, 1963): “The looseness of the capsule is so great that the arm will fall about an inch from the scapula when the muscles are dissected and a hole made in it to remove the atmospheric pressure.” Kumar and Balasubramaniam (138) again demonstrated this effect in cadaver shoulders. They fixed the scapula to a frame in the vertical position while the arm hung free. Radiographs were taken to determine the presence of glenohumeral subluxation. The results of these studies are so striking that they are quoted here:

> In none of the shoulders was any subluxation of the joint demonstrable radiographically after dividing the muscles; but, when the capsule was then punctured [with an 18-gauge needle], marked inferior subluxation of the humeral head was seen. This occurred regardless of where the capsule was punctured. Provided atmospheric air was able to gain access into the glenohumeral joint, subluxation was always noted. As soon as the capsule was punctured percutaneously a hissing sound was heard as air rushed into the joint and it subluxated: the subluxation was confirmed radiographically. The point of puncture of the capsule did not affect these findings. No further subluxation beyond the position reached after percutaneous puncture of the capsule occurred when the overlying muscles were subsequently divided.

They found that once air had been admitted, the intact shoulder could be subluxated manually into any position with minimal force. Before air had been admitted, “a fair amount of force” was necessary to produce subluxation. It seems likely that the air admitted into the joint eliminated the stabilizing effect of the limited joint volume and also interrupted the continuity of the fluid cohesion holding the wet joint surfaces together. The change in shoulder stability with admission of air has been quantitated by Sidles and co-workers (242). Habermeyer and colleagues (95) found a mean atmospheric pressure stabilizing force of 146 N. In stable shoulder joints of patients under general anesthesia, traction on the arm resulted in an increase of negative intraarticular glenohumeral pressure that was correlated to the amount of force exerted. Warner and associates (272) also reported that negative intraarticular pressure has a significant effect on superoinferior translation. The addition of blood to the joint in an intracapsular fracture may produce inferior subluxation by similar mechanisms. Finite volume and adhesion/cohesion also operate in the subacromial bursa, providing additional resistance to inferior displacement of the humerus.

These stabilizing mechanisms may be overwhelmed by the application of traction, as in the cracking of the metacarpophalangeal joint. A “crack” is produced as the joint cavitates: subatmospheric pressure within the joint releases gas (>80% carbon dioxide) from solution in the joint fluid. This is accompanied by a sudden jump in the joint separation. Once a joint has cracked, it cannot be cracked again until about 20 minutes later when all the gas has been reabsorbed (267).

Scapular Inclination

Scapular inclination is yet another passive mechanism of shoulder stability. The scapular stabilizing muscles (i.e., trapezius, serratus anterior, and rhomboids) have long been recognized for their important role of providing a stable platform for glenohumeral motion. Itoi and colleagues (121) studied the influence of scapular inclination on inferior stability of the glenohumeral joint in 11 fresh-frozen cadaver shoulders. At lower angles of inclination the shoulders were very unstable and dislocated inferiorly, but at higher angles of inclination they were stabilized and did not dislocate even after venting. The stable position of inclination was termed the critical angle and was between 0 and 30 degrees for 90% of shoulders. The authors attributed this phenomenon to a “bony cam effect” where an increase in scapular inclination and slope of the glenoid fossa tightened the superior capsuloligamentous structures.

Ligamentous and Capsular Restraints

Ovesen and co-workers (191), Turkel and colleagues (264), and Warren and associates (275) have demonstrated the role of the anterior and posterior capsule and capsular ligaments in limiting the translation and rotation of the humerus. Harryman and associates (99) evaluated the role of the rotator interval capsule in stability of the shoulder. Operative alteration of the capsule was found to affect essentially all glenohumeral rotations and translations. Sectioning of the rotator interval capsule resulted in instability and occasional frank dislocation of the shoulder joint both inferiorly and posteriorly. Conversely, imbrication of this portion of the capsule increased the resistance of the glenohumeral joint to inferior and posterior translation. We emphasize that glenohumeral ligaments can exert an effect only if they are under tension. Thus, these ligaments provide a checkrein function that is the last guardian of shoulder stability after all other passive and dynamic mechanisms have been overwhelmed. Examples of restraint provided by capsular ligaments have been demonstrated in cadaver studies as follows:

1. The anteroinferior capsule restrains anterior subluxation of the abducted arm (191).
2. The middle glenohumeral ligament limits external rotation at 45 degrees of abduction (264).
3. The inferior glenohumeral ligament limits external rotation at 45 to 90 degrees of abduction (264).
4. The posterior capsule and the teres minor restrain internal rotation (191).
5. The lower two-thirds of the anterior capsule and the lower subscapularis restrain abduction and external rotation (191).

Schwartz and co-workers (238) performed selective arthroscopic cutting experiments on cadaver shoulders to quantitate the contribution of the capsular structures to glenohumeral stability. They pointed out that clinically, instability was usually accompanied by both anterior and posterior lesions. They concluded:

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1. The inferior glenohumeral ligament in concert with the posteroinferior capsule

provided the primary restraint to anterior translation.

2. The middle glenohumeral ligament (when present) provided a secondary restraint to anterior dislocation.
3. The posteroinferior capsule provided the primary posterior restraint to posterior dislocation.
4. The posterosuperior capsule and superior glenohumeral ligament provided secondary restraint to posterior dislocation.

Howell and associates (115) used axillary roentgenograms to document the AP position of the humeral head on the glenoid. They found that posterior translation of the humeral head occurs in normal subjects with the arm in extension and external rotation. This posterior translation is absent in shoulders with anterior instability. These authors suggest that this posterior translation is the result of the tension in the intact anterior capsule and ligaments.

The coracohumeral ligament extends from the lateral border of the horizontal arm of the coracoid process, below the coracoacromial ligament, to the transverse humeral ligament bridging the greater and lesser tuberosities between the supraspinatus and subscapularis tendon insertions. Basmajian and Bazant (17) have carried out cadaver dissections demonstrating that the coracohumeral ligament and the superior capsule became quite taut when the arm was in adduction, and they suggested that this tension helped stabilize the humeral head in the glenoid. In contrast, when the shoulder was abducted to the midrange, the superior capsule became more lax and the humeral head became more unstable. They proposed that the coracohumeral ligament held the humeral head on the slope of the glenoid, providing substantial stability that was further enhanced by upward rotation (abduction) of the scapula and by supraspinatus contraction. Ovesen and Nielsen (191) demonstrated that cutting the coracohumeral ligament gave rise to distal subluxation of the humerus in the vertically mounted shoulder. The authors concluded that the superior capsuloligamentous structures are the most important structures preventing distal subluxation of the humeral head. However, they did not consider that cutting the superior capsuloligamentous structures must have admitted air to the joint—an action that in itself can produce downward subluxation (see Finite Joint Volume, and Adhesion/Cohesion, above). Thus, although the coracohumeral ligament provides stability to the adducted shoulder, it is probably insufficient by itself, as was demonstrated in the 24 shoulders studied by Kumar and Balasubramaniam (138) that became downwardly unstable with only the admission of air into the joint.

Active Mechanisms

The role of dynamic stability can easily be demonstrated in the normal subject. When the subject is completely relaxed, the humerus can be pushed forward and backward with respect to the scapula. If the subject contracts the muscles (e.g., by slightly abducting the shoulder), the AP excursion is virtually eliminated.

Dynamic glenohumeral stability is provided by the long head of the biceps and the muscles of the rotator cuff: the subscapularis, the supraspinatus, the infraspinatus, and the teres minor. Itoi and co-workers (121) studied the contributions of the long and short heads of the biceps in cadaver shoulders with variable loads and at variable positions of external rotation. The shoulder capsule was intact, vented, or damaged by a Bankart lesion. The study revealed that tension on both heads of the biceps stabilized the humeral head to anterior translation with the arm in abduction and external rotation for all three capsular conditions. The cuff muscles serve several stabilizing functions. First, by virtue of the blending of their tendons with the glenohumeral capsule and ligaments, selective contraction of the cuff muscles can adjust the tension in these structures, producing "dynamic" ligaments, as proposed by Cleland in 1866 (41). Second, by contracting together, they press the humeral head into the glenoid fossa, locking it into position and thus providing a secure scapulohumeral link for upper extremity function. Sidles and associates (242) demonstrated that the resistance of the shoulder to distal subluxation is proportionally increased by 67% of the applied compressive load. Thus, a 3-kg increase in the forces pushing the head into the glenoid increases the resistance to distal subluxation by 2 kg. Third, by contracting selectively, the rotator cuff muscles can resist displacing forces resulting from contraction of the principal shoulder motors. For example, when the pectoralis major and anterior deltoid muscles elevate and flex the shoulder, they tend to push the humeral head out the back of the glenoid fossa; this displacement is resisted by contraction of the subscapularis, infraspinatus, and teres minor muscles. Similarly, when the lateral deltoid initiates shoulder abduction, the supraspinatus and the long head of the biceps actively resist upward displacement of the humeral head relative to the glenoid fossa. Patients who can consciously relax these stabilizing muscles can achieve voluntary glenohumeral subluxation and dislocation. Conversely, patients with capsular instability can increase the security of their glenohumeral joints by strengthening the rotator muscles. Dynamic stability is most effective if the contractions of all shoulder muscles are coordinated with one another; strength alone is insufficient. Thus, repetitive coordination exercises such as swimming are an important tool for enhancing dynamic stability.

Summary

We conclude that the shoulder has a hierarchy of supporting mechanisms. Minimal loads, such as gravitational pull on the arm, are resisted by passive mechanisms such as the concavity of the joint surface provided by the glenoid and its labrum, the finite joint volume, and the adhesion/cohesion of joint fluid. Larger loads, such as those encountered in serving a tennis ball, washing a car, or picking up a child, are resisted by the action of cuff muscles whose contraction is coordinated with that of the prime movers to balance displacing forces. These mechanisms cost the body some energy but do not threaten its integrity. Finally, the ability of the shoulder to resist massive loads depends on the ligaments, the capsule, and the bony support of the joint. For example, the severe abduction–external rotation forces of a fall in skiing or a "clothesline" tackle in football challenge the anteroinferior glenohumeral ligaments. If these ligaments do not hold, a subluxation or dislocation occurs.