Stability and instability of the glenohumeral joint: The role of shoulder muscles

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Shoulder muscles contribute to both mobility and stability of the glenohumeral joint. To improve treatments for shoulder instability, we focused on the contribution of the shoulder muscles to glenohumeral joint stability in clinically relevant positions. Both computational and experimental models were used. A computational model of the glenohumeral joint quantified stability provided by active muscle forces in both mid-range and end-range glenohumeral joint positions. Compared with mid-range positions, the resultant joint force at end-range positions was more anteriorly directed, indicating that its contribution to glenohumeral joint stability was diminished. In end-range positions, simulated increases in rotator cuff muscle forces tended to improve stability whereas increases in deltoid or pectoralis major muscle forces tended to further decrease stability. To validate these results, a cadaveric model, simulating relevant shoulder muscles, was used to quantify glenohumeral joint stability. When infraspinatus muscle activity was decreased, compressive forces decreased. When pectoralis major muscle activity was increased, anteriorly directed forces increased. If anteriorly directed forces increase or compressive forces decrease, stability of the glenohumeral joint decreases. This cadaveric model was then used to evaluate the effect of placing the joint in the apprehension position of abduction, external rotation, and horizontal abduction. Consistent with the results of our computational model, apprehension positioning increased anteriorly directed forces. Knowledge gained from these models was then used to develop a cadaveric model of glenohumeral joint dislocation. Dislocation resulted from the mechanism of forcible apprehension positioning when the appropriate shoulder muscles were simulated and a passive pectoralis major muscle was included. Capsulolabral lesions resulted that were similar to those observed in vivo. Shoulder muscle forces are usually powerful stabilizers of the glenohumeral joint, especially in mid-range positions when the passive stabilizers are lax. However, muscle forces can contribute to instability as well. Certain muscle forces decrease glenohumeral joint stability in end-range positions. We found this to be the case with both active and passive pectoralis major forces. Improved understanding of the contribution of muscle forces not only toward stability but also toward instability will improve rehabilitation protocols for the shoulder and prove useful in the treatment of joint instability throughout the body. (J Shoulder Elbow Surg 2005; 14:32S-38S.)

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INTRODUCTION

Current treatment of an initial episode of traumatic anterior glenohumeral joint instability includes a period of restricted activity followed by rehabilitation of the shoulder muscles.[5,10,19,33] In patients aged less than 25 years, this treatment fails in 60% to 94% of patients and they have recurrent anterior instability.[4,14,26,35,37,42] In older patients, nearly 15% have recurrence and many more have weakness, pain, and loss of motion.[29] Surgical treatment minimizes recurrent instability but fails to restore normal joint function in more than 70% of patients.[8,28] These complications may limit the patient's ability to participate in athletic activities, return to overhead activities, or perform daily activities.

Shoulder muscles contribute to both mobility and stability of the glenohumeral joint. Shoulder instability is specific to certain end-range positions. For example, anterior instability occurs in the apprehension position of abduction, external rotation, and horizontal abduction.[33] When the shoulder is forcibly placed

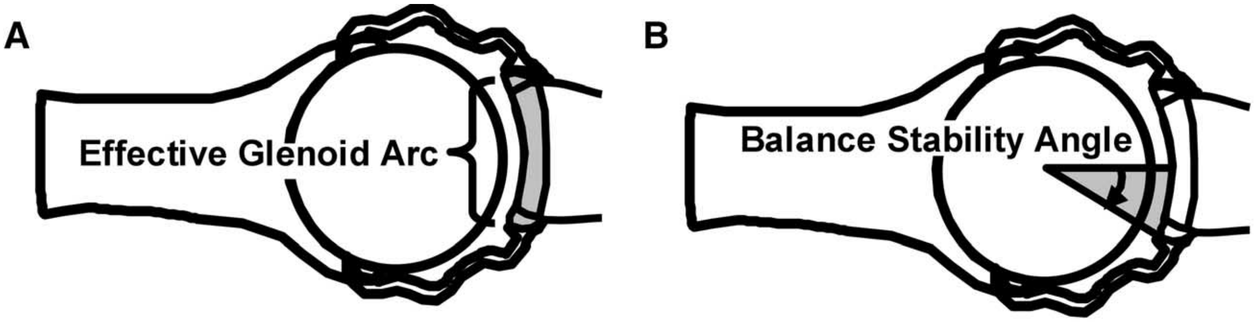

Figure 1 Axial views of glenohumeral joint. **A**, The effective glenoid arc (*gray area*) is defined as the area of the glenoid's articular surface available for humeral head compression. **B**, The balance stability angle (*gray area*) is defined as the angle between the center of the glenoid and the end of the effective glenoid arc.

in this position, traumatic glenohumeral joint dislocation may occur.[27,36] Subsequently placing the glenohumeral joint in the apprehension position may elicit symptoms of anterior instability.[15] To improve treatments of shoulder instability, we have focused on defining the contribution of the shoulder muscles to glenohumeral joint stability in clinically relevant positions.

PRIOR STUDY OF SHOULDER MUSCLES' ROLE IN GLENOHUMERAL JOINT STABILITY AND INSTABILITY

Concavity-compression mechanism

Shoulder muscle activity stabilizes the glenohumeral joint by compressing the humeral head against the concave glenoid surface, allowing concentric rotation of the humeral head on the glenoid.[15,17,18,32] Through this mechanism, termed concavity-compression, shoulder muscles may be the primary stabilizers of the glenohumeral joint during the mid ranges of motion, where the capsuloligamentous structures are lax.[24] Concavity-compression may also be important at the end ranges of motion, where forces acting on the glenohumeral joint are increased.[2,30,31,43] In end-range positions, shoulder muscle activity protects the capsuloligamentous structures by limiting the joint's range of motion[11,17] and by decreasing strain in these structures.[11,34]

The effectiveness of the concavity-compression mechanism depends on characteristics of the shoulder muscle forces and the articular surfaces. Shoulder muscle forces may be defined by their magnitude and direction (line of action). Shoulder muscle forces may be resolved into 3 components: compressive forces, superior-inferiorly directed forces, and anterior-posteriorly directed forces. Whereas compressive forces stabilize the glenohumeral joint, anteriorly, posteriorly, inferiorly, and superiorly directed forces are termed translational forces and destabilize the glenohumeral joint. Glenohumeral joint stability may be quantified by the ratio between the translational forces in any direction and the compressive forces.[21,24,25] As the ratio between the translational forces and compressive forces decreases, stability of the glenohumeral joint increases. As the ratio between the translational forces and compressive forces increases, stability of the glenohumeral joint decreases.

Stability of the glenohumeral joint provided by concavity-compression also depends on the effective glenoid arc, the area of the glenoid's articular surface available for humeral head compression (Figure 1, *A*).[33] This contact area may be quantified by the balance stability angle, the angle between the center of the glenoid and the end of the effective glenoid arc in any direction (Figure 1, *B*).[25,33] The balance stability angle was experimentally and mathematically determined to be 18° ± 2° in the anterior direction.[21,24,25] All of the shoulder muscles can be summed into a single resultant force that compresses the humeral head into the glenoid. Resultant forces directed within the balance stability angle stabilize the glenohumeral joint, but resultant forces directed outside of the balance stability angle destabilize the glenohumeral joint.

Contribution of shoulder muscles to glenohumeral joint stability

The rotator cuff muscle forces are ideally aligned for effective compression of the glenohumeral joint at all shoulder positions.[23] In cadaveric models, simulated rotator cuff activity increased compressive forces at the glenohumeral joint and decreased the amount of humeral head translation that occurred in response to external loading.[9,16,43] Wuelker et al[43] showed that a 50% decrease in the rotator cuff muscle forces resulted in nearly a 50% increase in anterior displacement of the humeral head in response to external loading at all glenohumeral joint positions. With the glenohumeral joint in its anatomic position, Blasier et al[9] found that each rotator cuff muscle significantly contributed to anterior joint stability and that each muscle's contribution was not significantly different from the others. However, with the glenohumeral joint in end-range positions, Itoi et al[16] found that the subscapularis was a less effective stabilizer of the glenohumeral joint than the other rotator cuff muscles and that biceps brachii activity may also contribute to glenohumeral joint stability. These studies have discrepancies as a result of differences in experimental design but were compelling in demonstrating that shoulder muscle forces are usually powerful stabilizers of the glenohumeral joint.

Contribution of shoulder muscles to glenohumeral joint instability

Other investigators have suggested that in certain positions, deltoid or pectoralis major muscle activity may decrease stability of the glenohumeral joint. Lee and An[22] quantified the contribution of deltoid muscle activity to glenohumeral joint stability based on its compressive and translational components. At 60° of glenohumeral abduction in the scapular plane, deltoid activity increased glenohumeral joint stability. However, at 60° of glenohumeral abduction in the coronal plane, deltoid activity decreased glenohumeral joint stability. Arciero and Cruser[3] presented a case study in which a patient sustained a concomitant anterior glenohumeral joint dislocation and pectoralis major tendon rupture while bench-pressing. They theorized that eccentric contraction of the pectoralis major muscle had led to both injuries. Furthermore, Sinha et al[38] reported that a refractory shoulder dislocation associated with pectoralis major spasm was successfully reduced after paralysis of the pectoralis major with botulinum A toxin.

OUR STUDY OF THE SHOULDER MUSCLES' ROLE IN GLENOHUMERAL JOINT STABILITY AND INSTABILITY

Active stability of the glenohumeral joint decreases in end-range positions

Previous biomechanical studies have quantified active stability of the glenohumeral joint provided by individual muscles or small groups of muscles, usually limited to the rotator cuff and deltoid.[9,22,23,43] However, electromyographic studies identified that not only the rotator cuff but also the biceps brachii, latissimus dorsi, pectoralis major, teres minor, and scapulothoracic muscles are active during shoulder motion.[1,7,33] We developed a computational model, based on force-vector analysis, to quantify active stability provided by the summation of relevant shoulder muscles that cross the glenohumeral joint. This model was used to quantify stability provided by active muscle forces in both mid-range and end-range positions of the glenohumeral joint.

Eight shoulder muscles were included in the study: the deltoid, infraspinatus, latissimus dorsi, pectoralis major, subscapularis, supraspinatus, teres major, and teres minor. These muscles were selected because they are the main movers of the glenohumeral joint, they have electromyographic activity during abduction and external rotation, and they have insertion sites on the humerus.[12,20,33] Two mid-range glenohumeral joint positions (15° and 30° of glenohumeral abduction in the coronal plane) and two end-range glenohumeral joint positions (60° of glenohumeral abduction and the apprehension position) were studied. For the apprehension position, 30° of external rotation was added. Shoulder muscle forces were defined by the direction (line of action) and magnitude of their forces in both mid-range and end-range positions. For each shoulder muscle, lines of action were derived from a standard 3-dimensional geometric shoulder model.[39,40] Muscle force magnitudes were estimated from known values of physiologic cross-sectional area[39,41] and normalized electromyographic activity during active abduction[20] and the early cocking phase of pitching,[12] which includes the apprehension position. Resultant muscle forces were calculated by summing individual muscle forces. The lines of action of the resultant forces were expressed in a spherical coordinate system with respect to the scapular plane. For our illustrations, the resultant muscle forces were placed at the center of the humeral head. The ratio between anteriorly directed forces and compressive forces is the sine of the balance stability angle. The angle between the scapular plane and the projection of the line of action in the transverse plane was termed the deviation angle (Figure 2, *A*).

Compared with mid-range positions, the lines of action of the resultant forces were more anteriorly directed in the apprehension positions. At 15° of glenohumeral abduction, the line of action was anteriorly directed by 9°. In the apprehension position, the line of action was anteriorly directed by 35°, a 289% increase compared with 15° of glenohumeral abduction. To determine the functional significance of these differences, the resultant forces were compared with the mean balance stability angle of 18° ± 2° in the anterior direction.[21,24,25] In mid-range positions, the lines of action of the resultant forces were within the balance stability angle. In end-range positions, they exceeded the balance stability angle (Figure 2, *B*). This study provided a biomechanical rationale for the effects of muscles forces on anterior glenohumeral joint stability. In the apprehension position, shoulder muscle forces, unopposed by the passive restraints, may promote anterior humeral head translation, pre-

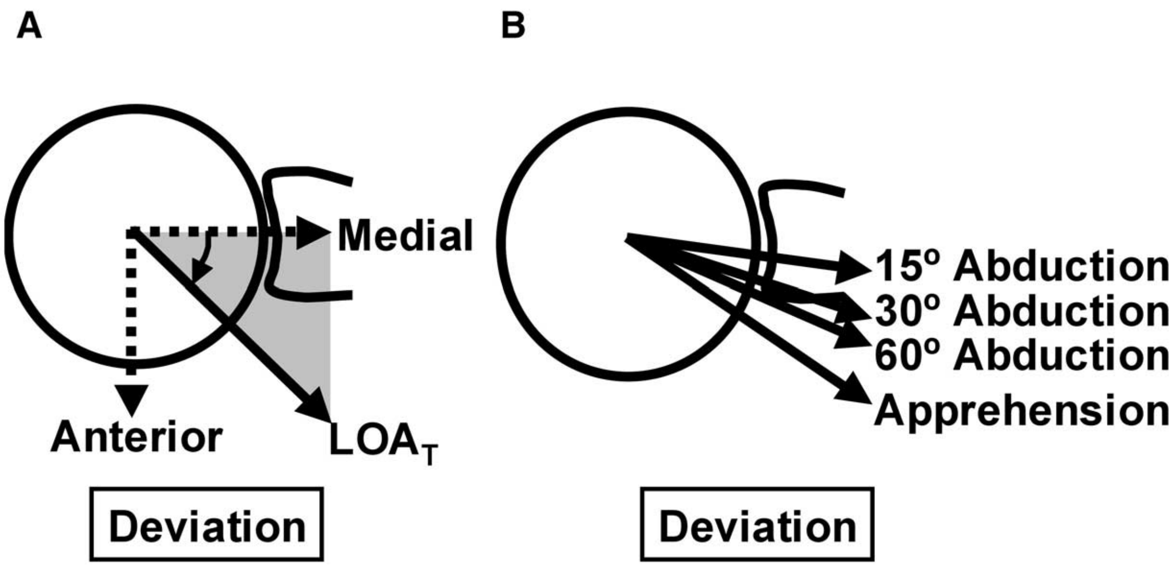

Figure 2 Axial views of glenohumeral joint (transverse plane). **A**, Definition of deviation. LOA_T, Projection of line of action into transverse plane. **B**, Anterior deviation of the lines of action of the resultant forces was greater in end-range positions (60° of glenohumeral abduction and the apprehension position) than in mid-range positions (15° and 30° of glenohumeral abduction).

disposing the glenohumeral joint to anterior instability.

To aid in rehabilitation of shoulder instability, we then studied each shoulder muscle in our model for its contribution to glenohumeral joint instability. We determined the effect of increasing the magnitude of individual muscle forces on the lines of action of the resultant forces. For each muscle, the magnitude of its force was increased by 25% or 50% and the line of action of the resultant force was then recalculated. The lines of action were less anteriorly directed when the magnitude of supraspinatus, infraspinatus, or teres minor muscles was increased, tending to improve stability of the glenohumeral joint. However, the lines of action were more anteriorly directed with increases in deltoid or pectoralis major muscle forces, tending to decrease stability. Changing the magnitude of the teres major, subscapularis, or latissimus dorsi muscles had no effects on the lines of action of the resultant force.

Dysfunctional shoulder muscle activity may decrease glenohumeral joint stability

To test the results of our computational model, a cadaveric model that simulated relevant shoulder muscles was used to quantify stability resulting from the muscle forces in end-range positions. Two patterns of shoulder muscle dysfunction were modeled: (1) decreased infraspinatus muscle activity and (2) increased pectoralis major muscle activity.

Five fresh-frozen human full upper extremities were dissected to isolate the tendons of the rotator cuff, deltoid, and pectoralis major muscles and mounted onto a custom joint-loading frame, which allowed individual control of simulated muscle forces. The scapula was abducted 30°, and then loads were applied to the tendons of the rotator cuff and deltoid until 60° of glenohumeral abduction was achieved, simulating 90° of shoulder abduction. Load varied slightly among upper extremities because of differences in weight and length. Because the resulting abduction was in the plane of the scapula, a minimal load of 100*g* was applied to the wrist to move the glenohumeral joint to maximum external rotation, simulating the apprehension position. This position was repeated after 2 additional loading conditions when all load was removed from the infraspinatus tendon or load was applied to the pectoralis major tendon. To ensure that the glenohumeral joint reached the same position with each loading condition, an electromagnetic tracking device was used to monitor the position of the humerus relative to the scapula. A 6–degree-of-freedom load cell was used to measure the glenohumeral joint force at 60° of glenohumeral abduction. Glenohumeral joint forces were resolved into 3 components: compressive force, superiorly directed force, and anteriorly directed force. A 2-way repeated-measures analysis of variance was used to determine the effect of the 2 muscle-loading conditions on the glenohumeral joint forces, with significance set at $P < .05$.

When load was removed from the infraspinatus, compressive forces decreased from 151.5 ± 29.7 N

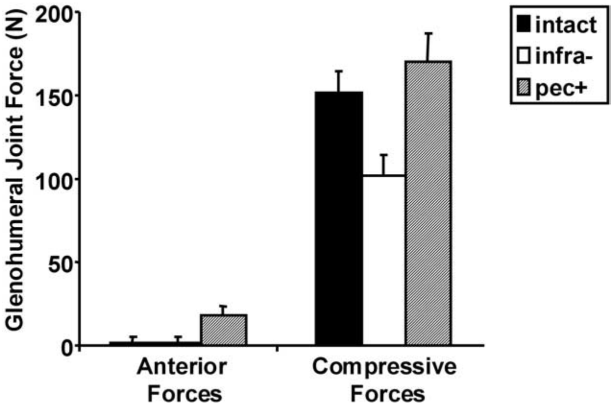

Figure 3 Histogram showing anterior and compressive components of resolved glenohumeral joint forces for loading conditions. The effect of decreased infraspinatus activity (*infra-*) and increased pectoralis major activity (*pec+*) at 60° abduction in the scapular plane is shown.

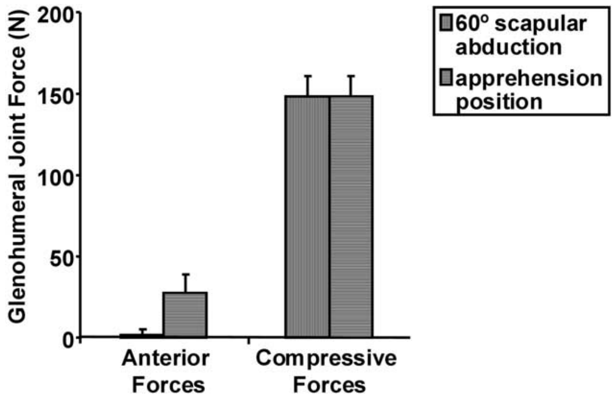

Figure 4 Histogram showing anterior and compressive components of resolved glenohumeral joint forces for loading conditions. The effect of positioning the joint at 60° of glenohumeral abduction in the scapular plane compared with the apprehension position is shown.

to 101.5 ± 28.8 N ($P < .05$) (Figure 3). When pectoralis major activity was increased, compressive forces increased by 12% but anteriorly directed forces increased by 1180%, from 1.4 ± 10.0 N to 17.9 ± 13.1 N ($P < .05$). Although the joint did not dislocate and the position of the humeral head on the glenoid was not measured, the ratio between anteriorly directed and compressive forces increased in both conditions, tending to diminish stability of the glenohumeral joint. These results were consistent with our computational model.

Apprehension positioning decreases glenohumeral joint stability

This cadaveric model was then used to evaluate the effect of simply placing the joint in the apprehension position. Five fresh-frozen human full upper extremities were prepared and mounted on the custom joint-loading frame. Once again, the scapula was abducted 30° and loads were applied to the tendons of the rotator cuff and deltoid until 60° of glenohumeral abduction was achieved. After simulated active abduction of the cadaveric full upper extremity, an external load was applied to the wrist to gently move the glenohumeral joint from the scapular plane to the apprehension position. A 6–degree-of-freedom load cell was used to measure the glenohumeral joint force, which was again resolved into 3 components. A 2-way repeated-measures analysis of variance was used to determine the effect of glenohumeral joint position on the glenohumeral joint forces, with significance set at $P < .05$.

When the glenohumeral joint was moved from 60° of glenohumeral abduction in the scapular plane to the apprehension position, anteriorly directed forces significantly increased from 1.4 ± 10.0 N to 27.7 ± 27.7 N ($P < .05$) (Figure 4). This indicates that, as in our computational model, the resultant forces would be more anteriorly directed in the apprehension position than in the mid-range position.

Simulation of glenohumeral joint dislocation

Knowledge gained from our computational and cadaveric models was then used to develop a cadaveric model of glenohumeral joint dislocation. The joint was forcibly placed into the apprehension position, simulating an in vivo mechanism of glenohumeral joint dislocation, and both active and passive shoulder muscle forces were included.

Fourteen fresh-frozen human full upper extremities were dissected to isolate the tendons of the rotator cuff, deltoid, and pectoralis major muscles and mounted onto a custom joint-loading frame with the scapula positioned in 30° of abduction (Figure 5). Loads were applied to the deltoid and rotator cuff muscles to achieve 60° of glenohumeral abduction and 30° of external rotation. A force was then applied to the humerus at 50 mm/s to move it into horizontal abduction until the glenohumeral joint either dislocated or moved beyond 45° of horizontal abduction. A 6–degree-of-freedom load cell was used to measure the glenohumeral joint force, which was then resolved into 3 components: compressive forces, superior-inferiorly directed forces, and anterior-posteriorly directed forces. No loads were applied to the pectoralis major muscle; instead, its tendon was fixed, and the force that developed passively as the joint moved into horizontal abduction was measured with an independent uniaxial load cell. A pilot study had found that horizontal abduction of the abducted and externally rotated humerus did not result in dislocation unless a passive force was allowed to develop in the simulated pectoralis major muscle.

All 14 glenohumeral joints dislocated in an anterior-

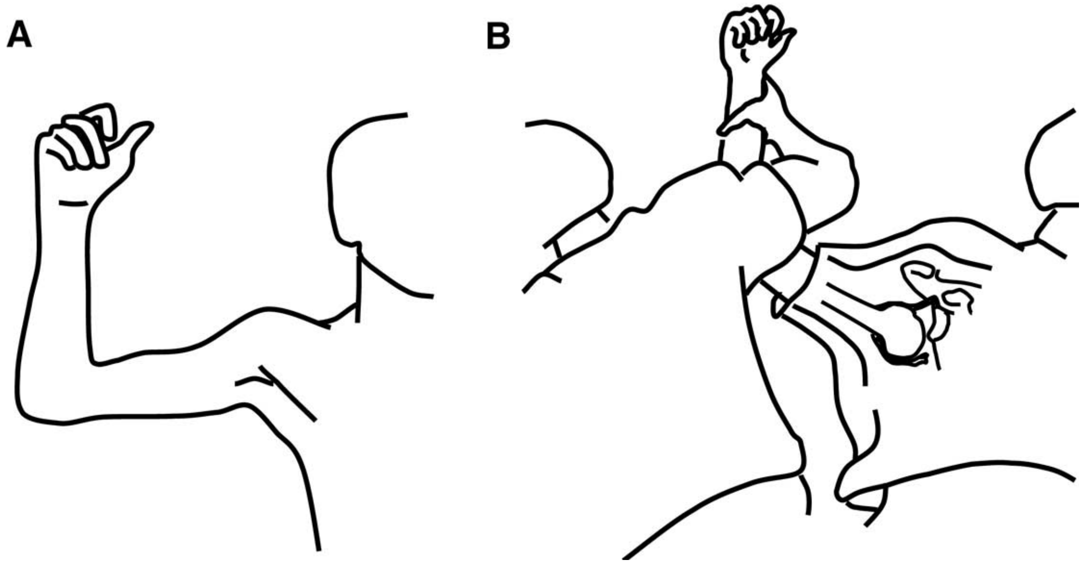

Figure 5 Bird's-eye view schematic of custom shoulder-testing device with servomotor-controlled system that resulted in dislocation of cadaveric glenohumeral joints.

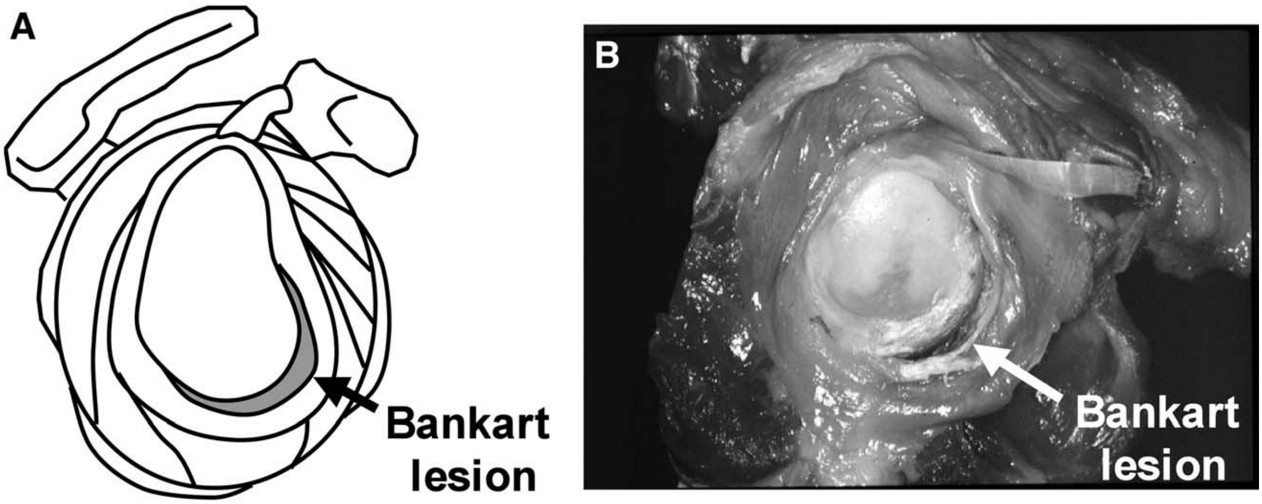

Figure 6 Sagittal views of glenohumeral joint, with humeral head removed. **A**, Drawing of Bankart lesion. **B**, Cadaveric specimen showing avulsion of the capsulolabrum from the anterior-inferior glenoid rim.

inferior direction. The pathoanatomy was similar to that reported after in vivo glenohumeral joint dislocation.[6,8,13,33] In 6 shoulders the capsulolabrum and glenoid rim avulsed from the anteroinferior glenoid, resembling a Bankart lesion (Figure 6). In the remaining 8 shoulders, glenohumeral joint dislocation resulted without avulsion or tearing; capsular stretching had occurred. At the time of dislocation, the magnitude of the pectoralis force, 609.6 ± 65.2 N, was similar to that of the compressive glenohumeral joint force, 569.6 ± 37.8 N. We surmised that, when the arm exceeded its normal range of motion, forces generated within the pectoralis major may have increased anteriorly and inferiorly directed forces that lead to glenohumeral joint instability. In this instance, shoulder muscle forces that are usually powerful stabilizers of the glenohumeral joint may have contributed to dislocation.

SUMMARY

Normally, the shoulder muscles move and stabilize the glenohumeral joint. However, with overhead athletic activities and some manual labor tasks, individuals repeatedly position the glenohumeral joint at an extreme range of motion, which may compromise the shoulder muscles in stabilizing the glenohumeral joint.

The idea that muscle forces may contribute to instability is novel. Our models revealed that both active and passive major forces may, in certain conditions, contribute to glenohumeral joint instability. Improved understanding of the contribution of muscle forces to both stability and instability may improve treatments not only for instability of the shoulder but also for other joints of the body as well.

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