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ANATOMY AND BIOMECHANICS OF THE SHOULDER

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GLENOHUMERAL JOINT

Anatomy

The shoulder complex has the greatest mobility of all joints. On one hand, this mobility is because of little bony congruity of its articulating surfaces. The joints of the shoulder complex have to rely on adjacent ligaments and muscles to provide stability. Consequently, they are susceptible to injury and degeneration. On the other hand, the shoulder complex is composed of the scapulothoracic articulation and the glenohumeral joint to share the overall motion and increase its range. This composition allows the involved muscles to work in the most efficient part of their length-tension curve[82] and the glenoid to be placed underneath the humeral head to bear some weight of the arm.[40]

Glenoid

Inferior to the acromion, the flat scapula thickens to form the glenoid (Fig. 1). The spinoglenoid notch separates the base of the acromion from the glenoid. Its slightly concave surface is shaped like an inverted comma with an anterior incision, and the radius of curvature is larger than that of the humerus.[29] The total surface area is three to four times smaller than that of the humerus. The central portion of the glenoid shows frequently an area of thinned cartilage. The glenoid faces laterally, being 10° to 15° superiorly tilted relative to the medial border of the scapula. Relative to the plane of the scapula, the glenoid surface is nearly perpendicular: Saha[93] noted retroversion of an average of 7.4° with an incidence of 75% or anteversion of an average of 2° to 10° with an incidence of 25%. On its superior tip, the supraglenoid tubercle is origin of the long head of the biceps. On its inferior pole, the infraglenoid tubercle is the origin of the long head of the triceps.

Glenoid Labrum

The glenoid labrum is a ring of triangular shape in section overlying the peripheral circumference of the glenoid with its free rim projecting into the joint. It consists of dense fibrous tissue. Its base is attached to the margin of the glenoid fossa by fibrocartilage and fibrous bone.[88] It is attached to the glenohumeral ligaments and blends superiorly with the origin of the long head of the biceps tendon at the supraglenoid tubercle. Its function is to

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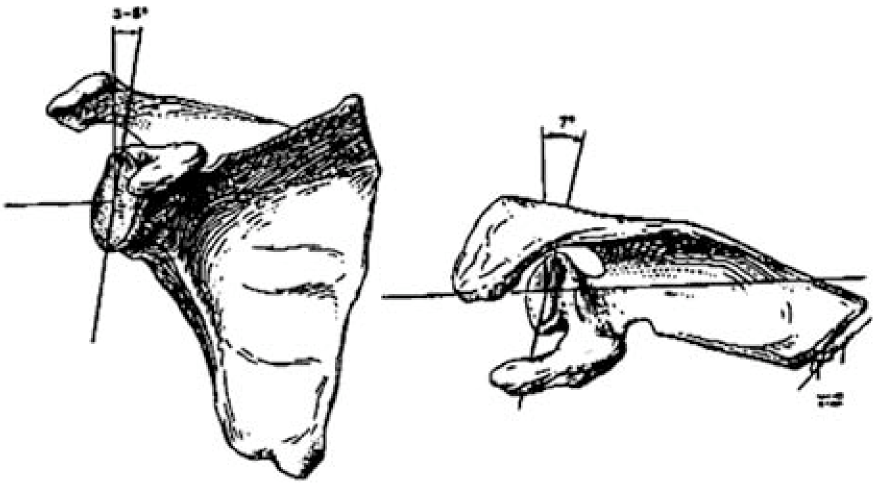

Figure 1. The two-dimensional orientation of glenoid with respect to the medial border and the plane of the scapula. (By permission of the Mayo Foundation.)

increase congruity, generating a suction effect and enhancing stability of the glenohumeral joint.

Glenohumeral Joint Capsule

The capsule of the glenohumeral joint has a large volume of normally about 10 to 15 mL and twice the surface area of the humeral head.[70] On the inside, it is covered with synovium; on the outside, rotator cuff tendons protect the capsule on all but the inferior aspect. The tendons of the subscapularis and supraspinatus are even fused with the capsule close to their insertion. The capsule begins at the border of the labrum, is attached to its outer surface, and is anchored onto the bone of the glenoid neck. It extends superiorly to the coracoid process and in varying length along the biceps tendon into the intertubercular groove. It inserts into the anatomic neck close to the cartilage of the humeral head and with some distance inferiorly to form the axillary recess. Apart from the outlet for the biceps tendon, the capsule has a gap for the subscapular recess anteriorly.

Histologically the capsule is composed of three layers: an outer and an inner layer with fibers running in the frontal plane from the glenoid to humerus and a middle layer with fibers running in the sagittal plane. The glenohumeral ligaments reinforce the joint capsule. They are an abrupt thickening of the inner layer with organized collagen bundles in the frontal plane. A thickening of middle layer reinforces the axillary pouch. Contrary to the anterior joint capsule, the posterior is quite thin.[70]

Glenohumeral Ligaments

The coracohumeral ligament (Fig. 2) originates from the base and lateral border of the coracoid process and runs transversely to the greater tuberosity. Its anterior border is distinct medially and merges laterally, whereas its posterior border is indistinct.[70] It is a primary restraint to the long head of the biceps tendon.[84,96]

The transverse humeral ligament is the roof of the proximal end of the bicipital groove and acts as the retinaculum for the long head of the biceps tendon. It is made of transverse fibers of the capsule.

Although constant in presence, the superior glenohumeral ligament is variable in size and origin. It arises from the anterior labrum, sometimes as far superior as the long head of the biceps tendon and sometimes as far inferior as the middle glenohumeral ligament or in between.

The middle glenohumeral ligament shows the largest variation in diameter. It can be as thin as the capsule or as thick as the subscapularis tendon. It originates from the anterior labrum or glenoid neck to insert into the lesser tuberosity underneath the subscapularis tendon with which it is mingled.[101]

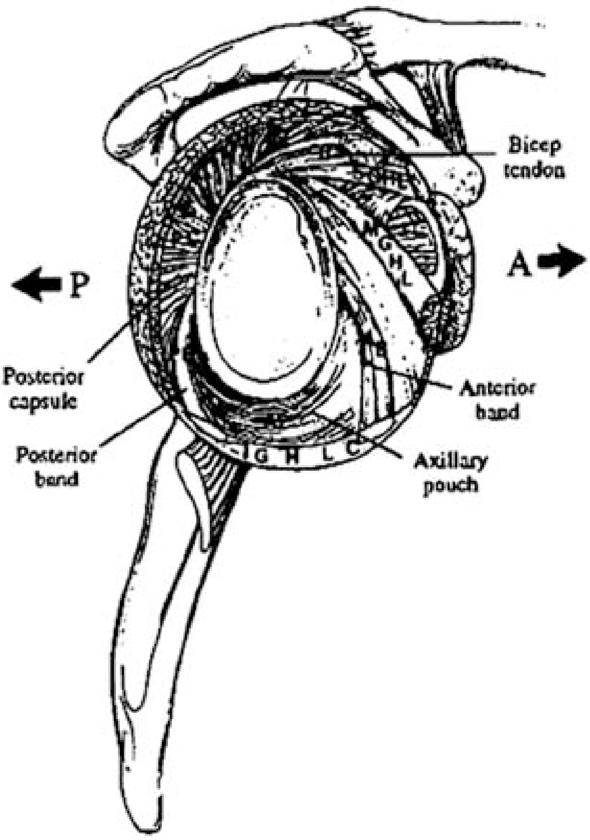

Figure 2. The long head of biceps tendon (B). SGHL = superior glenohumeral ligament, MGHL = middle glenohumeral ligament; PC = posterior capsule; IGHLC = inferior glenohumeral ligament complex; AB = anterior band; PB = posterior band; A = anterior; P = posterior. (*From* O'Brien SJ, Answorth AA, Fealy S, et al: Developmental anatomy of the shoulder and anatomy of the glenohumeral joint. *In* Rockwood CA Jr, Matsen FA III: The Shoulder, ed 2, vol 1. Philadelphia, WB Saunders, 1998, p 26.)

The inferior glenohumeral ligament is thicker than the rest of the capsule, although variable in size and attachment site. Its structure resembles a hammock consisting of a prominent anterior band,[101] a posterior band, and the axillary pouch in between. Looking at the glenoid being divided like a clock, the anterior band originates from the glenoid or labrum from the 2- to 4-o'clock position and the posterior band from the 7- to 9-o'clock position. It inserts into the anatomic neck of the humerus inferior to the cartilage in a U- or V-shaped fashion.[71,72]

Humeral Head

The articular surface has an ovoid shape[9] facing medially, superiorly, and posteriorly. The humeral head (Fig. 3) is inclined about 130° relative to the shaft with 30° of retrotorsion relative to the condyles of the elbow.[29] The articular surface of the humeral head forms almost a true sphere.[98] The margin is tilted 45° relative to the humeral shaft. In contrast to the glenoid, the central portion of its hyaline cartilage is the thickest.

The anterior border of the articular surface is the lesser tuberosity, and its lateral border is the greater tuberosity with the intertubercular groove in between. Together with the medial surface of the surgical neck, they are sites for a ring of tendinous and ligamentous attachments around the articular surface. This ring functions to stabilize the joint by centralizing the humeral head while tightening around the prominent articular surface.[40]

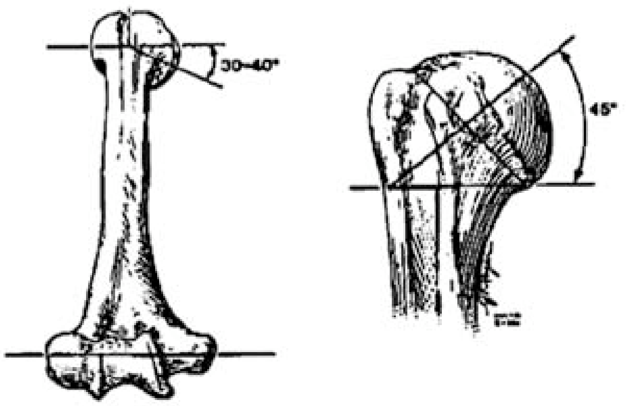

Figure 3. The three-dimensional orientation of the articular surface of the humeral head, with respect to the bicondylar axis of the elbow. (By permission of the Mayo Foundation.)

The intertubercular groove lies 30° medial[70] or 9 mm anterior to the central axis of the articular surface.[100] It is bordered by the lesser tuberosity anteriorly and by the greater tuberosity posteriorly. The transverse ligament bridges the intertubercular groove proximally to act as a retinaculum for the long head of the biceps tendon. Distally the subscapularis tendon inserting onto the lesser tuberosity forms the floor of the sheath. The supraspinatus tendon inserting onto the greater tuberosity forms its roof. The depth of the intertubercular groove seems to play a role in the pathogenesis of long head of the biceps tendinitis by more or less exposing the tendon to an impingement process.[67]

There are three facets on the greater tuberosity: the superior, the middle, and the inferior.[57,97] The supraspinatus muscle inserts onto the superior facet and the superior half of the middle facet.[57] Anterior fibers of the supraspinatus tendon mingle with the subscapularis tendon fibers. Posteriorly the infraspinatus tendon attaches to the middle facet, covering the posterior border of the supraspinatus tendon. The teres minor tendon inserts onto the inferior facet.[57]

Scapulohumeral Muscles

Supraspinatus. The supraspinatus muscle takes fleshy origin in the supraspinatus fossa to have a tendinous insertion onto the greater tuberosity. The muscle belly has a fusiform shape with a thick tendinous core, the intramuscular tendon, located in the anterior third. Approximately 70% of the muscle fibers attach to the intramuscular tendon, whereas 30% attach directly to the extramuscular tendon.[59] This muscle is categorized as a circumpennate muscle.[58] The superficial tendon fibers run longitudinally, whereas the deep ones run obliquely[40] to mingle with adjacent muscles and create a tendinous ring. The supraspinatus is part of the force couple to stabilize the glenohumeral joint by compression and initializes elevation.[27] Elevation in case of supraspinatus paralysis requires more deltoid force, but the other rotator cuff muscles are still able to stabilize the humeral head sufficiently for full range of motion.[82] The suprascapular nerve (C4–6) supplies innervation.

Infraspinatus. The infraspinatus muscle takes fleshy origin in the infraspinatus fossa and scapular spine to insert with a flat tendon onto the middle facet of the greater tuberosity. It is a circumpennate muscle with an intramuscular tendon located in the center of the muscle belly. The infraspinatus muscle stabilizes the glenohumeral joint by resisting posterior[75] and superior translation and generates 60% of the overall external rotation force.[12] The suprascapular nerve (C4–6) supplies innervation.

Teres Minor. Origin of the teres minor muscle is the lateral border of the scapula and the infraspinatus fascia, and its fleshy insertion is located inferior to the infraspinatus muscle on the inferior facet of the greater tuberosity. Similar to the infraspinatus, this is a circumpennate muscle with a single intramuscular tendon located in the center of the muscle belly. The teres minor muscle acts as stabilizer of the glenohumeral joint by resisting posterior and superior translation and generates 45% of the total external rotation force.[12] The posterior branch of the axillary nerve (C5–6) supplies innervation.

Subscapularis. The subscapularis muscle takes fleshy origin in the subscapularis fossa and inserts onto the lesser tuberosity. Its tendinous bands are interspersed evenly in the medial portion of the muscle to condense laterally into a flat tendon in the superior two thirds, whereas the inferior third remains muscular.[45] This muscle with multiple intramuscular tendons is a multicircumpennate muscle. The subscapularis sends fibers of its tendinous insertion across the intertubercular groove to form the floor of the bicipital sheath. As the only component of the anterior rotator cuff, it stabilizes actively the glenohumeral joint by resisting anterior and inferior translation[31,94] and acts as a strong internal rotator. It is considered to be a passive stabilizer,[99,101] too, because of the dense collagen structure of its tendon and its fusion with the middle and inferior glenohumeral ligament. Two branches of the subscapular nerve (C5–8) for the superior and inferior portion of the muscle supply innervation.

Deltoid. The deltoid muscle is composed of the clavicular part originating from the lateral clavicle, the acromial part from the acromion, and the spinal part from the scapular spine. Their common insertion is the deltoid tubercle on the humerus. The deltoid is the most important abductor of the glenohumeral joint. Although the acromial portion is the strongest one and starts the movement, the clavicular and spinal portions participate at higher degrees of abduction. Conversely, in low degrees of abduction, the medial fibers of the anterior and posterior portions can take part in adduction of the arm.[42] Additionally the anterior portion affects flexion and the posterior portion extension. Paralysis of the deltoid results mainly in 50% loss of abduction strength.[13] The axillary nerve (C4–5) innervates the deltoid.

Teres Major. The teres major originates from the posterior surface of the inferior angle of the scapula to take a tendinous insertion on the medial margin of the intertubercular groove. On its way to the humerus, it takes a 180° spiral course with the posterior fibers inserting anteriorly.[40] Its functions are internal rotation, adduction, and extension of the humerus. The subscapular nerve (C5–7) supplies innervation.

Biceps. The long head of the biceps muscle has its origin at the supraglenoid tubercle. Ensheathed by the synovial membrane, it runs intra-articularly on top of the humeral head to exit the joint capsule through the intertubercular groove. The short head of the biceps originates from the coracoid process. Both heads have a common insertion onto the tuberosity of the radius laterally and onto the ulnar fascia of the forearm medially.[40] Although it acts as a stabilizer of the humeral head,[33,37,82] its main function is to effect elbow flexion and forearm supination. The biceps muscle is innervated by the musculocutaneous nerve (C5–6).

Triceps. The long head of the triceps originates from the infraglenoid tubercle and the inferior labrum to insert in common with both other heads onto the olecranon. The long head participates in extension and adduction of the glenohumeral joint, whereas the main function of the whole muscle is extension of the elbow joint. The radial nerve (C6–8) supplies innervation.

Coracobrachialis. The coracobrachialis muscle originates in common with the short head of the biceps on the coracoid process to insert onto the anteromedial surface of the central humerus. It participates in flexion and adduction of the glenohumeral joint.

The musculocutaneous nerve enters the coracobrachialis muscle between 2 and more than 5 cm inferior to the tip of the coracoid process[89] to innervate it.

Biomechanics

Motion

The humeral head and the glenoid articular surface show a high degree of conformity.[97] The humeral head is believed to be more convex in the anterior-posterior direction than in the superior-inferior direction.[29,56] Soslowsky et al[97] measured the sphericity of the humeral head using stereophotogrammetry, however, and concluded that the articular surface of the humeral head could be approximated by a sphere with small deviations of less than 1% of the radius. According to Boileau and Walch,[9] the difference between the two diameters of the humeral head is less than 1 mm in 88.2% of the tested specimens. The motion of the glenohumeral joint is basically ball-and-socket in nature.

During active and passive arm elevation, the superior-inferior translation of the humeral head is only 0.3 to 0.35 mm in normal shoulders.[11,23] Anterior-posterior translation is substantially larger. The head translates anteriorly 3.8 mm on average during flexion, translates posteriorly 4.9 mm during extension,[23] and translates 4 mm during horizontal extension.[26] Larger translations in the anterior-posterior direction than in the superior-inferior direction occur as a result of the bony configuration of the glenoid because it is more concave in the superior-inferior direction (radius of curvature = 32.2 ± 7.6 mm) than in the anterior-posterior direction (radius of curvature = 40.6 ± 14 mm).[56]

Glenohumeral kinematics is affected by various pathologic conditions of the shoulder. Partial-thickness or full-thickness rotator cuff tears typically are associated with superior migration of the humeral head during arm elevation. This migration is caused by the imbalance between the deltoid and the insufficient cuff muscles (Fig. 4).[80,87,107] Even with the intact cuff tendons, muscle fatigue might cause superior shift of the humeral head.[11] In shoulders with anterior instability, the humeral head is located more anteriorly with the arm in horizontal extension and external rotation.[80] In stiff shoulder joints, the humeral head moves upward during the first degrees of arm elevation.[20]

In a spatial motion analysis, Browne et al[10] observed that the maximal glenohumeral elevation was obtained in a plane 23° anterior to the scapular plane with the arm in 35° of external rotation. The maximal humerothoracic elevation is achieved in a plane 4° posterior to the scapular plane.[81] This discrepancy seems to result from a difference between isolated motion of the glenohumeral joint and combined motion of the glenohumeral and scapulothoracic joints. External rotation at the glenohumeral joint during arm elevation is necessary to clear the greater tuberosity from the coracoacromial arch and to accommodate the retroverted articular surface in an optimal position for glenoid contact. With the arm in external rotation, a larger portion of the articular surfaces are in contact.[41]

Harryman et al[23] demonstrated that translation of the humeral head reproducibly accompanied passive movements of the glenohumeral joint. The humeral head translates anteriorly with the arm in flexion and posteriorly with the arm in extension. This forced translation is thought to be induced by the tightening of the capsuloligamentous structures during motion (Fig. 5). Excessive tightness of the anterior capsule after anterior capsulorrhaphy leads to posterior subluxation.[55]

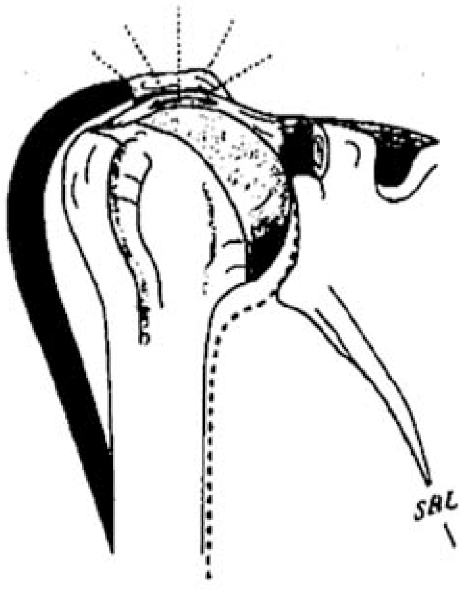

Figure 4. Partial- or full-thickness rotator cuff tears typically are associated with superior migration of the humeral head during arm elevation, caused by the imbalance between the deltoid and the insufficient cuff muscles. (*Modified from* Matsen FA III, Lippitt SB, Sidles JA, et al: Practical Evaluation and Management of the Shoulder. Philadelphia, WB Saunders, 1994.)

Stability

Ligaments. The superior glenohumeral ligament is an anterior stabilizer[73] and an inferior stabilizer in the hanging arm position.[74,104] The major role of the middle glenohumeral ligament is anterior stabilization with the arm in adduction[73] up to 30° to 45° of abduction.[39,101] This function is apparent in 90° of abduction with the arm in neutral rotation but not in external rotation.[7] It is also an inferior stabilizer with the arm in adduction.[74]

The inferior glenohumeral ligament is the most important anterior stabilizer with the arm in abduction and external rotation, the position of anterior dislocation.[7,39,101] The function is by its anterior band and the axillary pouch but not by its posterior band.[103] The posterior band is a posterior stabilizer with the arm in flexion and internal rotation[7,66,106] or in 90° of abduction.[14] With abduction and external rotation, the anterior band fans out to support the humeral head, whereas the posterior band becomes cordlike. The opposite happens in internal rotation (Fig. 6).[71,72]

The coracohumeral ligament (CHL) is known to be an inferior stabilizer with the arm in adduction.[4,74] It functions as an inferior sta-

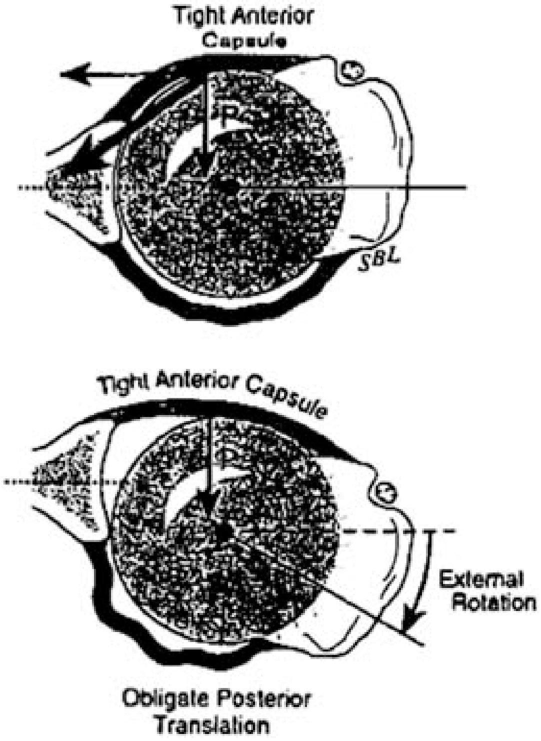

Figure 5. Translation of the humeral head accompanies even passive movements of the glenohumeral joint. This forced translation is induced by the tightening of the capsuloligamentous structures during motion. Excessive tightness of the anterior capsule following anterior capsulorrhaphy leads to posterior subluxation. P = displacing force. (*Modified from* Matsen FA III, Lippitt SB, Sidles JA, et al: Practical Evaluation and Management of the Shoulder. Philadelphia, WB Saunders, 1994.)

bilizer and tightens in external rotation.[32] The CHL also stabilizes the head in the superior direction but to a minor degree.[32]

A rotator cuff interval lesion is clinically apparent as inferior instability with the arm in internal rotation but not in external rotation.[68] The rotator interval capsule indirectly stabilizes the shoulder inferiorly by means of maintaining the negative intra-articular pressure.[32] In external rotation, the CHL prevented inferior instability even after the interval capsule was sectioned. The rotator interval capsule also provides posterior stability.[24]

Glenoid Concavity. The glenoid fossa has a concavity, which centers the humeral head on the glenoid. It is deeper in the superior-inferior direction than in the anterior-posterior direction.[56] The humeral head is more stable in the superior-inferior direction than in the anterior-posterior direction (Fig. 7). When the head is compressed onto the glenoid fossa, the force necessary to dislocate the head is approximately 60% of the compressive force (stability ratio) in the superior-inferior directions and 35% in the anterior-posterior directions.[52]

Labrum. The function of the labrum is to increase the stability of the humeral head on the glenoid socket by increasing the depth of its cavity.[26] After removal of the labrum, the stability ratio decreases by 20% on average.[53]

Scapular Inclination. Basmajian and Bazant[4] noticed that the shoulder was unstable inferiorly when the arm was in abduction, but it was stabilized with the arm in adduction. They thought that in adduction, the superior capsuloligamentous structures became tight because of the slope of the glenoid fossa, which prevented inferior translation of the humeral head (Fig. 8). This situation was confirmed by Itoi et al,[36] who demonstrated that the shoulder was stabilized inferiorly by the scapular inclination angle in the hanging arm position. In shoulders with multidirectional instability, the scapula is less abducted during arm elevation than in healthy shoulders.[77] Inferior instability as part of multidirectional instability can thus be explained by the lack of the stabilizing effect of scapular inclination.

Intra-articular Pressure. The shoulder joint is concealed by the capsule, and the pressure inside the capsule is negative when the arm is in hanging position.[48] With a downward load applied to the arm, the negative pressure increases, preventing the inferior translation of the humeral head.[35] The negative pressure provides inferior stability with the arm in abduction.[105]

Muscles. Muscles are supposed to stabilize the joint by the following five mechanisms[60]: (1) passive muscle tension from the bulk effect of the muscle itself,[48,74] (2) contraction causing compression of the articular surfaces,[52] (3) joint motion that secondarily tightens passive ligamentous constraints,[15] (4) barrier effect of the contracted muscle,[99] and (5) redirection of the joint reaction force to the center of the glenoid surface by coordination of muscle activity.[52]

Deltoid. The deltoid is a large, powerful muscle and is supposed to be an effective stabilizer. In static condition, the deltoid provides little inferior stability.[64] Dynamically the anterior and middle portions of the deltoid do not contribute extensively to posterior stability with the arm in flexion.[8] The role of this muscle in anterior or inferior stability has not been clarified yet.

Rotator Cuff. The subscapularis was described as the most important active and pas-

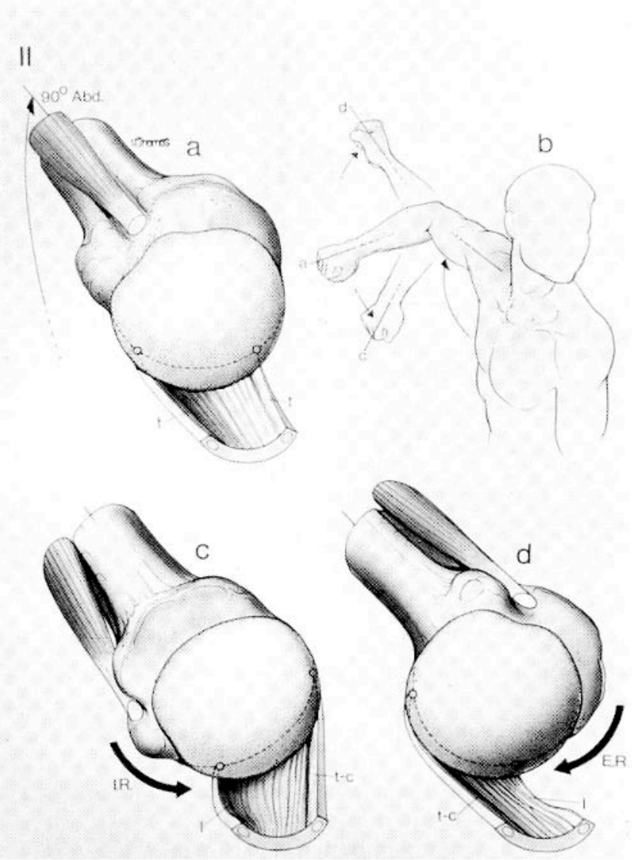

Figure 6. With abduction and external rotation (ER) the anterior band of the inferior glenohumeral ligament fans out to support the humeral head while the posterior becomes cord-like. The opposite happens in internal rotation (IR). (*From* O'Brien SJ, Answorth AA, Fealy S, et al: Developmental anatomy of the shoulder and anatomy of the glenohumeral joint. *In* Rockwood CA, Jr, Matsen FA III: The Shoulder, ed 2, vol 1. Philadelphia, WB Saunders, 1998, p 20.)

sive anterior stabilizer among the rotator cuff muscles.[16] Blasier et al[7] demonstrated in a displacement control study, however, that the subscapularis, supraspinatus, and infraspinatus and teres minor equally contributed to anterior stability of the abducted shoulder with the arm in neutral and in external rotation. With the arm in 90° of flexion, the subscapularis is the primary posterior stabilizer.[8]

The rotator cuff muscles usually function together. Inman et al[31] introduced a concept of a force couple in the frontal plane consisting of the deltoid and supraspinatus muscles as elevators and inferior portions of the rotator cuff muscles as depressors. Saha[92] described the force couple in the horizontal plane comprising the subscapularis anteriorly and infraspinatus and teres minor muscles posteriorly. If the rotator cuff muscles are loaded simultaneously, the humeral head is stabilized in the superior-inferior direction[95] as well as in the anterior-posterior direction (Fig. 9).[107]

Biceps. Clinical data suggest that the biceps functions as stabilizer of the shoulder. In patients with rupture of the long head of the biceps tendon, the humeral head translates superiorly during arm abduction.[102] In anteriorly unstable shoulders, electromyographic activity of the biceps during throwing motion is increased.[22] Studies using cadaveric shoulders have clarified the stabilizing function of the biceps in the superior,[49,79] inferior,[37,79] anterior,[33,37,79,91] and posterior directions.[7,79] Stabilization by the long head of the biceps depends on the integrity of the superior labrum. After creating a superior labral lesion, the stabilizing

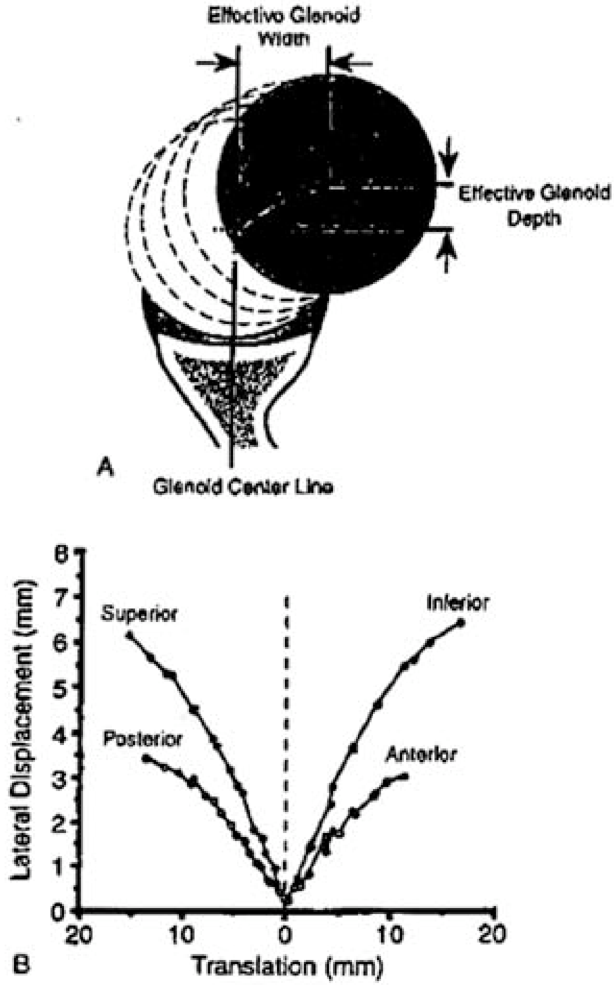

Figure 7. The glenoid fossa has a concavity, which centers the humeral head on the glenoid (*A*). The glenoid fossa is deeper and, thus, the humeral head is more stable in the superior-inferior direction than in the anterior-posterior direction (*B*). (*Modified from* Matsen FA III, Lippitt SB, Sidles JA, et al: Practical Evaluation and Management of the Shoulder. Philadelphia, WB Saunders, 1994.)

function of the biceps becomes less efficient as a result of the lax labrum and the elongated tendon.[78]

Force

Physiologic Cross-Sectional Area. Maximal muscle force is proportional to the physiologic cross-sectional area of the muscle, which is obtained by dividing muscle volume by muscle fiber length. The absolute maximal force of the muscle is calculated by multiplying the physiologic cross-sectional area by a conversion factor depending on muscle pretension, which varies from 4.7 kg/cm^2 with the elbow flexed and 6.3 kg/cm^2 with the elbow extended[30] to 9.2 kg/cm^2.[61]

Moment Arm. The effectiveness of a muscle as a mover depends on the orientation of the muscle relative to the center of rotation. The distance from the center of rotation to the line of force is defined the moment arm, which can be calculated by the geometric method, tendon excursion–joint rotation method, or direct load measurement.[1]

Kuechle et al[47] used an electropotentiometer to measure the moment arms of the rotator cuff muscles during abduction and adduction. According to their study, the supraspinatus is

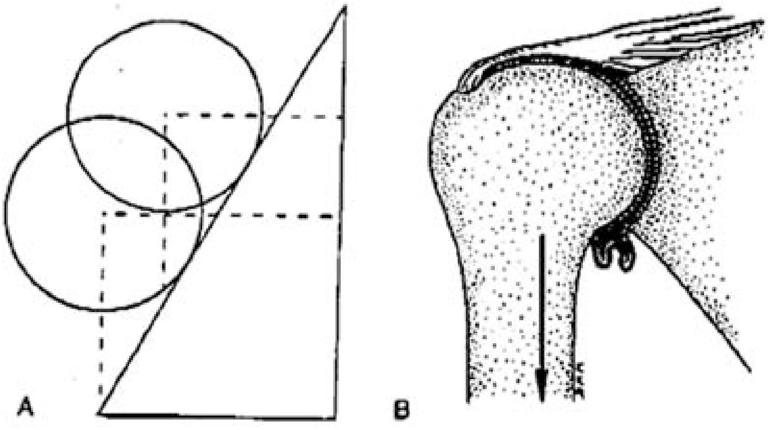

Figure 8. *A* and *B*, In adduction, the superior capsuloligamentous structures become tight because of the slope of the glenoid fossa, which prevents inferior translation of the humeral head. (*From* Basmajian JV, Banzat FJ: Factors preventing downward dislocation of the adducted shoulder joint. J Bone Joint Surg 41A:1182,1959; with permission.)

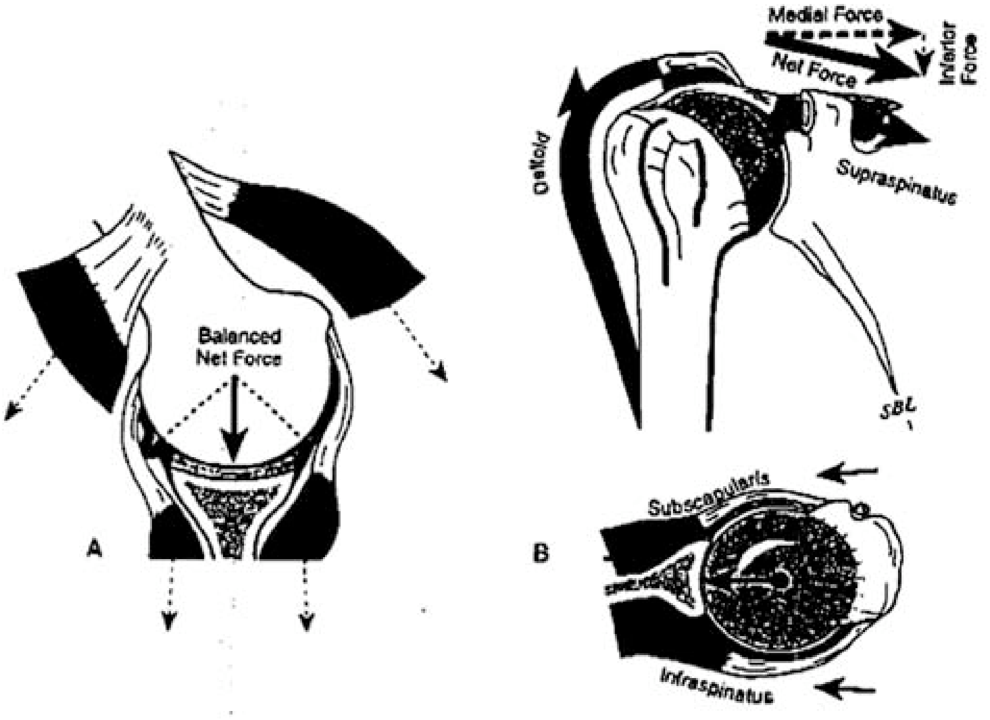

Figure 9. The force couple in the frontal plane consists of the deltoid and supraspinatus muscles as elevators and inferior portions of the rotator-cuff muscles as depressors (*A*). The force couple in the horizontal plane comprises the subscapularis anteriorly and infraspinatus and teres minor muscles posteriorly (*B*). If the rotator-cuff muscles are loaded simultaneously, the humeral head is stabilized in the superior-inferior direction as well as in the anterior-posterior direction. (*Modified from* Matsen FA III, Lippitt SB, Sidles JA, et al: Practical Evaluation and Management of the Shoulder. Philadelphia, WB Saunders, 1994.)

the most efficient elevator, and the teres minor is the most efficient depressor of the rotator cuff muscles throughout the entire range of motion. The infraspinatus changes from being an elevator to being a depressor, and the subscapularis changes from being a depressor to being an elevator with increasing elevation angle (Fig. 10).

Kuechle[46] also reported the moment arms of 10 muscles around the shoulder. The results showed that during horizontal flexion and extension, the pectoralis major and the anterior deltoid were the most efficient horizontal flexors, whereas the posterior deltoid along with the posterior rotator cuff muscles were the most effective horizontal extensors. During rotation with the arm at the side, the infraspinatus and the teres minor were the most efficient external rotators. The subscapularis was the most efficient internal rotator followed by the pectoralis major, latissimus dorsi, teres major, and anterior deltoid. During rotation with the arm abducted, the most efficient external rotators were the teres minor followed by infraspinatus, whereas the most efficient internal rotators were the subscapularis followed by pectoralis major, latissimus dorsi, and teres major.

Muscle Activity. The electromyographic study by Inman et al[31] showed that the abductors were the deltoid, pectoralis major, and supraspinatus, whereas the depressors were the infraspinatus, teres minor, and subscapularis. The abductors and depressors are coupled and act together during elevation. Electromyographic activity of the biceps increased in one third of the patients with rotator cuff tears.[44] Because these patients showed decreased strength in abduction and external rotation, it is likely that the biceps functions as a supplementary mover.

Torque. Theoretic torque is calculated by the physiologic cross-sectional area, a constant, the percentage of maximal voluntary contraction, and the moment arm. The model proposed by Hughes and An[28] predicted the highest rotator cuff muscle forces during maximal internal rotation (subscapularis) and external rotation exertions (infraspinatus, teres minor, and supraspinatus). The results indicate that abduction exertions may not produce the highest loads on the supraspinatus tendon.

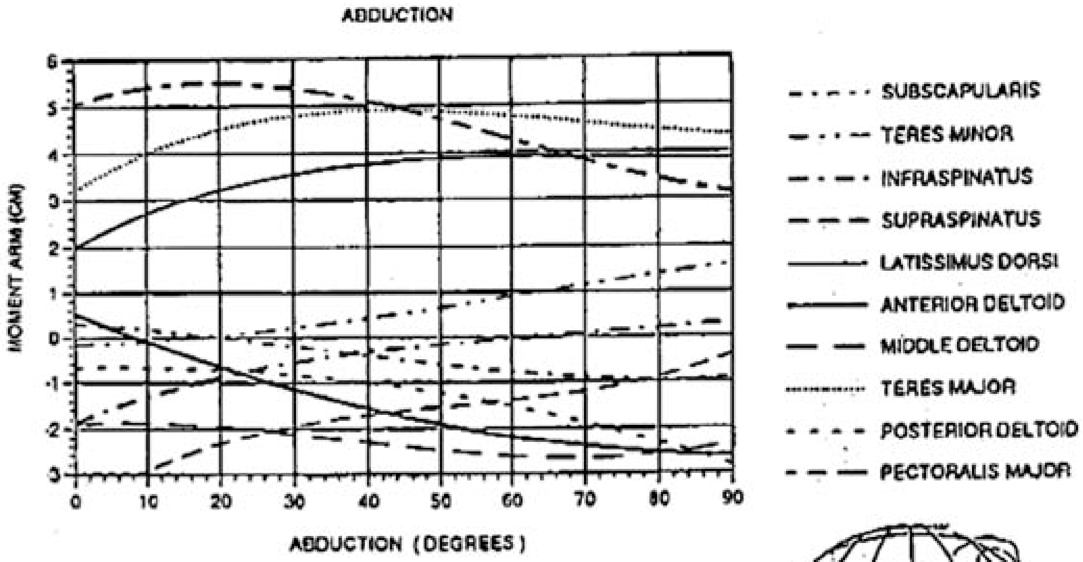

Figure 10. Shoulder-muscle moment arms during elevation in the frontal plane. (*From* Kuechle DK, Newman SR, Itoi E, et al: Rotator cuff function during humeral elevation in four planes. Trans Orthop Res Soc 18:138, 1993; with permission.)

Clinically, shoulder torques in various movements are measured with use of an isokinetic dynamometer. Ivey et al[38] established isokinetic normative torque of the shoulder muscles. Internal rotation is higher than external rotation torque (3:2), extension is higher than flexion torque (5:4), and adduction is higher than abduction torque (2:1). Overall, adduction strength is highest, followed by extension, flexion, abduction, internal rotation, and external rotation.

The overall strength of the shoulder is measurable, but the function of each of the shoulder muscles cannot be specified by this method. To isolate the function of the supraspinatus, Itoi et al[34] measured isokinetic strength of the shoulders with isolated tears of the supraspinatus tendon. The decreases in torque of 19% to 33% in abduction and 22% to 33% in external rotation appear to represent the contribution of the supraspinatus to the overall strength of the shoulder.

Selective nerve blocking is used to examine single muscle functions, although isolation is not complete. Howell et al[27] measured the reduction in shoulder torque produced by paralysis of the suprascapular nerve and axillary nerve. Each of the suprascapular and axillary nerve palsies produced a similar 50% reduction in torque compared with the nonparalyzed shoulder. As the suprascapular nerve innervates the supraspinatus and infraspinatus and the axillary nerve innervates the deltoid and teres minor muscles, it is likely that the supraspinatus–infraspinatus unit and the deltoid–teres minor unit are equally responsible for producing torque about the shoulder joint.

Resultant Force. Inman et al[31] calculated the joint reaction force of the glenohumeral joint with only the deltoid and the rotator cuff muscles taken into account. Poppen and Walker[86] calculated the joint reaction force using the same method but took all the muscles active at each phase of the motion into account. The joint reaction force reached a maximum of 0.89 times body weight at 90° of abduction in the scapular plane, whereas the shear force component on the glenoid reached a maximum of 0.42 times body weight at 60° of abduction.

Karlsson and Peterson[43] introduced a three-dimensional biomechanical model of the shoulder to analyze static load sharing between the muscles, bones, and ligaments. The musculoskeletal forces were predicted using the optimization technique with the sum of squared muscle stresses as an objective function. Using this model, the joint reaction force reached a peak value of 650 N at 60° abduction.

SCAPULOTHORACIC JOINT

Anatomy

Scapula

The scapula (see Fig. 1) functions mainly as a site of muscle attachment. It is a flat, triangular bone that is thicker at its superior and inferior angles and at its lateral border to support the attachment of powerful muscles. The anterior subscapular fossa is flat and slightly concave, whereas the posterior, slightly convex infraspinatus fossa is separated from the supraspinatus fossa by the scapular spine, which is one of four scapular processes.

Processes

Spine. The scapular spine originates from the medial scapular border with a triangular thickening and runs superolaterally on the posterior surface to form the trapezoidal acromion process. It stiffens the body of the scapula and suspends the acromion as lever arm for the deltoid muscle.

Acromion. As the acromion extends anterolaterally in bipeds to form a sufficient insertion site for the strong deltoid muscle, it is placed on top the rotator cuff tendons. It limits the space mainly for the supraspinatus tendon confined inferiorly by the humeral head. For this reason, the shape of the acromion is believed to be decisive in the development of rotator cuff degeneration. Bigliani et al[6] defined three types of the acromion: flat, curved, and hooked. A curved undersurface of the acromion as well as an increased inferior tilt seems to be associated with rotator cuff tears.[3] An unfused acromion epiphysis causes functional deformability and decreased subacromial space.[65] Based on the size of the unfused bone, Liberson[51] defined a preacromion, mesoacromion, metaacromion, and basiacromion, of which the meso-metaacromion has the highest incidence.[51]

Coracoid. Anterior to the base of the acromion, the coracoid process originates from the neck of the glenoid. The round process hooks to point anterolaterally and ends flattened. In 1% of the population, an abnormal connection, such as a bony bar or an articulation to the clavicle, is described.[69] The coracoid process is the attachment site of muscles—the pectoralis minor, short head of the biceps, and coracobrachialis—and ligaments—the coracoclavicular, coracoacromial, and coracohumeral ligaments. Medial to the coracoid process, the suprascapular notch separates it from the flat body of the scapula.

Glenoid. The glenoid process is discussed under the glenohumeral joint.

Ligaments. Apart from the ligaments linking the scapula to the clavicle and to the humerus, there are ligaments connecting scapular processes. The coracoacromial ligament has a broad base at the horizontal part of the coracoid and tapers toward the acromion to insert on its undersurface. Together with the coracoid and the acromion, it forms the roof of the shoulder. The superior transverse scapular ligament closes the suprascapular notch medial to the coracoid process. The inferior transverse scapular ligament connects the base of the acromion with the posterior-superior border of the glenoid and bridges the spinoglenoid notch.

Thoracohumeral Muscles (Figure 11)

Latissimus Dorsi. The broad latissimus dorsi muscle originates from the spinous processes of T7–12 with its vertebral part, from the thoracolumbar fascia and the iliac crest with its iliac part, and from the 10th through 12th rib with its costal part. Frequently a scapular part originates from the inferior angle of the scapula.[85] It is the most powerful adductor, an internal rotator, and an extensor of the shoulder joint. Indirectly, it depresses the lateral angle of the scapula and retracts it. The thoracodorsal nerve innervates it (C7–8).

Pectoralis Major. The clavicular part of the pectoralis major muscle originates from the anterior medial clavicle, the sternocostal part from sternum and the second through fourth ribs, and the abdominal part from the fifth and sixth ribs and the external oblique muscle fascia. Their common insertion site is the lateral rim of the intertubercular groove. The muscle fibers are twisted 180° so that the inferior fibers insert superiorly to form the anterior axillary fold.[85] The pectoralis muscle is a strong adductor and internal rotator, and the clavicular part is active in flexion. Indirectly, it depresses the lateral angle of the scapula. The lateral pectoral nerve (C5–7) innervates the clavicular portion, whereas the medial pectoral nerve (C8–T1) innervates the remaining parts.

Scapulothoracic Muscles

Trapezius. The trapezius is shaped similar to a tent and consists of a descending, a transverse, and an ascending part. The descending part originates from the occipital protuberance and the nuchal ligament to insert onto the lateral clavicle. The transverse part originates from the spinous processes of C-7 through T-3 and inserts onto the medial acromion and lateral scapular spine. The ascending part originates from the spinous processes of T-3 through T-12 to insert onto the medial scapular spine. The main passive task of the trapezius is static support of the scapula.[85] Active functions are retraction of the scapula, elevation of its lateral angle, and upward rotation.[31] Consequently, paralysis leads to protraction and downward rotation of the scapula, with arm elevation in the scapular plane being limited to 90°.[18] It is innervated by the accessory nerve—cranial nerve XI—and gets sensory branches from C2–4.[85]

Rhomboids. The rhomboid minor muscle originates from the spinous processes of C-6 and C-7 and the rhomboid major muscle from the spinous processes of T-1 through T-4. Their insertion site is the medial margin of the scapula superior and inferior of the scapular spine. Their function is retraction and elevation of the scapula. The dorsal scapular nerve (C4–5) innervates them.

Levator Scapulae. The levator scapulae muscle originates from the transverse processes of C-1 through C-4 to insert onto the superior angle of the scapula. It elevates the scapula and rotates it downward. The dorsal scapular nerve (C4–5) innervates it.

Serratus Anterior. The serratus anterior muscle consists of superior, middle, and inferior parts. Their origins are the anterior aspects of the first through the ninth rib, whereas two heads attach to the second rib.[85] The insertion site extends from the superior to the inferior angle of the scapula along the entire anterior aspect of the medial margin. Its main function is fixation of the scapula onto the thoracic cage as well as scapular protraction and upward rotation. Paralysis results in winging of the scapula[54] and limits flexion to 90°. The innervation of the serratus anterior muscle is the long thoracic nerve (C5–7).

Pectoralis Minor. The pectoralis minor muscle originates from the anterior aspects of the third through fifth ribs to insert onto the medial border of the coracoid process with frequent aberrant fibers to the humerus. Its functions are depression of lateral angle of the scapula or downward rotation and protraction. Its innervation is the pectoral nerves (C5–T1).

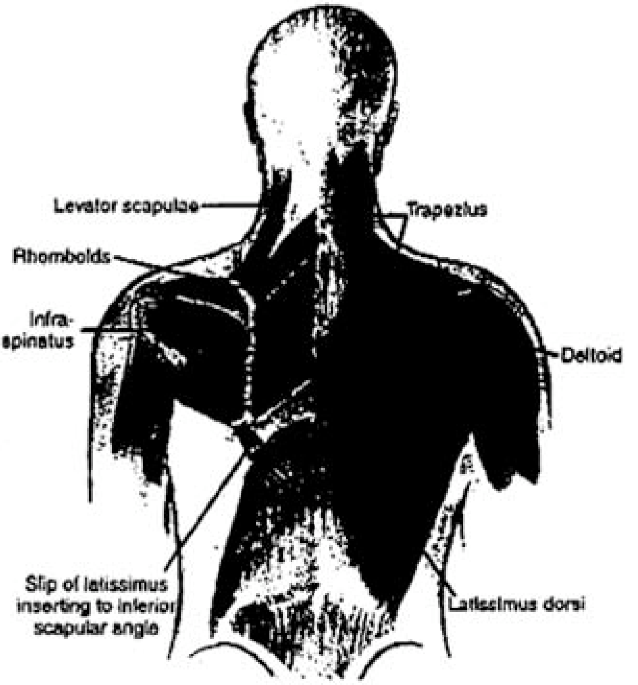

Figure 11. Posterior scapulothoracic muscles, the infraspinatus and the deltoid. (*From* Butters KP: The scapula. *In* Rockwood CA Jr, Matsen FA III: The Shoulder, ed 2, vol 1. Philadelphia, WB Saunders, 1998, p 393.)

Subclavius. The tendinous origin site of the subclavian muscle is the medial part of first rib, and it has a fleshy insertion on the subclavian groove on the inferior surface of the clavicle. By pulling the clavicle toward the sternum, it stabilizes the sternoclavicular joint. The subclavian nerve (C5–6) innervates it.

Biomechanics

Motion

The scapula is positioned on the thorax about 30° internally rotated in the horizontal plane, 3° abducted in the frontal plane, and 20° tilted anteriorly in the sagittal plane.[50] Laumann[50] measured the three-dimensional motion of the scapula using stereophotogrammetry and concluded that the scapula abducted 60°, tilted posteriorly 20°, and rotated internally 6° during the first half of elevation, then externally rotated 16° during the second half of elevation. As a result, the scapula externally rotated 10°. In addition to these three rotatory motions, there are two translatory movements: superior-inferior movement and forward-backward movement. These movements do not occur independently. Protraction is the combination of forward movement of the scapula away from the vertebral column, rotation of the scapula around the acromioclavicular joint (anterior tilt), and internal rotation.[13] Retraction is the combination of opposite movements. Abduction of the scapula is advantageous from a biomechanical point of view: (1) It increases the range of humerothoracic motion, (2) it maintains muscle efficiency by enabling the muscles to work in the optimal portion of their length-tension curve, and (3) it allows the glenoid to be brought underneath the humerus to share some weight of the arm.

If the scapulothoracic joint is fused, glenohumeral extension and external rotation are significantly decreased, whereas internal rotation remains unchanged.[25] This situation is due to the fact that internal rotation occurs mainly in the glenohumeral joint. Healthy subjects use about 15° of scapulothoracic internal rotation to perform personal care activities. In contrast, an average of 51° of scapulothoracic internal rotation is used to perform these activities after glenohumeral fusion. In contrast to scapulothoracic fusion, glenohumeral fusion decreases patients' abilities to perform personal care activities requiring extremes of internal rotation despite the increased scapulothoracic internal rotation.[25]

Stability

Scapulothoracic stability depends on the muscles and fasciae attached to the scapula. The deep fascia of the neck that encases the trapezius and sternocleidomastoid muscles connects the head, clavicle, and scapular spine, providing passive suspension. The deep fascia of the back also provides static stability. Although vertical muscles, such as the upper trapezius, levator scapulae, and upper digitations of the serratus anterior, are important dynamic suspensors, they are also supposed to provide passive suspension.[31] No electromyographic activities were recorded in these muscles during standing,[5] whereas continuous activity of the upper trapezius is recorded during walking.[2] This activity indicates that the trapezius provides active suspension during arm swinging while walking.

Active elevation of the arm initiates active contraction of the vertical muscles as well as other parascapular muscles. Dynamic contractions of the middle and inferior trapezius, serratus anterior, and rhomboids stabilize the scapula and provide the upper extremity with a firm, yet mobile socket. Functional loss of these muscles makes the scapula unable to counterbalance the weight of the arm during arm elevation, resulting in scapular winging.

Force

The movers for scapular abduction are the trapezius and the serratus anterior muscles. The serratus anterior and pectoralis minor muscles are the prime movers for protraction, whereas the middle trapezius and rhomboid muscles effect retraction.[62] Inman et al[31] developed the concept of a force couple about the scapula. He noted three force directions: upward rotation, medial contraction, and anterolateral force at the inferior angle. The upper trapezius, upper digitations of the serratus anterior, and levator scapulae form the upper part of the force couple. The lower trapezius and lower digitations of the serratus anterior form the lower part of the force couple. This was confirmed by an electromyographic study by Moseley et al.[63] The pectoralis minor, which was described as the main protractor, was less active than the serratus anterior during push-up (scapular protraction) but more active than any other muscles during press-up (scapular depression). This difference indicates that the pectoralis minor muscle is more important as a scapular depressor rather than as a protractor. Considering its small size, the pectoralis minor may be active for fine motor control rather than strength.[83]

Normal Scapulohumeral Rhythm

The coordinated movements in the glenohumeral and scapulothoracic joint effecting arm elevation are known as *scapulohumeral rhythm*. Inman et al[31] estimated the ratio between the glenohumeral and scapulothoracic motion to be 2:1 (Fig. 12). The ratio was inconsistent during the first 30° of elevation[19,21] but overall about 2:1.[21,87] Harryman et al[25] measured the ratio for planes other than the scapular or coronal plane and concluded that it was consistent and essentially 2:1. Paletta et al[80] reported that the ratio was 2:1 at the initial 45°, then changed to 3:2 during the rest of the motion. Although the ratio is shown to be nonlinear in elevation, the overall ratio averages about 2:1.

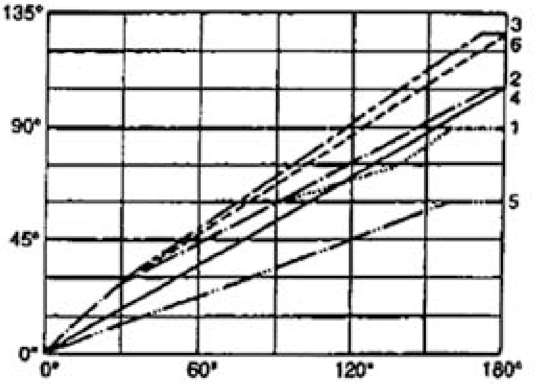

Figure 12. The coordinated movements in the glenohumeral and scapulothoracic joint-effecting arm elevation are known as scapulohumeral rhythm. Angular changes of the glenohumeral joint with respect to arm elevation were measured by several investigators. Nobuhara et al, 1977; Poppen U. Walker, 1976; Inman et al, 1944; Freedman U. Munro, 1966; Wallace, 1982; Reeves, 1972. (*From* Bergmann G: Biomechanics and pathomechanics of the shoulder joint with reference to prosthetic joint replacement: *In* Koelbel R, Helbig B, Blauth W (eds): Shoulder Replacement. Berlin, Springer-Verlag, 1987; with permission.)

Abnormal Scapulothoracic Rhythm

Poppen and Walker[87] noticed that the rhythm became abnormal in patients with shoulder pain, but they did not correlate this with the clinical diagnosis. Glenohumeral-to-scapulothoracic ratio increases in shoulders with multidirectional instability[77] and decreases in shoulders with impingement and rotator cuff tear.[17] Paletta et al[80] specified that in anteriorly unstable shoulders, the ratio increased during the first half of elevation, then decreased during the second half of elevation. Relatively increased motion at the glenohumeral joint may be caused by imbalance of the scapular movers, and decreased motion at the glenohumeral joint may be the result of restricted motion in the subacromial space to avoid pain.

Future

Although the glenohumeral joint has been thoroughly investigated, research should further elucidate biomechanics of the scapulothoracic articulation.

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