10 Anatomy and Kinematics of the Shoulder Joint

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10.1 Introduction

The shoulder joint is the most mobile joint of the entire body. This mobility is achieved due to the lack of bony restraints and dependence on soft-tissue static and dynamic stabilizers.

The "shoulder joint" is, in itself, comprised by four "joints" and a space worth mentioning. Three of them are proper joints: glenohumeral, acromioclavicular, and sternoclavicular. On the other hand, the fourth "joint," not a joint in itself, is the scapulothoracic interface. The subacromial space, a gap between bones filled with soft tissues, completes this list.

The shoulder girdle, formed by the scapula and clavicle, connect the shoulder and upper limb to the rest of the body: the spine and thorax being the axis on which the shoulder supports itself in order to perform its main function, which is to adequately and precisely position the upper limb, and ultimately the hand, in space.

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10.2 Shoulder Anatomy

10.2.1 Scapula and Glenohumeral Joint

The scapula is a somewhat flat, triangular-shaped bone located posterolateral to the rib cage [1], with a "resting" orientation of 30 degrees of anteversion [2], 3–10 degrees of abduction [3] and 10–20 degrees of anterior tilt [4]. It is located vertically from the second (superior angle) to the seventh to ninth rib (inferior angle). It has three borders and three apices or angles, with a posterior ridge that goes from the spinal trigone at the medial border to the superolateral angle called the spine of the scapula; its lateral end bends an average of 78 degrees anteriorly [5] forming the acromion. The spine divides the posterior surface of the scapula into two fossae: the supraspinatus (origin of the supraspinatus muscle) and infraspinatus (origin of the infraspinatus and teres minor muscles) fossae (Fig. 10.1). Its slightly concave anterior surface, the subscapular fossa, holds the origin of the subscapularis muscle and anterior to it the scapulothoracic interface. On its lateral side, the coracoid process emerges anteriorly, superiorly and slightly laterally; medial to its origin it forms with the body of the scapula the supraglenoid notch (Fig. 10.2), covered by the superior transverse scapular ligament and traversed by the suprascapular nerve.

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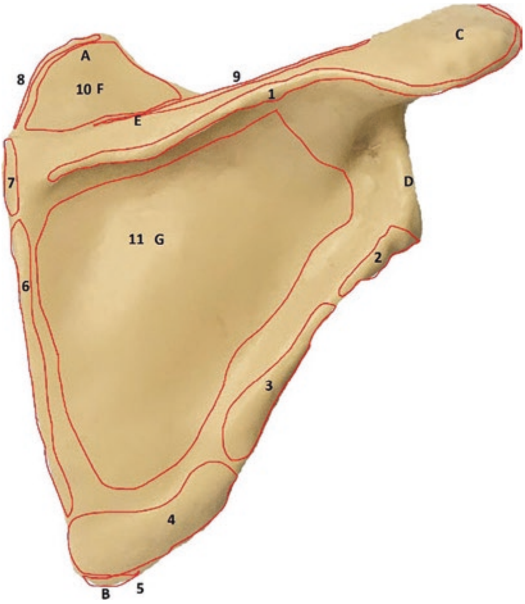
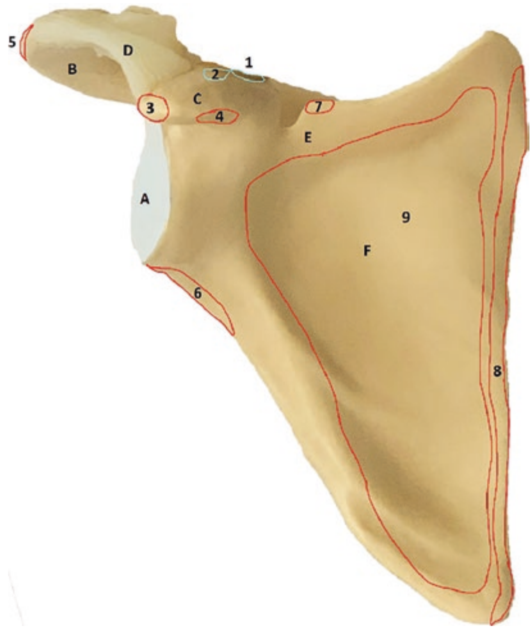


Landmarks	Muscle insertions/origins
A: Superior angle	1: Deltoid
B: Inferior angle	2: Triceps, long head
C: Acromion	3: Teres minor
D: Glenoid	4: Teres major
E: Spine	5: Latissimus dorsi
F: Supraspinatus fossa	6: Rhomboid major
G: Infraspinatus fossa	7: Rhomboid minor
	8: Levator scapulae
	9: Trapezius
	10: Supraspinatus
	11: Infraspinatus

Fig. 10.1 Osseous landmarks and muscular insertions of the posterior scapula



Landmarks	Muscle/ligament insertions/origins
A: Glenoid fossa	1: Conoid ligament
B: Acromion process	2: Trapezoid ligament
C: Coracoid process	3: Conjoined tendon
D: Coracoacromial ligament	4: Pectoralis minor
E: Spinoglenoid notch	5: Deltoid
F: Subscapularis fossa	6: Long head of triceps
	7: Omohyoid
	8: Serratus anterior
	9: Subscapularis

Fig. 10.2 Osseous landmarks and muscular/ligamentous insertions of the anterior scapular face

From its lateral end, the scapula projects the glenoid process (or simply "glenoid"). It arises from the body of the scapula and extends laterally, superiorly and slightly posteriorly and has a truncated "cone" shape (the articular surface constituting the base). We should remember that the scapular main transverse axis is oriented with 30/40 degrees of anteversion related to the main body axis. The glenoid surface typically has an average of 1.4–3.2 degrees of retroversion [6] related to, but it is generally considered perpendicular to, the scapular axis. The glenoid has a neck that measures approximately 2 cm from its base at the junction of the spine and the coracoid and presents at its posteromedial side a notch for the passage of the suprascapular nerve, called the spinoglenoid notch (Fig. 10.2), which in turn is covered by the inferior transverse scapular ligament (and traversed by the suprascapular artery and nerve). The glenoid widens from medial to lateral, ending on its lateral side (the "base" of the cone) as a concave, pear-shaped fossa; if we think of it as the intersection of two "circles," the superior one would have a smaller diameter than the inferior (which is considered by many to be a true circle [7]) and the center of the latter being slightly more anterior (Fig. 10.3). This fossa, covered in cartilage, has a radius of curvature 2.3 ± 0.2 mm longer than that of the humeral head (24 ± 2.1 mm) [8], but its surface is about 3–4 times smaller than the latter, resembling a golf ball over a tee (Fig. 10.4).

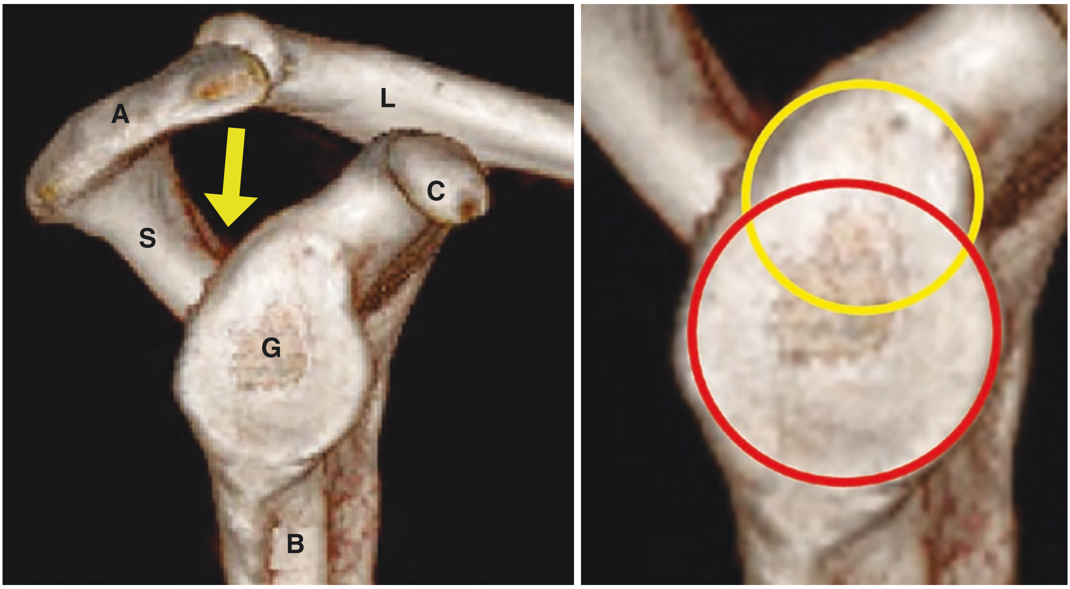


Fig. 10.3 Left: 3D-CT scan of right scapula. Note the pear-shaped glenoid surface. G: Glenoid. A: Acromion. S: Scapular spine. C: Coracoid process. L: Clavicle. B: Scapular body. Yellow arrow: spinoglenoid notch. Right: The pear-shaped glenoid can be seen as the combination of two intersecting circles, the inferior one being larger and more anterior than the superior one

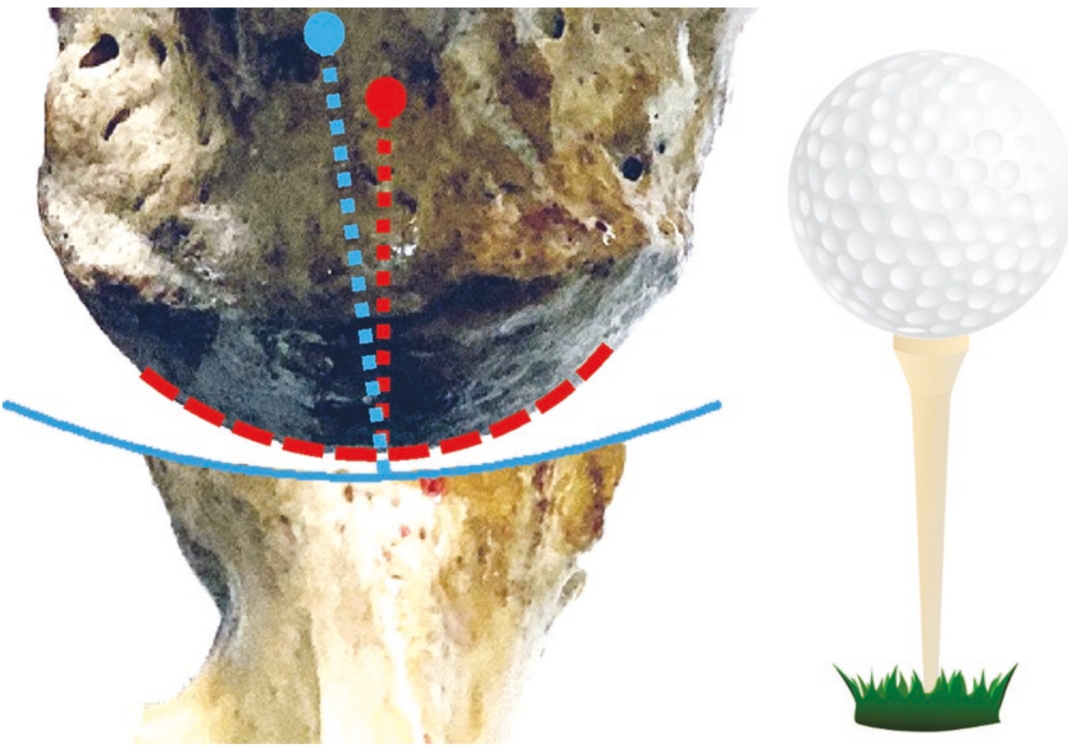


Fig. 10.4 Left: Comparison of radii of curvature of the humeral head (red) and glenoid (blue). Note how the glenoid's radius is larger than the humeral head's due to its being flatter. Right: The relationship of the sizes of the articular surfaces and shapes of the humeral head and glenoid approaches that of a golf ball over a tee (these having the same radii of curvature instead)

The glenoid fossa is circled by a fibrocartilaginous ridge called the labrum. This labrum, formed primarily by circumferential (also some radial and spiral) collagen fibers [9] (type II collagen was found in its internal layers), has a cross-section with the shape of a concave wedge approximately 3.8–6.3 mm in both thickness and height (it is thicker at 9–12 o'clock positions and thinner at 3 o'clock position) [10]. This shape gives the impression of being in a stadium; the glenoid fossa being the field and the labrum being the bench area. The labrum increases the total area of the glenoid by about 50%, adding to the stability of the glenohumeral joint. This labrum is firmly attached to the glenoid bone, including Sharpey-type fibers [9] (there is up to 4 mm of overlap of labral tissue over the glenoid surface) except on its superior part, where a synovial lining covers a recess between the posterosuperior labrum and its corresponding glenoid ridge at about 6 mm off the glenoid surface, allowing some mobility to enhance superior joint stability at elevation of the shoulder [11]. This in part is also possible by the insertion of the tendon for the long head of the biceps (LHBT), which insets partially on the superior aspect of the labrum (and partially on the supraglenoid fossa, a bony depression just medial to the superior labrum). Thus, a continuity exists between the superior glenoid and the tendon of the long head of the biceps (LHBT) (Fig. 10.5). Also, at the inferior part of the glenoid, the infraglenoid fossa is where the tendon of the long head of the triceps attaches (Figs. 10.1 and 10.2).

There are two main normal variants of the labral attachment on the anterosuperior border of the glenoid fossa [12]: the first one, called the sublabral foramen, consists of a lack of attachment of the labrum in this area, and has the aspect of an oval space. The second one, called Buford's complex, is characterized by a complete absence of the anterosuperior labrum and the middle glenohumeral ligament appears to bridge the gap in a chord-like fashion (Fig. 10.6).

The glenohumeral capsule is a serous membrane that seals the glenohumeral joint; its area is twice that of the humeral head and usually has a volume of 10–15 cm^3 [13]. It anchors itself medially on the glenoid neck, with fibrous attachments to the labrum, and laterally on the lateral edge of the articular surface of the humeral head. This capsule, histologically comprised by type I collagen, has three recognizable fibrous layers: External (fascia and tendons), intermediate (100–400 μm fibrous bundles) and internal (20 μm fibrous bundles) [14]. It is stronger in its anterior aspect, mainly due to the presence of three "folds" or capsular ligaments that cross it from medial to lateral (Fig. 10.5). The first is the superior glenohumeral ligament (SGLH), and it originates from to the supraglenoid tubercle; it covers the superior aspect of the rotator interval (which will be discussed later) and part of its fibers go posterior to the LHBT and laterally to its humeral insertion. The second one is the middle glenohumeral ligament (MGHL), which originates from the anterior labrum and is oriented inferiorly and

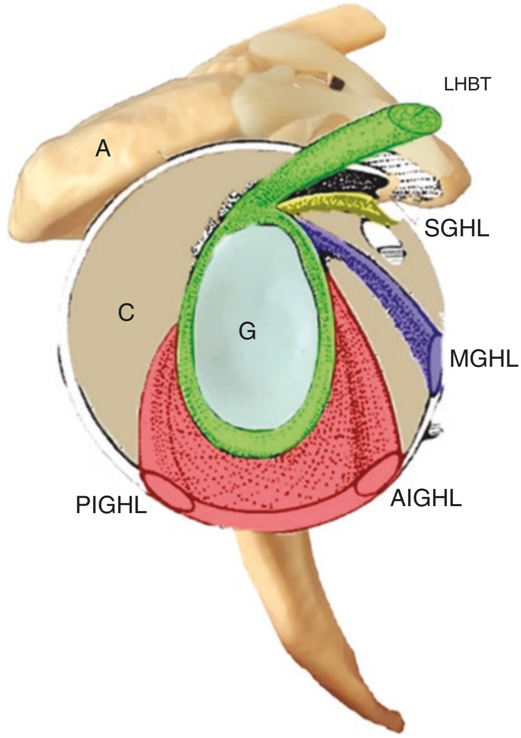


Fig. 10.5 Insertions around the glenoid. C: capsule; G: glenoid; A: acromion; LHBT: Tendon of the long head of the biceps SGHL: Superior glenohumeral ligament; MGHL: middle glenohumeral ligament; AIGHL: anterior band of the inferior glenohumeral ligament; PIGHL: posterior band of the inferior glenohumeral ligament

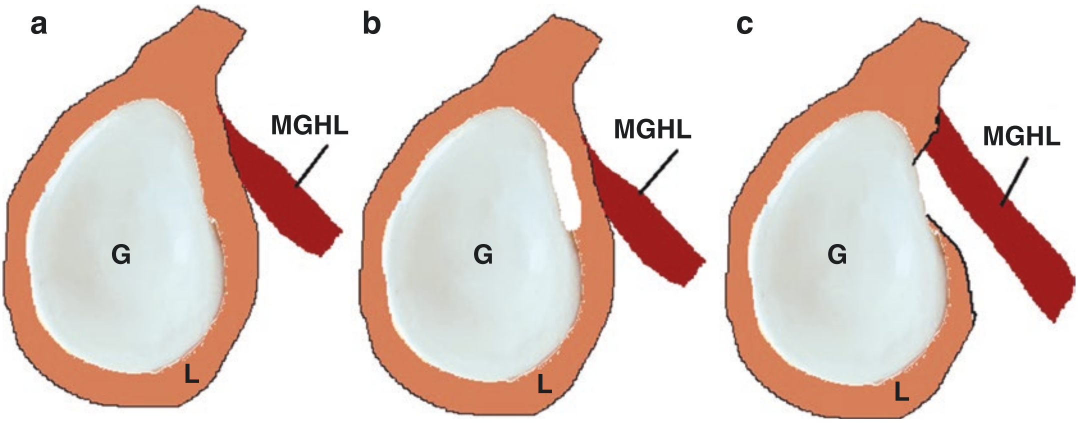


Fig. 10.6 **a:** Normal anterosuperior labrum and middle glenohumeral ligament (MGHL). **b:** Sublabral foramen. Anterosuperior glenoid rim is bare. **c:** Buford's complex. Absence of anterosuperior labrum and chord-like MGHL

laterally and can be seen next to the anterosuperior margin of the labrum. The third one, the inferior glenohumeral ligament (IGHL), thicker that the other two, starts medially on the inferior glenoid and has two bands: the anterior band (AIGHL) originates from the glenoid and labrum at the 3-to-5 o'clock position and the posterior band (PIGHL) starts from the 7-to-9 o'clock position in the glenoid and labrum. Both bands reach the humeral surgical neck and can be found at the capsular recess (a lax section of the capsule in its inferior aspect), one slightly anteriorly and the other one slightly posteriorly, the posterior band being less conspicuous (Fig. 10.7); Their disposition resembles and functions as a hammock that supports the head across the range of motion [15]. The IGHL receives a branch from the axillary nerve, which gives this ligament a proprioceptive function [16]. Also, the transverse humeral ligament (THL) originates from the capsule and makes the "roof" of the more proximal part of the bicipital groove.

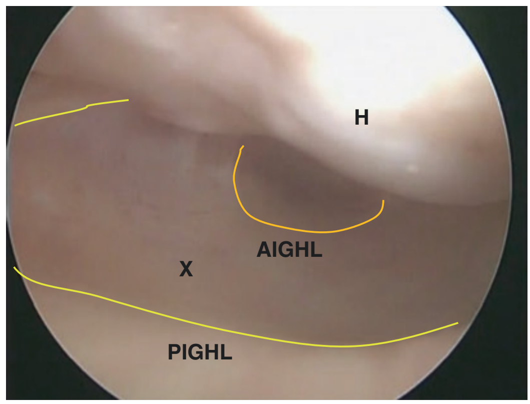


Fig. 10.7 Arthroscopic view of the anterior (AIGHL, orange) and posterior (PIGHL, yellow) bands of the inferior glenohumeral ligament. H: Humeral head. X: Axillary recess

The capsule is covered by synovium on its interior face and covers the interior aspect of the rotator cuff (the latter being extracapsular). The coracohumeral ligament enters through the rotator interval and merges partially with the superior face of the capsule; its superficial layer covers the articular surface of the supraspinatus and the deep layer attaches to the greater tuberosity [17]. Also, the capsule creates a fibrous band around the LHBT as it exits the intra-articular space, called the biceps pulley. Being completely sealed, the capsule, along with the labrum, have a negative pressure that creates a suction effect or the humeral head, thus adding to the stability of the glenohumeral joint.

On the lateral side of the joint, the humeral head is almost hemispherical, oriented at an average of 130–140 degrees superomedially and with 20–30 degrees of retroversion (Fig. 10.8); the sphere center has a medial offset of 6.9 mm and a posterior offset of 2.6 mm [18]. Its articular surface averages 20–30 cm^2 [19]. This hemisphere's cartilage cover is thickest in its central portion; but only 25% of its surface is in contact with the

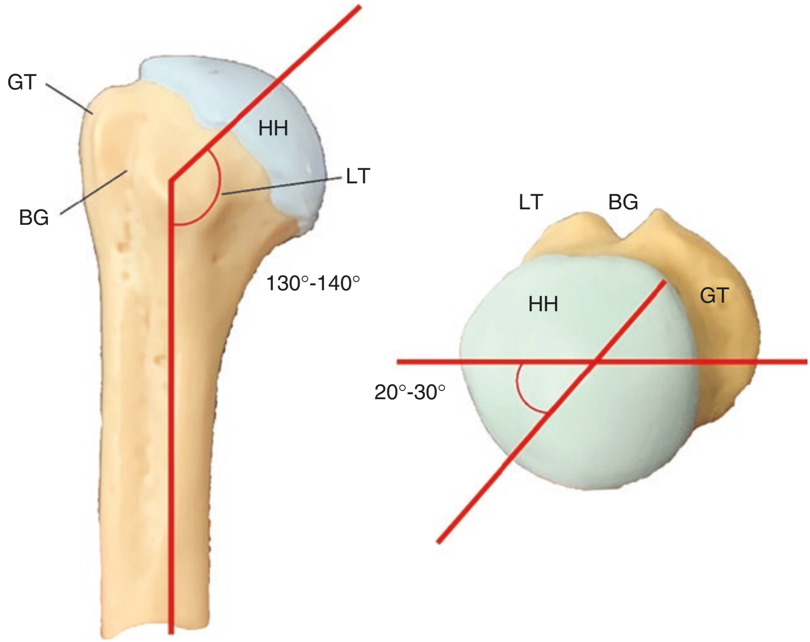


Fig. 10.8 Anatomic landmarks of the proximal humerus, inclination (related to the humeral longitudinal axis) and retroversion (related to the distal humeral transepicondylar axis) of the humeral neck. *HH* humeral head, *BG* bicipital groove, *LT* lesser tuberosity, *GT* greater tuberosity

glenoid at any point in time. Its upper border is located 5–8 mm from the upper edge of the greater tuberosity.

The greater tuberosity is a bony prominence that lies at the lateral side of the proximal humerus (Fig. 10.8); it holds the insertions of three of the rotator cuff tendons: the supraspinatus, more anterosuperiorly, the infraspinatus, posterosuperiorly (which has the largest area of insertion) and the teres minor, posteroinferiorly. This area of insertion or footprint has an uneven distribution (Fig. 10.9) [20]. These three tendons' attachments are not separate; some fibers interdigitate with the adjacent ones forming a somewhat common insertion [21]. The area where these tendons insert is commonly referred to as the footprint. There is a bare area on the posterosuperior aspect of the greater tuberosity that can be identified arthroscopically. The superior capsule attaches slightly medially to the cuff footprint, adjacent to it, in an area measuring 3 to 9 mm in width and spans across the greater tuberosity (Fig. 10.10) [22].

The lesser tuberosity is a bony prominence located medial to the greater tuberosity and adjacent to the anterior edge of the humeral head (Fig. 10.8). It holds the insertion of the subscapularis tendon. There is a space between both tuberosities called the bicipital groove; it is located 30 degrees medial from the sagittal plane of the humerus and 9 mm anterior to the bone's longitudinal axis (Fig. 10.8). Its dimensions are highly variable (length 3–8 cm, width 8–9 mm, depth

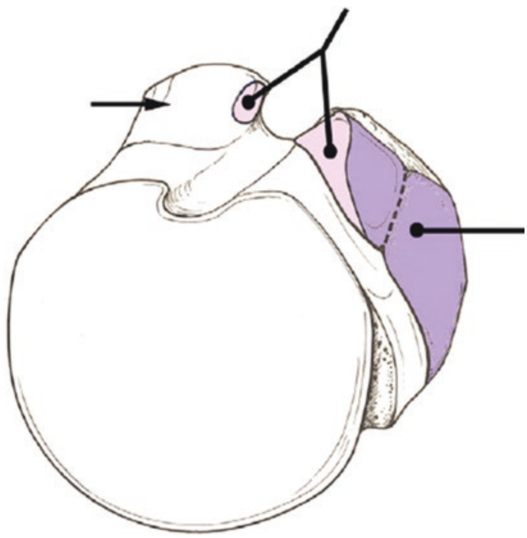


Fig. 10.9 Footprint distribution for the rotator cuff tendons in the greater tuberosity according to Mochizuki et al. [20] (reprinted with permission)

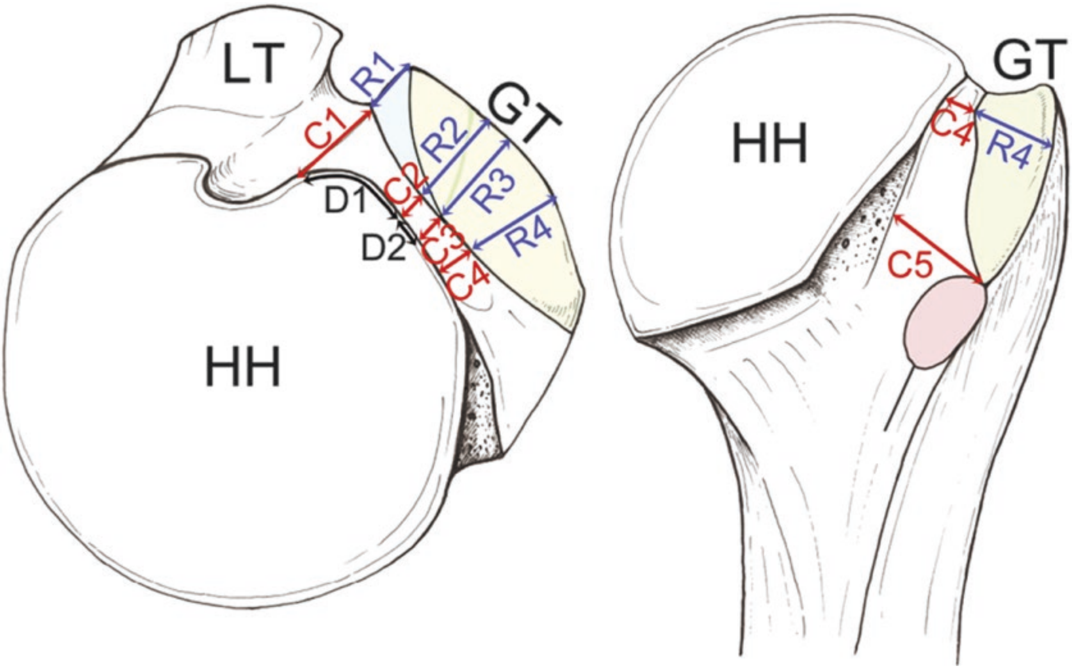


Fig. 10.10 Capsular insertion at the greater tuberosity according to Nimura et al. [22] (reprinted with permission)

4–7 mm) [23–25], and it contains the LHBT, covered by the THL. Some fibers coming from the subscapularis tendon cover its bony surface.

The humeral head receives its nutrition from both the anterior and the posterior circumflex arteries. Of note, the posterior circumflex artery enters the calcar (the stronger posteromedial area of the humeral metaphysis) within 5–8 mm inferior to the edge of the humeral head; it gives the humeral head about 64% of its blood supply [26] and includes the greater tuberosity and the head's subchondral bone. The anterior circumflex artery, mostly through its branch, the arcuate artery, supplies the lesser tuberosity and the bicipital groove [23]. Both arteries supply intraosseous branches with its terminal ones located at the subchondral head bone.

10.2.2 The Rotator Cuff

The rotator cuff is a combination of four muscles and their inserting tendons. Apart from specific movements, the cuff becomes the most important dynamic stabilizer of the glenohumeral joint.

The supraspinatus originates from the supraspinatus fossa, located on the upper third of the posterior face off the scapula. Its fibers run laterally and its tendon inserts in the anterior 1.5–2 cm of the superior aspect of the greater tuberosity (Fig. 10.11). The musculotendinous junction, located at an average of 3–4 cm from its insertion, has a mixed transition: 70% of the tendinous fibers come from intramuscular tendon and 30% from extramuscular tendon [27].

The infraspinatus muscle originates from the upper two thirds of the infraspinatus fossa on the posterior face of the scapula; its tendon originates intramuscularly and centrally and reaches its insertion on the posterosuperior aspect of the greater tuberosity (Fig. 10.11). It accounts for 60% of the external rotational force [28]. The teres minor originates on the lower third of the infraspinatus fossa and its circumpennate single tendon attaches to the posteroinferior aspect of the greater tuberosity [1]; it generates about 45% of the external rotational force [28].

Both the supraspinatus and infraspinatus have a layered composition (Fig. 10.12) [21]: Layer 1, superiorly; 1 mm thick, composed of fibers from

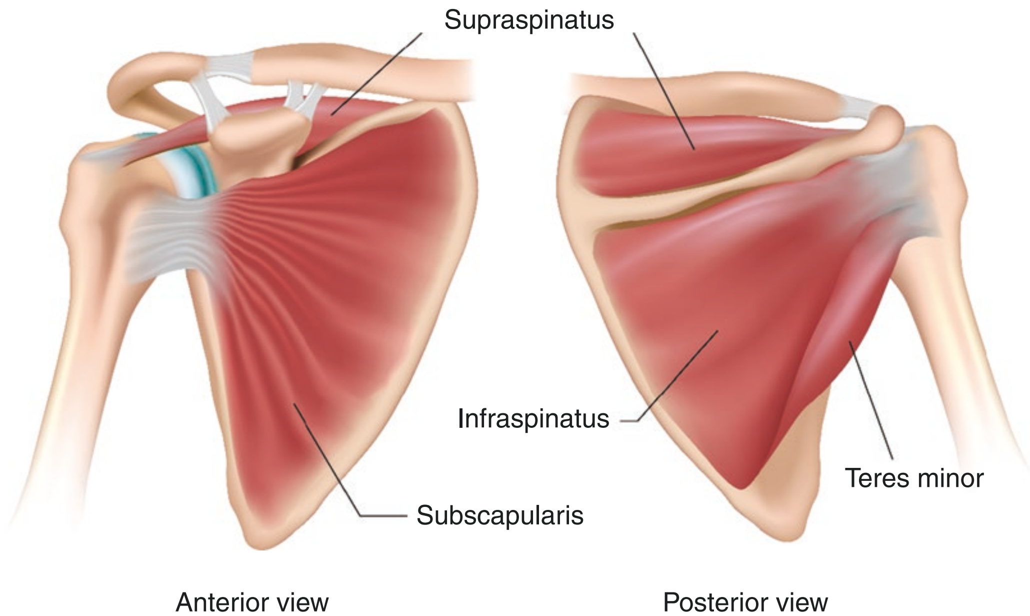


Fig. 10.11 Rotator cuff muscles and tendons (modified from Alila Medical Media/ Shutterstock.com)

the CHL. Layer 2, 3–5 mm thick, composed of parallel tendon fibers. Layer 3, 3 mm thick, composed of intercrossing fibers (at about 45 degrees); layer 4, composed of loose connective tissue and merging with the CHL at the anterior edge of the supraspinatus. Finally, layer 5, 1.5–2 mm thick, comprised by the superior capsule.

The subscapularis muscle originates from the entire anterior face of the scapula; its tendon passes under the coracoid and inserts at the lesser tuberosity (Fig. 10.11). This insertion is mixed: the upper two-thirds of it are tendinous and the lower third is entirely muscular [29]. It accounts for 50% of the dynamic stabilization force of the glenohumeral joint.

These muscles have a distinct innervation: Both the supraspinatus and the infraspinatus are innervated by the suprascapular nerve; the teres minor receives its own from the posterior branch of the axillary nerve, and the subscapularis from two branches of the subscapular nerve.

One can find a fibrous thickening lies at the lateral part of the tendons' insertions called the rotator cable [30]. This cordlike band spans from the most superolateral part of the bicipital groove all the way across the suprapinatus and to the inferior part of the infraspinatus' tendon, and originates from the deep layer of the CHL [21]. This cable seems to thicken over time and may be

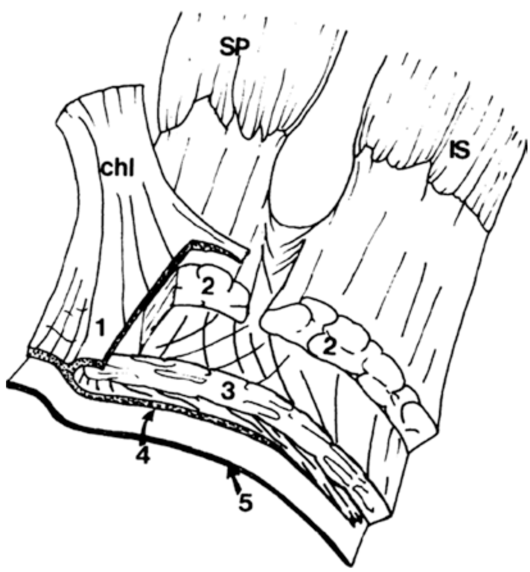


Fig. 10.12 The 5 histological layers of the supra/infraspinatus tendon [21]: 1: superficial fibers form the coracohumeral ligament (CHL); 2: parallel fibers; 3: oblique fibers of the supraspinatus and infraspinatus; 4: deep extension of the CHL; 5: articular capsule. *SP* supraspinatus, *IS* infraspinatus (reprinted with permission)

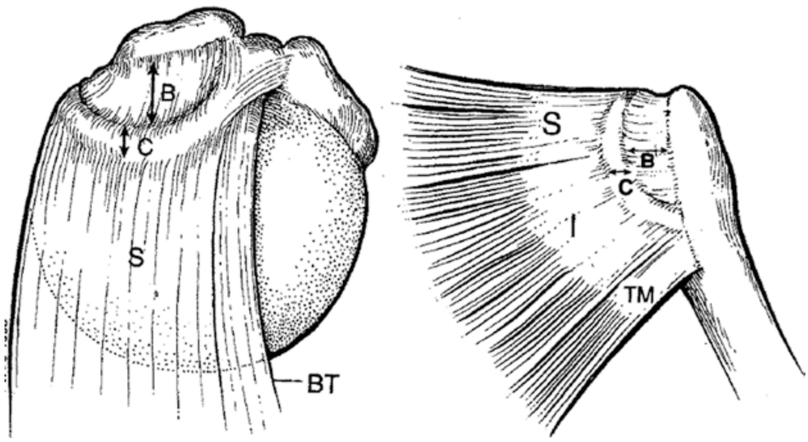


Fig. 10.13 Rotator cable (C) and rotator crescent (B) as described by Burkhart et al [30] *S* Supraspinatus tendon, *I* Infraspinatus tendon, *TM* Teres minor tendon (reprinted with permission)

related to ageing [30]. Lateral to this cable lies a crescent-shaped area called the rotator crescent, the most lateral part of the cuff tendons' insertion, which in turn seems to become thinner over the years (Fig. 10.13). The cable acts as a suspensory bridge that "holds" the lateral cuff and keeps stress away from the crescent, which is more prone to tear [21].

The gap between the supraspinatus and subscapularis tendons is known as the rotator interval. It is triangular-shaped, with its base located toward the base of the coracoid, and its tip at the anterior edge of the greater tuberosity. It is covered at the bursal side by the coracohumeral ligament, which starts to merge with the capsule, and at the articular side by fibers of the SGHL. The LHBT crosses this space from the articular side toward the bicipital groove; at this transition point, the groove portion of the CHL creates a sleeve around the LHBT and, by merging with the transverse humeral ligament (THL) at that level, creates the biceps pulley, which holds this portion of the LHBT in place as it enters the groove.

10.2.3 The Superior Shoulder Suspensory Complex (SSSC) [31]

The superior shoulder suspensory complex (SSSC) is a sort of ring-shaped rack connected to the thorax by the clavicle and scapulothoracic muscles. This ring is formed by the distal clavicle, the acromion, the glenoid process and the coracoid; these structures are connected by the acromioclavicular and coracoclavicular ligaments. This rack is connected to the trunk by two struts: the superior strut is formed by the medial clavicle and connects it to the sternum through the sternoclavicular joint, and the inferior strut is formed by the lateral scapular spine and connects to the trunk by the scapulothoracic muscles. (Fig. 10.14). In turn, this ring holds the humerus through the glenohumeral capsule and ligaments. This complex also allows for stable attachment for several soft-tissue static and dynamic glenohumeral stabilizers.

10.2.4 The Acromial Arch and Subacromial Space

The acromion process, a bony hook that originates as a lateral extension of the scapular spine, serves as an anchoring point for the deltoid and for the coracoacromial ligament. It runs from posterior to anterior and from inferior to superior, with a slight inferior concavity. It has two surfaces, superior (which is subcutaneous) and inferior; and a lateral, medial and anterior edges. The inferior surface is slightly concave and this concavity can vary: the resultant acromial shape is classified into three categories according to Bigliani [32]: Type I, which is a mainly flat inferior surface; type II which shows a slight inferior concavity; and type III, in which the concavity is more pronounced and the posteroinferior aspect shows a hooklike appearance.

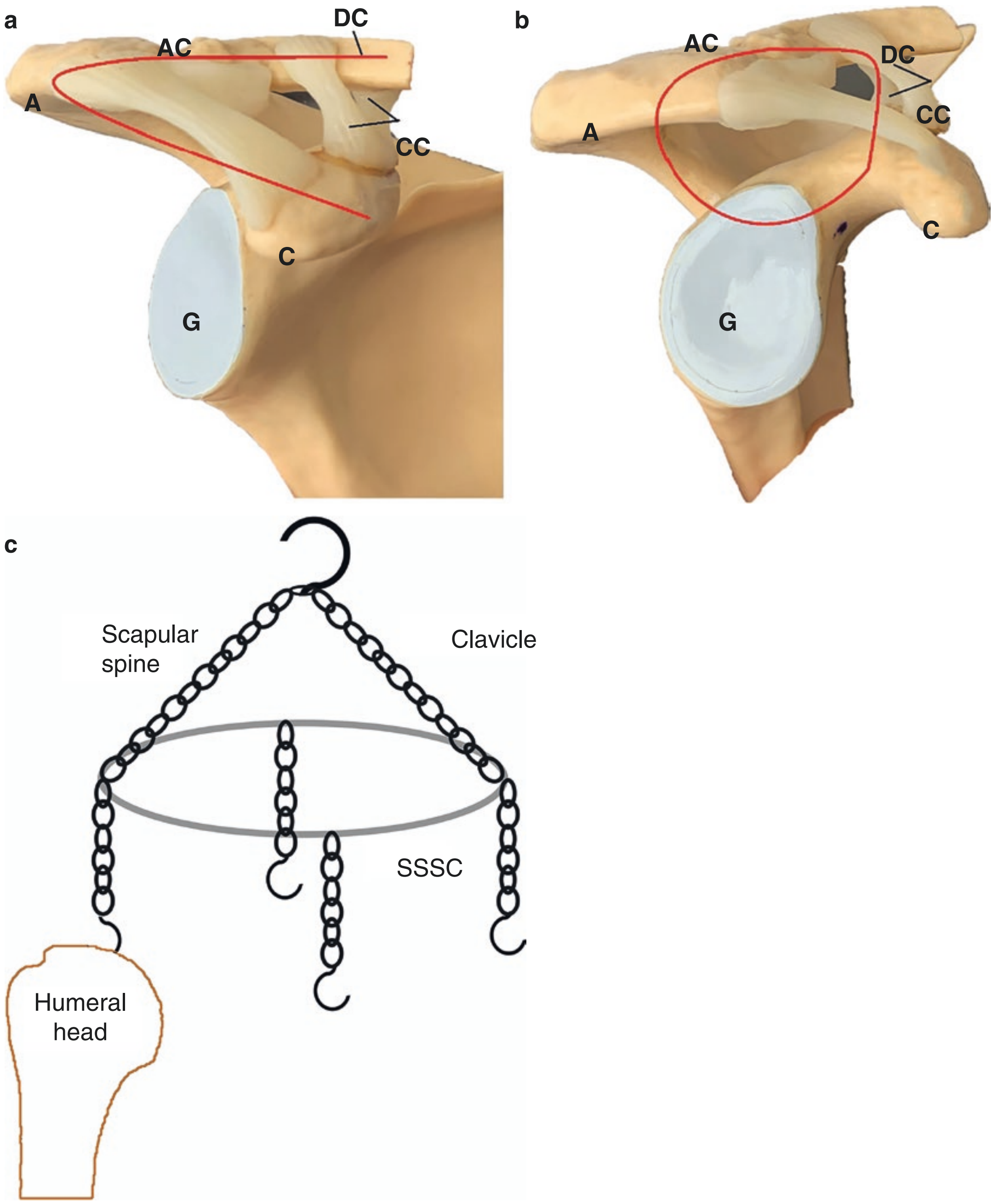


Fig. 10.14 Superior shoulder suspensory complex (SSSC), formed by the distal clavicle, acromion, glenoid, and coracoid; these structures are connected by the acromioclavicular and coracoclavicular ligaments, and the complex is connected to the trunk but the medial clavicle and scapular spine (as described by Goss et al. [31]). (**a**): Coronal view. (**b**): Sagittal view. (**c**): Representation of the SSSC as a ringed rack, connected to the trunk (ceiling) by the scapular spine and clavicle; it holds the humerus from the glenoid (hooks)

The middle portion of the deltoid anchors itself at the lateral border and the most lateral part of the anterior border if the acromion. This insertion comprises about 74% of the anterior acromial thickness and is about 5.4 mm thick [33]. On the other hand, the coracoacromial ligament

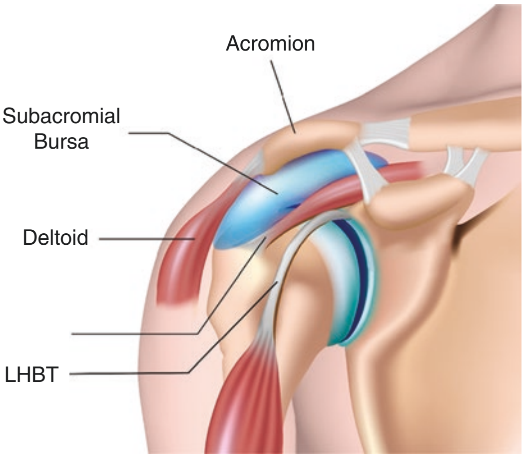
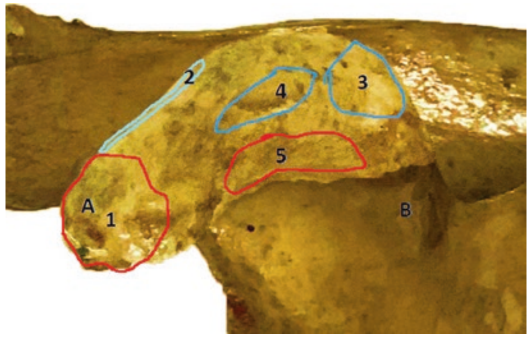


Fig. 10.15 Subacromial space and subacromiosubdetoid bursa. LHBT: long head of the biceps tendon (modified from Alila Medical Media/ Shutterstock.com)



Landmarks	Muscle/Ligament insertions
A: Tip	1: Conjoined tendon
B: Base	2: Coracoacromial ligament
	3: Conoid ligament
	4: Trapezoid ligament
	5: Pectoralis minor

Fig. 10.16 Tendon and ligament insertions at the coracoid

runs from the anterolateral part of the coracoid to the medial undersurface and the most medial part of the anterior border of the acromion with an insertion area width of 7.3 mm [34]. It has two bands: the lateral (thicker) and medial bands [35]. At the acromioclavicular joint, the acromial posteromedial acromion adjacent to the joint has the greatest bone mineral density [36].

Both the acromion and the coracoacromial ligament form the coracoacromial arch, which limits upper translation of the humeral head. Under it lies a virtual space known as the subacromial space, which measures an average of 9.7 ± 1.5 mm [37], its inferior limit being the superior surface of the supraspinatus and infraspinatus tendons. This space is filled by the subacromial bursa, which covers not only the supraspinatus but most of the rotator cuff as well; sometimes it is named subacromio-subdeltoid bursa because of its extension (Fig. 10.15). Its function is to provide a sliding surface and a cushion for friction protection to the superior cuff.

10.2.5 The Coracoid and Surrounding Structures

The coracoid process is a bony hook that arises from the lateral part of the scapular body and its tip is oriented anterolaterally. A visible notch (the suprascapular notch) separates it from the scapular body; its roof is comprised by the superior transverse scapular ligament. Laterally the space between the inferolateral coracoid and the glenoid can have the following shapes: Type I, rounded (45%), type II, square-angled (34%), and type III, hooked (21%) [38]. Its average dimensions [39] are: length 4.26 ± 0.26 cm; width and height at the tip 2.11 ± 0.2 and 1.49 ± 0.12 cm. Its base lies about 1.1 to 1.3 cm distal to the inferior clavicle.

The coracoid has multiple structures attached (Fig. 10.16): on its superior face, close to the base, the two coracoclavicular ligaments: the trapezoid ligament, more laterally (its anterior edge at about 3.33 cm average from the tip of the coracoid), and the conoid ligament, more medially. On its lateral face, the two bands (lateral and medial) of the coracoacromial ligament more anteriorly, and the coracohumeral ligament, more posteriorly, can be appreciated. On its medial face one can find the insertion of the pectoralis minor tendon (distance from the tip to the anterior margin of pectoralis minor 0.1 cm and to the posterior margin 1.59 cm) [39] and, on its tip, the insertion of the conjoined tendon (formed by the tendons of the coracobrachialis and of the short head of the biceps). Adjacent to its inferior face and close to the base, one can find the subcoracoid bursa and the subscapularis tendon (Fig. 10.11).

The anteromedial margin of the coracoid is close to many major neurovascular structures [40]: the closest one to the tip is the lateral chord of the brachial plexus (28.5 ± 4.4 mm) and the closest ones to the base are the axillary (29.3 ± 5.6 mm) and the musculocutaneous nerve (36.5 ± 6.1 mm).

10.2.6 The Acromioclavicular Joint

This synovial, diarthrodial joint has two surfaces: the acromial, convex surface and the clavicular, concave surface, although this may vary. Frequently but not always, a wedge-shaped fibrocartilage disc (also called the meniscus) fills the articular space between the two [23]. The joint has an axial inclination of about 51 degrees and a coronal inclination of approximately 12 degrees. The joint has a thin, fibrous capsule that spans from an average of 2.8 mm lateral to the acromial surface to about 3.5 mm medial to the clavicular surface [34]; with four ligaments, of which the superior one is the strongest. The anterior, posterior, superior and inferior ligaments have a capsuloligamentous insertion at an average of 6.4, 6.3, 6.6 and 5.4 mm medial to the clavicular surface, and 5.6, 4.3, 5.3 and 4.0 mm lateral to the acromial surface. The trapezoid ligament is located at an average of 14 mm from the distal clavicular edge, and the conoid at an average of 32.1 mm from it [34].

10.2.7 The Clavicle and Sternoclavicular Joint

The clavicle is an S-shaped bone that connects the scapula and upper limb to the sternum. Its cross-section varies from the wide and flat distal end to the more tubular shaft and then to a thick, somewhat flatter proximal end. It holds many important muscular insertions for movement and stability of the shoulder girdle (Fig. 10.17).

The only joint that connects the shoulder girdle to the axial body is the sternoclavicular joint, located subcutaneously and saddle-shaped. The round-edged, flat distal clavicle has a fibrocartilaginous dorsoinferior surface that articulates with the manubrium and the second rib's synchondrosis; less than 50% of the distal clavicular surface articulates [41]. It has a thin capsule with intrinsic ligaments and two extrinsic (interclavicular and costoclavicular) ligaments that provide good stability (they especially restrict upward displacement of the clavicle). The subclavius muscle stabilizes it by pulling the clavicle toward the sternum and acting as a shock absorber; the sternocleidomastoid and pectoralis major's aponeuroses, along with the clavipectoral fascia, envelop the joint, adding to its stability. Also, a fibrocartilaginous disc lies within the joint.

10.2.8 The Scapulothoracic Interface

This interface between the scapular body and the rib cage does not have a capsule; six bursae [42] lie between the scapula and scapulothoracic muscles and the rib cage. The two major ones are the supraserratus (between the serratus anterior and the subscapularis) and the infraserratus (between the serratus anterior and the rib cage, Fig. 10.18) [62]; the other four minor or adventitial bursae are infrequent and respond to pathologic conditions [42].

10.2.9 External Glenohumeral and Scapulothoracic Muscles

Deltoid: The deltoid is a powerful muscle that originates at the lateral border of the clavicle anteriorly, the superolateral border of the acromion laterally and the lateral portion of the scapular spine posteriorly. There are three recognizable "portions" of the deltoid, the anterior, middle and posterior thirds (one can appreciate a soft fascial division between anterior and middle thirds). On the other hand, Sakoma et al. described up to

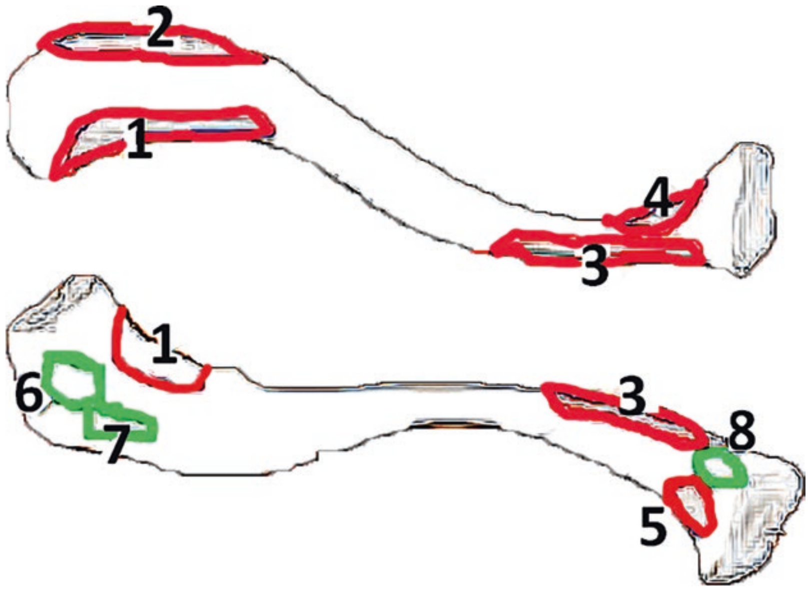


Fig. 10.17 Muscular and ligamentous insertions around the clavicle

1: Deltoid
2: Trapezius
3: Pectoralis major
4: Sternocleidomastoid
5: Sternohyoid
6: Trapezoid ligament
7: Conoid ligament
8: Costoclavicular ligament

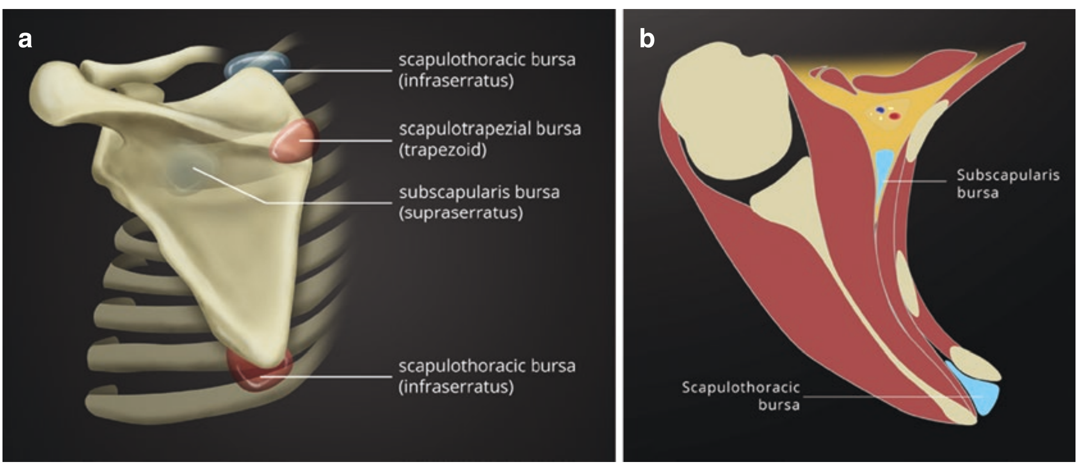


Fig. 10.18 Scapular Bursae. (**a**) Posterior and (**b**) axial illustrations of the scapula show the locations of the adjacent bursae (reproduced with permission) [62]

seven functional units (three posterior, one middle and three anterior units) (Fig. 10.19) [43]. These portions merge together into a common tendon that inserts at the deltoid tubercle, located laterally in the humeral shaft. The muscle receives its innervation from the anterior branch of the axillary nerve, which runs from anterior to posterior through the quadrilateral space (formed by

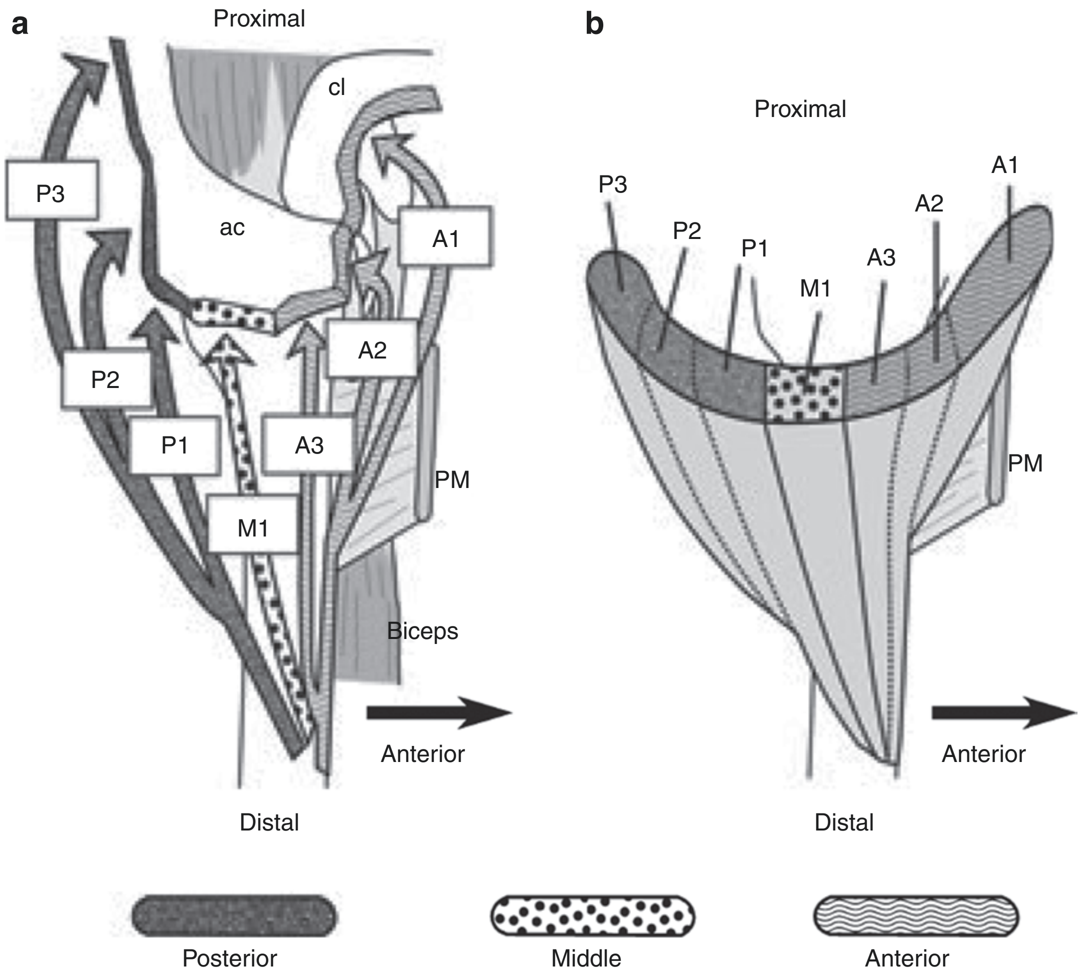


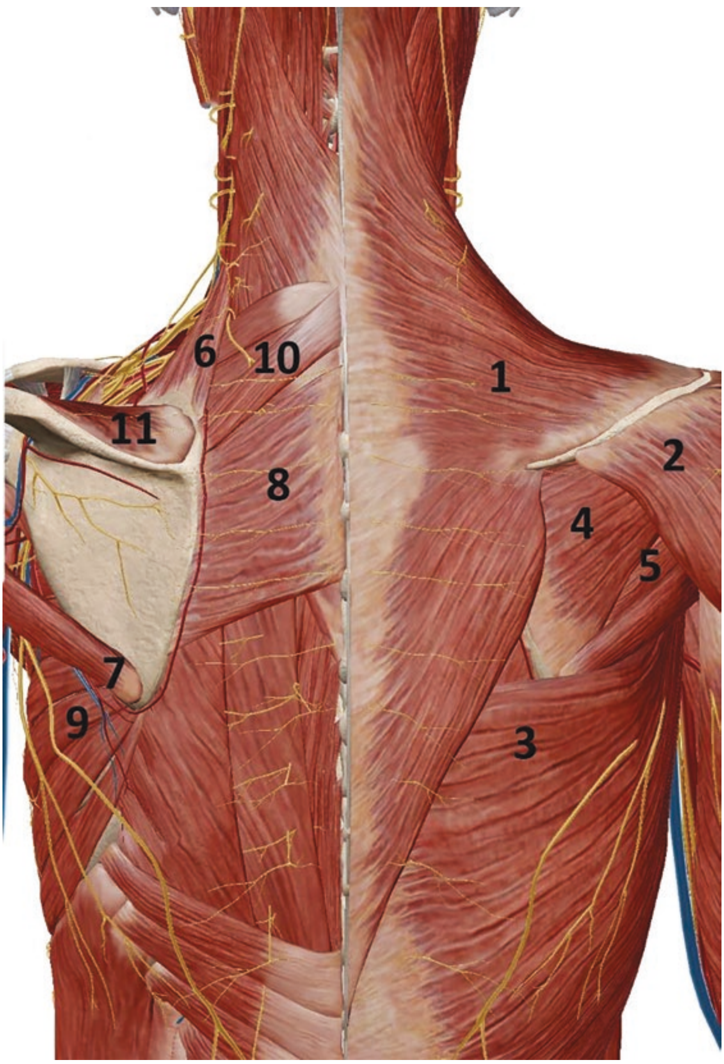
Fig. 10.19 (**a**) Directions of the intramuscular tendons of the deltoid, and (**b**) Division of deltoid segments: three anterior (A1 to A3), one middle (M1) and three posterior (P1 to P3) according to Sakoma et al. (reproduced with permission) [43]

the humeral surgical neck laterally, the long head of the triceps medially, the teres minor superiorly and the teres major inferiorly; the nerve runs along the posterior circumflex artery, which also gives irrigation to the deltoid) and divides in two branches at approximately the 6-o'clock position under the glenoid, just posterior to the long head of the triceps [44]; the anterior branch being responsible for innervating the deltoid as it travels anteromedially around the humeral surgical neck. Most times, a branch from the posterior branch reaches the posterior deltoid as well; the relative contribution from the anterior and posterior branches may take one of three patterns [45]. The anterior branch can be easily palpated under the posterior and middle thirds of the muscle at about 4.0–6.7 cm from its acromial origin [46]. Also, its position can be estimated from outside at a distance of 7.8 cm inferior to the posterolateral corner of the acromion [47] and approximately 6.08 cm inferior to the anterior margin [48], but these distances are highly variable among subjects.

The anterior portion is responsible for shoulder flexion movements and the posterior extension; the middle third is an abductor of the shoulder (the other two portions can contribute to abduction at low angles of abduction).

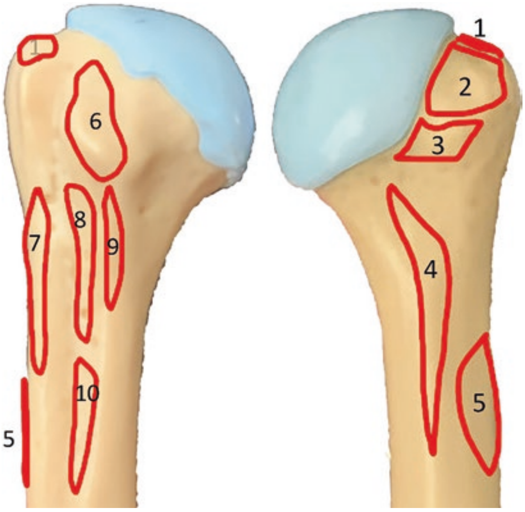
Pectoralis Major: This powerful muscle originates from the medial clavicle (clavicular head), the sternum and the second to fourth rib (sternocostal head). Its fibers twist 180 degrees and they form a common tendon which inserts at the lateral lip of the bicipital groove (the clavicular fibers inserting inferior to the sternocostal ones), covering it as well as the distal portion of the LHBT. It acts on the shoulder as a powerful adductor, internal rotator and (slightly) flexor. It is innervated by the lateral (clavicular fibers) and medial (sternocostal fibers) pectoral nerves (Figs. 10.20 and 10.21).

Trapezius: This enormous rhombus-shaped muscle has three distinct sections: upper or descending (goes from the occipital tubercle to the lateral clavicle), middle (from the spinous processes of C7 to D3, to the lateral scapular spine and acromion) and lower or ascending (from D3 to D12, to the medial scapular spine). It acts passively as a scapular stabilizer and actively as a scapular retractor, upward rotator and lateral elevator. Its innervation comes from the spinal or accessory nerve (cranial pair XI) (Figs. 10.20 and 10.21).



1: Trapezius
2: Deltoid
3: Latissimus dorsi
4: Infraspinatus
5: Teres minor
6: Levator scapulae
7: Teres major
8: Rhomboid major
9: Serratus anterior
10: Rhomboid minor
11: Supraspinatus

Fig. 10.20 Periscapular muscles (modified from SciePro /Shutterstock.com)



1: Supraspinatus
2: Infraspinatus
3: Teres minor
4: Triceps (lateral head)
5: Deltoid
6: Subscapularis
7: Pectoralis major
8: Latissimus dorsi
9: Teres major
10: Coracobrachialis

Fig. 10.21 Humeral insertions of periscapular and glenohumeral muscles

Latissimus Dorsi: This huge muscle originates from the thoracic spine (D7 to D12), iliac crest and the last three ribs and inserts on the medial lip of the bicipital groove. It acts as a shoulder adductor, extensor and internal rotator. Its innervation comes from the thoracodorsal nerve (Figs. Q and R).

Teres Major: It originates from the posterior surface at the inferolateral edge of the scapula and runs anterolaterally, twisting 180 degrees, toward its insertion at the medial margin of the bicipital groove, slightly posteromedial to that of the latissimus dorsi. It acts both as a scapular stabilizer and, like the latissimus, as a shoulder adductor, extensor and internal rotator. It is innervated by the subscapular nerve (Figs. 10.20 and 10.21).

Other glenohumeral muscles: The long head of the triceps acts in the shoulder as an extensor and adductor; it is innervated by the radial nerve. Also, both the coracobrachialis and the short head of the biceps (SHB) insert in a common tendon (the conjoined tendon) and act as adductors and flexors of the glenohumeral joint. They are innervated by the musculocutaneous nerve, which pierces the coracobrachialis muscle at about 2–5 cm from the tip of the coracoid (Fig. R).

Other periscapular muscles: The levator scapulae (goes from C1-C4 to the superior scapular angle) elevates and downward rotates the scapula and is innervated by the dorsal scapular nerve; the serratus anterior, which goes from the first nine ribs to the entire anterior face of the medial scapular border, acts as a scapular stabilizer and actively as a scapular upward rotator and protractor, and is innervated by the long thoracic nerve. The pectoralis minor, which goes from the second to fifth ribs to the medial coracoid, downward rotates and protracts the scapula and is innervated by the lateral and medial pectoral nerves (Fig. Q).

10.3 Shoulder Normal Kinematics

To understand normal shoulder movement, we have to understand that it is the result of the combination of simultaneous scapulothoracic motion (including sternoclavicular and acromioclavicular motion as well) and glenohumeral motion. This combination is called scapulohumeral rhythm and will be discussed later. First, we will describe glenohumeral and scapulothoracic movement individually.

10.3.1 Glenohumeral Kinematics

To understand glenohumeral kinematics we have to set a frame of reference, which in this case is the scapula.

The humeral head is almost spherical, more convex anteroposteriorly than superoinferiorly (its diameters show a difference of less than 1 mm) [18]. On the other hand, the glenoid is more convex superoinferiorly than anteroposteriorly [49]; this gives some static stability to the humeral head, especially in the superoinferior direction.

The articular surface area of the glenoid is approximately one fourth of the humeral head's surface; this resembles a golf ball laying over a tee. Also, the congruity of the humeral head and the glenoid is almost perfect resembling a ball-and-socket joint; however, the radius of curvature of the glenoid is 2.3 mm longer than that of the humeral head [8], leaving a slightly flatter glenoid relative to the head (Fig. 10.4). This congruity is reinforced by the labrum, which increases glenoid depth by 50% and surface area by 75%; it accounts for approximately 20% of the joint stability achieved by compression [50]. Due to these factors, the humeral head movement is a combination of rolling (predominant) and gliding. This gliding displaces the humeral head depending on the movement. In abduction, the head moves superiorly (3 mm in the first 30 degrees, and approximately 1 mm for every additional 30 degrees); in external rotation, it moves backward and on internal rotation, forward. In flexion, it moves 3.8 mm anteriorly in flexion and 4.9 mm posteriorly in extension [51].

The humeral head is stabilized by numerous structures during its arc of motion. The glenohumeral ligaments play a substantial role. The superior glenohumeral ligament (SGHL) resists anterior and inferior (with the arm hanging) displacement; the middle glenohumeral ligament (MGHL) also performs this function but in adduction and in the first 30 degrees of abduction [61]. The two bands of the inferior glenohumeral ligament (IGHL) act as anterior stabilizers; the anterior band opens up in abduction and external rotation, and the posterior band in flexion and internal rotation. When one band stretches, the other one narrows. In short, as the shoulder abducts, the stress on the ligaments shifts progressively from the SGLH to the MGHL and then to the AIGHL.

The coracohumeral ligament is an inferior stabilizer, especially in external rotation. It also becomes one of the main proprioceptor organs of the shoulder [23, 53].

The joint capsule seals hermetically the joint, thus producing a negative pressure that stabilizes the head, preventing inferior translation.

Shoulder muscles stabilize the head mainly by dynamic contraction, pushing the head toward the glenoid (the pressure produced can reach up to 650 N during motion); these muscles contract in coordination in such a way that the joint reaction force is redirected toward the center of the glenoid (Fig. 10.22) [54].

The rotator cuff plays a major role in this dynamic stabilization. The co-contraction of the four muscles compresses the joint, creating a fulcrum point in the glenoid so motion can occur (otherwise, there would be only humeral head translation and no motion when the powerful external muscles contract). The subscapularis is the main anterior dynamic stabilizer of the head, and accounts for 50% of the cuff's co-contraction force; it also restricts posterior displacement at 90 degrees of flexion. The co-contraction can be analyzed in two planes [55]: The vertical plane, where the deltoid and supraspinatus elevate the head and the remaining cuff muscles pull down (a coronal force couple); and the horizontal plane, where the subscapularis pulls anteriorly and the infraspinatus/teres minor posteriorly (a transverse force couple) (Fig. 10.22). These create a net resultant force that ultimately pulls the head toward the center of the glenoid.

10.3.2 Scapulothoracic Kinematics

There are two aspects that are relevant to scapulothoracic kinematics: periscapular stabilization and scapular motion. One has to understand that scapular motion involves inherently clavicular motion, both at the sternoclavicular and at the acromioclavicular joints; both bones move synchronously. Here, the clavicle moves as a strut connecting the sternum (which will be our point of reference regarding the axial body) and the scapula, and ultimately helping scapular motion.

The scapula has a "normal" resting orientation of 30 degrees of anteversion [56], 3–10 degrees of abduction [3] and 10–20 degrees of

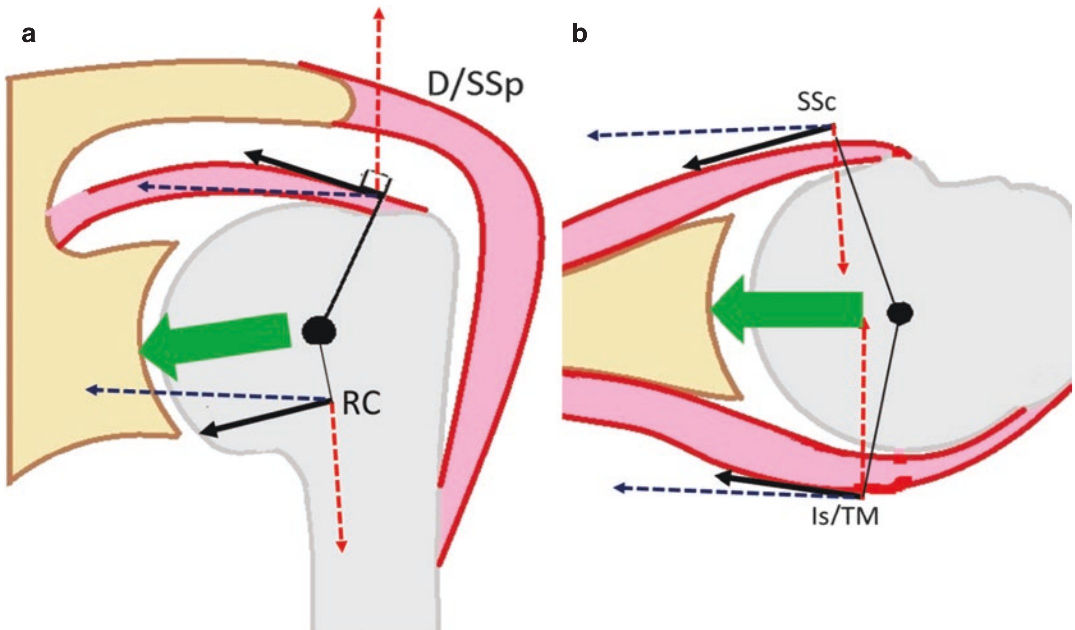


Fig. 10.22 Force couples in the shoulder. (**a**): Coronal-plane force couples: the deltoid and supraspinatus (D/SSp) pull the head upwards and the rest of the cuff (RC) downwards; (**b**): Transverse-plane force couples: the subscapularis (SSc) pulls forward and the infraspinatus and teres minor (Is/TM) pull backward. Vertical and antero-posterior forces cancel each other (red arrows) and the remaining medializing forces (blue arrows) produce a net resultant force (green arrow) that compresses the head toward the center of the glenoid (based on concepts by Lippitt et al. [54] and Saha et al. [55])

anterior tilt [4]. Usually it reaches up to 60 degrees of abduction, 20 degrees of posterior tilt and 10 degrees of external rotation (initially 6 degrees of internal rotation during the first half of elevation, to later add 16 degrees of external rotation) [57].

Scapular motion is a combination of rotational movements along three axes (anteroposterior, superoinferior, and lateromedial) with gliding movements around the posterolateral rib cage through the scapulothoracic interface. These movements can be described as follows (Fig. 10.23):

- Protraction: combination of lateral gliding (winging) away from the spine, anterotation at the acromioclavicular joint and anterior motion of the lateral clavicle.
- Retraction: combination of medial gliding toward the spine, retrorotation at the acromioclavicular joint and posterior motion of the lateral clavicle.
- Upward rotation: combination of coronal-plane rotation resulting in the glenoid facing upwards, superior displacement of the lateral clavicle and slight lateral scapular gliding.
- Downward rotation: combination of coronal-plane rotation resulting in the glenoid facing downwards, inferior displacement of the lateral clavicle and slight medial scapular gliding.
- Elevation: upward scapular gliding and superior lateral clavicular displacement.
- Depression: downward scapular gliding and inferior lateral clavicular displacement.

In elevation of the arm, scapular abduction has three effects: increase of humeral motion relative to the thorax, orients muscles for optimal function and positioning the glenoid under the humerus for load sharing.

The sternoclavicular joint works as a ball-and-socket joint. Its ranges go from 45 degrees of elevation to 15 degrees on depression, ± 30

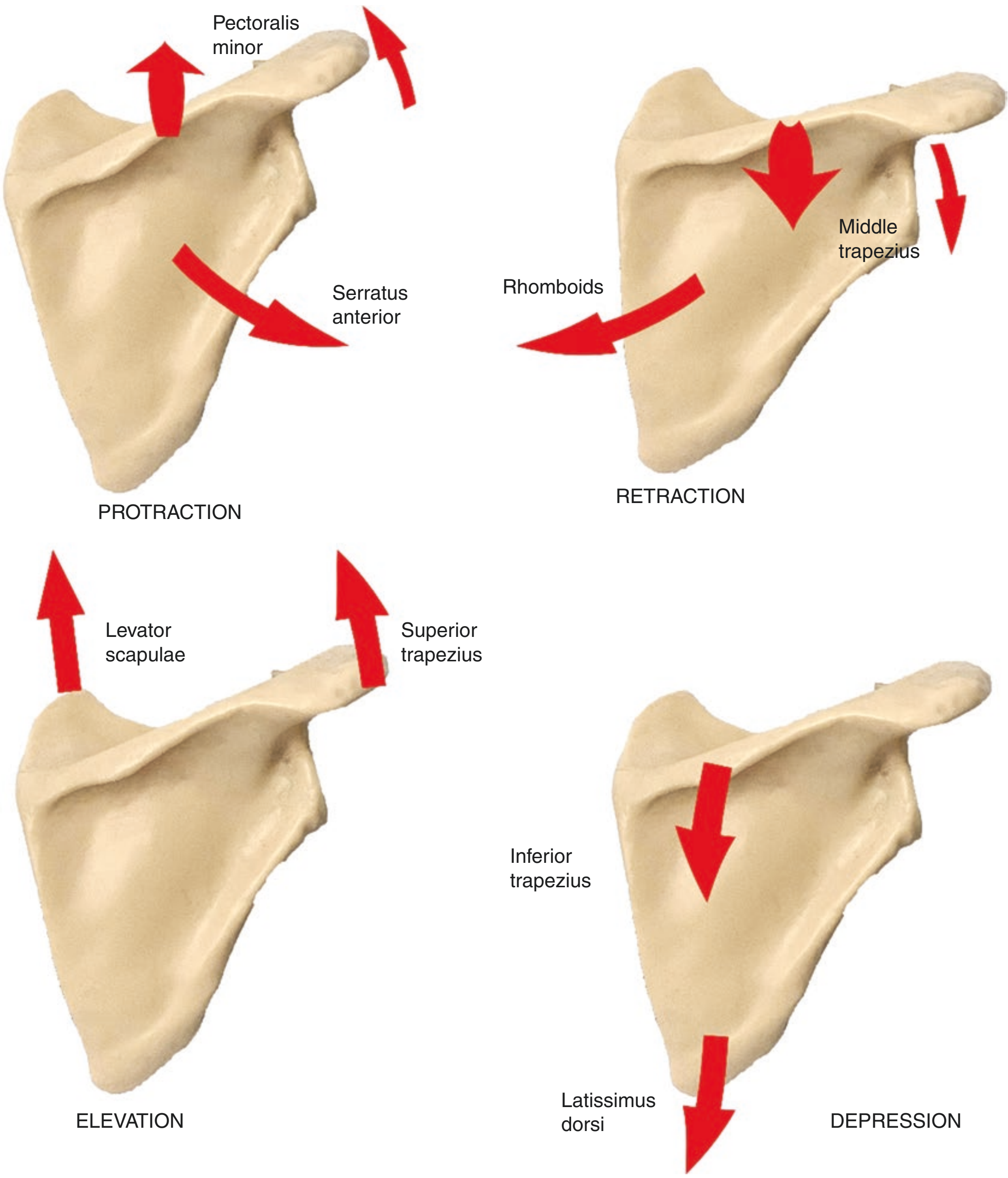


Fig. 10.23 Scapular movements and muscles

degrees on protraction/retraction, and 30–45 degrees on axial rotation. This motion allows the clavicular strut to move in coordination with the scapula. The acromioclavicular joint can rotate from 5 to 8 degrees [58] up to 40–50 degrees during elevation on a synchronous scapular and clavicular rotation.

Periscapular stability is paramount for arm motion: as mentioned before, glenohumeral movement uses the glenoid surface as a fulcrum point for the humerus to move. Thus, the glenoid must be stable when glenohumeral movement occurs. A good analogy is a fisherman (holding a fishing rod) standing on a raft in the

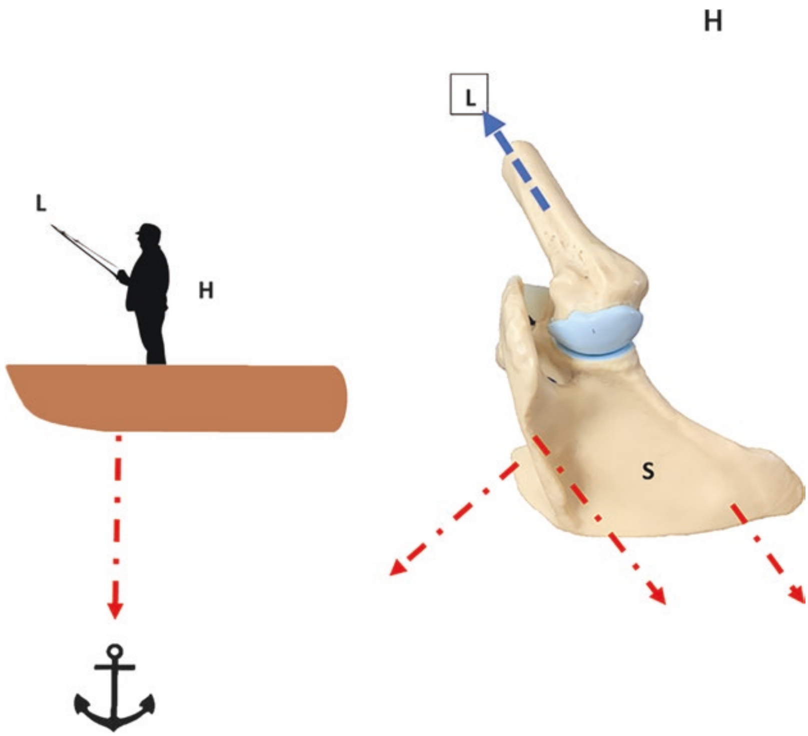


Fig. 10.24 Scapular stability contributes to efficient motion of the upper limb. The fisherman (humerus) standing on the boat (scapula) tries to move the rod (rest of upper limb) but has to expend energy to keep standing due to lack of stability of the boat on the water. If the boat is anchored (coordinated co-contraction of periscapular muscles, M), the fisherman (humerus and glenohumeral muscles) will expend less energy to remain standing (glenohumeral stability) and the rod (upper limb) will be moved more efficiently

middle of the ocean. Here, the raft is the scapula, the fisherman is the humerus and the rod is the distal upper limb; if the raft is not anchored (periscapular muscles not working appropriately), the fisherman will have to expend additional energy to stand in the raft and using the rod will be extremely difficult. If, on the other hand, the raft is anchored to the ocean floor (periscapular muscles coordinately contracted), the fisherman will remain standing (stable glenohumeral motion) and the rod can be easily used (efficient positioning of the arm and hand in space) (Fig. 10.24).

This stability is achieved by coordinated contraction of periscapular muscles: upper and lower trapezius, rhomboids, and serratus anterior, being the lower trapezius the most important scapular stabilizer because of its spinal insertions [52]. This coordinated contraction varies during arm movement to allow for coordinated combined scapulohumeral motion and still provide scapular stabilization; however, the most efficient scapular position for optimal muscle activation is of retraction and external rotation [52], thus acting as a stable "platform" for the rotator cuff muscles to produce optimal glenohumeral motion.

10.3.3 Scapulohumeral Rhythm

This term refers to the coordinated combination of scapulothoracic (including clavicular) and glenohumeral motions to achieve optimal arm positioning in space. To have a better understanding of this, one can picture the shoulder as a rack, with the shoulder girdle (scapula and clavicle as a unit) linked to the rib cage and sternum respectively, and the humerus linked to the glenoid.

Scapular motion plays a major role in maintaining scapulohumeral rhythm. First, it maintains an approximate "ball-and-socket" joint configuration by keeping glenohumeral alignment within normal limits (± 29.3 degrees) [59]. Second, it becomes a stable "platform" for optimal rotator cuff muscle activation and optimal force transmission from the core to the arm and hand, as previously discussed. Third, it keeps the acromion out of the way for the proximal humerus to elevate.

Fig. 10.25 Shoulder crane concept [53] (reprinted with permission from Dr. Gregory Bain). Images to maybe redraw (I used an app or stock pics from the web): 11, 15, 17, 20

In elevation, one can recognize the rhythm occur in two "phases": The setting phase, in which the motion is predominantly glenohumeral and occurs in the first 60 degrees of flexion or 30 degrees of abduction (the shoulder girdle barely moves); and after that the girdle starts to elevate as well. Generally speaking, after 60 degrees of elevation the ratio of glenohumeral-to-scapulothoracic motions is 1.25–1.5:1., with an average ratio for the full arc of elevation of 2:1 [60].

Acromioclavicular retrorotation around the clavicular long axis occurs after 90–100 degrees of elevation.

Scapulohumeral motion can also be understood according to the crane model proposed by Bain et al. (Fig. 10.25) [53]. In this model, the base of the crane (legs and pelvis) supports an axial tower (the spine) and a thoracic platform (the sternum and rib cage), stabilized by the core muscles. From it, the strut (clavicle) suspends from the anterior tower (sternum) and is powered by the posterior tower (trapezius). This strut in turn holds the suspensory cascade: this cascade starts from the skull to the cervical spine then to the trapezius and up to the clavicle; the force is transmitted then to the coracoclavicular ligaments to the coracoid, coracohumeral ligament and finally to the humerus. Here, the coracoid acts as a pulley, in which the scapular pivots aided by periscapular muscles, and the rotator cuff powers motion on the humeral head (supported by the scapula).

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