TUTORIAL

Diagnosis and Management of the Painful Shoulder. Part 1: Clinical Anatomy and Pathomechanics

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■ **Abstract:** Distinctive anatomical features can be witnessed in the shoulder complex, affording specific pathological conditions. Disorders of the shoulder complex are multifactoral and features in both the clinical anatomy and biomechanics contribute to the development of shoulder pain. The sternocalvicular, acromioclavicular, glenohumeral, and scapulothoracic joints must all participate in function of the shoulder complex, as each biomechanically contributes to functional movements and clinical disorders witnessed in the shoulder region. A clinician's ability to effectively evaluate, diagnose, and treat the shoulder is largely reliant upon a foundational understanding of the clinical anatomy and biomechanics of the shoulder complex. Thus, clinicians are encouraged to consider these distinctions when examining and diagnosing disorders of the shoulder. ■

Key Words: acromioclavicular, biomechanics, glenohumeral, scapula, shoulder, sternoclavicular

INTRODUCTION

The ability to effectively evaluate, diagnose, and treat shoulder problems is largely reliant upon a foundational understanding of the clinical anatomy and biomechanics of the shoulder complex. The shoulder complex is a significant component of the elevation chain and every attempt to elevate the upper extremity is dependent upon the interactions between the glenohumeral, acromioclavicular, and sternoclavicular joints in concert with functions at the scapulothoracic junction, cervicothoracic spine, and rib cage (see Figure 1).[1] For example, upper extremity elevation can be achieved through glenohumeral flexion or abduction in cooperation with complex movements of the scapula.[2] Kibler supported this notion when he suggested that the dynamic function and coordination of scapulothoracic primary movers, including the serratus anterior, latissimus dorsi, and trapezius, are critical to elevation mobility.[3]

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PATHOANATOMY

Scapula and Scapulothoracic Junction

The scapula is an irregular flat bone that serves as a mobile connection with the thorax, as well as an insertion site for numerous muscles. While not a true synovial articulation, the scapulothoracic junction and gliding surfaces formed by the subscapularis and serratus anterior fascia allow the junction to serve as a "joint."[4] The controlled mobility of this mechanism is strongly influenced by actions of the rhomboid, trapezius and serratus anterior muscles.[3,4] Bony projections of the scapula, including the scapular spine, acromion process, and coracoid process, serve as attachments for important soft tissue structures. Other clinically relevant scapular landmarks include the scapular notch, lateral scapular spine, and the glenoid fossa. The suprascapular nerve courses through the notch (containing afferent, efferent, and sympathetic fibers) and proceeds to provide a motor nerve supply to the supraspinatus

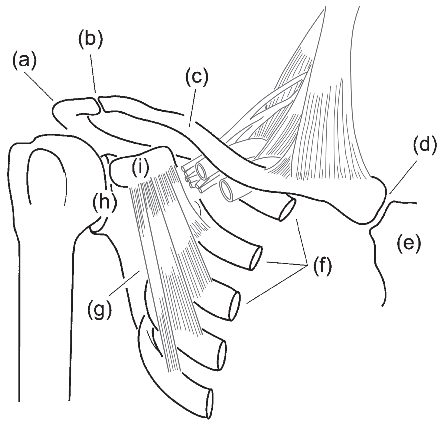

Figure 1. Joint Systems in the Shoulder Complex. (a) Acromion process; (b) Acromioclavicular joint; (c) Clavicle; (d) Sternoclavicular joint; (e) Sternal manubrium; (f) 1st through 3rd Ribs; (g) Scapulothoracic joint; (h) Glenohumeral joint; (i) Coracoid process.

muscle and a sensory nerve supply to the acromioclavicular joint.[5] Distally, it courses lateral to the spine of the scapula and, subsequently, innervates the infraspinatus muscle.

Moriggl developed a scapular notch classification system based on architectural shape and relationship of the notch to the transverse ligament.[6] Reductions in the ratio of scapular-notch size to nerve-diameter can lead to suprascapular nerve entrapment. As result, it appears that a deep-v or pinhole notch configuration heightens nerve entrapment potential, leaving the nerve less room for movement and greater incidence of deformation.

Sternoclavicular Joint (SCJ)

The only direct synovial articular attachment of the upper extremity to the axial skeleton is observed at the sternoclavicular joint (SCJ). The SCJ is formed by connection between the sternal manubrium and the clavicle. This joint is anatomically classified as a sellar, or saddle, mechanism. The joint surfaces are covered with fibrous cartilage and are completely separated by an intraarticular fibrocartilage disc, thus creating 2 joint compartments.[4] The disc serves to increase surface contact between the joint partners; contributing to the sellar joint behavior and ensuing motion control. It is important to note that the disc is attached to the sternum cranially and caudally but not anteriorly or posteriorly, allowing relative increased mobility in the anterior posterior directions.

The ventral and dorsal sternoclavicular ligaments augment the relatively thin SCJ capsule, thus contributing to the anterior-posterior stability of the SCJ. While the dorsal ligament system appears to be the most significant stabilizer of the joint,[7] the ventral partner appears to weaken with increased age, lending to anterior joint subluxation. While nontraumatic anterior subluxations are benign,[8] they can be cosmetically undesirable and contribute to SCJ motion deficits in response to surface incongruity. Conversely, posterior subluxations are commonly related to trauma and should be considered a medical emergency, due to potential compromise to the airway, esophageal, vascular, and neural structures.[9–12]

The interclavicular ligament, which spans between the cranial-medial ends of the clavicles, contributes to stability of each SCJ and creates a dynamic influence between the 2 joints. The costoclavicular ligaments connect the clavicle to the first rib, thus illustrating a potential influence that first rib mobility can have on clavicular function. In addition, a cartilaginous connection anchors interarticular disc to the first rib, thus reducing disc movement in the superior-inferior direction. There are no muscles that directly cross the SCJ and, therefore, the stability and function of the joint largely depend upon the competency of bony architecture or inert tissue. However, the sternocleidomastoid, pectoralis major, subclavius, and the sternohyoid muscles all attach to the medial end of the clavicle, indirectly influencing the mobility and stability of the SCJ.[13]

Acromioclavicular Joint

The connection between the scapular acromion and the clavicle comprises the acromioclavicular joint (ACJ). Similar to the sternoclavicular joint, the ACJ joint surfaces are covered with fibrous cartilage, while being separated by an intraarticular disc in 20% of the population. The fibers of the ACJ capsule are confluent with deltoid and trapezius fascia. In addition, the capsule is reinforced by the superior and inferior acromioclavicular ligaments, which provide the primary ventral and dorsal joint stability. The inferior capsular ligament is the primary restraint to anterior translation of the clavicle[14] and compromise to these ligaments will result in increased anterior-posterior instability. The extraarticular coracoclavicular ligaments (conoid and trapezoid) stabilize the ACJ in a cranial-caudal direction, keeping the scapula from moving downward in relation to the clavicle and serve as secondary stabilizers in the anterior-posterior direction.[4,15,16] Lee et al suggested that the trapezoid component of the coracoclavicular ligament is the most important of these secondary stabilizers, especially during posterior displacement of the clavicle.[14] These ligaments can be ruptured with a fall on the acromion, leading to a separated ACJ.[17]

Bureau et al suggested that a bursa could form between the conoid and trapezoid ligaments, creating a pseudo-articulation. An approximation between the coracoid process and the clavicle produces a "kissing coracoid syndrome" that is often accompanied by an increase in the density of nociceptive fibers under the clavicle.[18] This affliction can be associated with dysplastic changes in the coracoid process or malunion after distal clavicle fracture. Additionally, it can emerge after reconstruction of the coracoclavicular ligaments when the repair is excessively tight and the subclavicular space is appreciably narrowed.

The coracoacromial ligament attaches to the inferior AC capsular ligament, as well as the coracohumeral and coracoclavicular ligaments.[16] This ligament connects the coracoid to the acromion process and creates a roof over the supraspinatus and humeral head, producing a buffer between the rotator cuff and the bony acromion. However, the coracoacromial ligament is not important for ACJ stability unless the other ligaments are disrupted. Conversely, this ligament is clinically significant, in that it serves as a component in an acromiohumeral impingement syndrome.

The stability of the ACJ is largely dependent upon the integrity of the previously mentioned capsuloligamentous structures surrounding the joint. The deltoid and trapezius muscle insertions surround the ACJ, providing secondary stability. While these muscles do not provide direct stabilization or create voluntary movement at the ACJ, they should be a focus of a nonoperative stabilization program, should a clinical instability develop.

Glenohumeral Joint (GHJ)

The glenohumeral joint (GHJ) is composed of the connection between the spheroid humeral head and the concave glenoid fossa of the scapula. This glenoid concavity is shallow, creating a relatively small (30%) contact area with the large humeral head. This relationship is augmented by the fibrocartilaginous glenoid labrum, which contributes to 50% of the total socket depth in the glenohumeral interface.[19] While this relationship contributes greatly to the overall mobility of the joint, glenohumeral stability is potentially compromised by this same relationship.

The humeral head is inclined approximately 135–145° upward. This orientation, along with the 11° upward tilt of the glenoid fossa, lends to the GHJ maximum loose-packed position of 55° in the scapular plane. In addition, the humeral head is retroverted approximately 20° influencing available external and internal rotation, where an increase in retroversion lends to increased external rotation.[20] Symeonides et al correlated decreased retroversion with an increased incidence of anterior instability, suggesting that a combination of anterior capsular adaptation and decreased retroversion potentially leads to an increase in anterior humeral head exposure during the cocking phase of throwing.[21] In addition, McPherson et al suggested that the radius of the humeral head does not match that of the glenoid, lending the GHJ to better restraint of anterior-posterior versus superior-inferior translation.[22] The restraint to superior translation is largely due to the acromion and coracoid processes of the scapula, as well as the coracoacromial ligament. The size of the acromiohumeral interval (AHI—the space between the acromion and greater tubercle of the humerus), which does not appear to be sex or age specific,[23] is typically 1.0–1.5 cm on radiograph.[24] Muscle hypertrophy, disrupted scapular mechanics, GHJ capsular dysfunction, or architectural changes can compromise this space and potentially lead to impingement by virtue of increased pressure within the interval.[25,26]

The glenohumeral joint capsule is somewhat loose, allowing for relative unrestricted motion of the GHJ. This loose capsule is posteriorly reinforced by the rotator cuff muscles, while the anterior area is supported by anterior cuff muscles, as well as the superior, middle, and inferior glenohumeral ligaments (see Figure 2). The middle glenohumeral ligament is frequently underdeveloped or absent, while the superior and inferior glenohumeral ligament complexes contribute largely to the overall stability of the GHJ.[27,28] The superior glenohumeral ligament originates from the supraglenoid tubercle with the long head of the biceps tendon and inserts at the lesser tubercle, supplying an anterior sling over the long head biceps tendon.[29] In addition to the superior, middle, and inferior glenohumeral ligaments, Kolts et al described a "spiral glenohumeral ligament" that works in concert with the glenohumeral ligament complex.[30] This spiral ligament begins at the infraglenoid tubercle and the axillary portion of the inferior glenohumeral ligament. It courses upward and laterally to fuse with the anterior joint capsule, middle glenohumeral ligament, and superior glenohumeral lig-

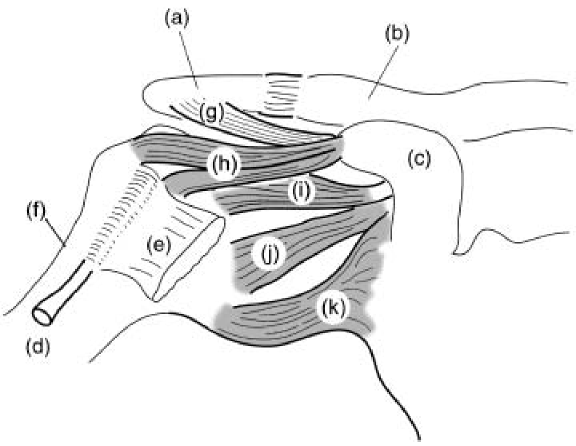

Figure 2. Ligaments in the Glenohumeral Region, Anterior View. (a) Acromion process; (b) Clavicle; (c) Coracoid process; (d) Biceps tendon, long head; (e) Subscapularis tendon; (f) Proximal humerus; (g) Coraco-acromial ligament; (h) Coraco-humeral ligament; (i) Superior anterior glenohumeral ligament; (j) Middle anterior glenohumeral ligament; (k) Inferior anterior glenohumeral ligament.

ament, ultimately inserting with the subscapularis tendon into the lesser tubercle. These ligament fibers spiral as they course toward their insertions during external rotation and abduction, thus lending to the name.[30]

The coracohumeral ligament demonstrates 2 divisions that course from the coracoid process to the greater and lesser tubercles of the humerus, strengthening the anterior-superior portion of the capsule (see Figure 2). Because they share attachments at the glenoid tubercles, the divisions are dynamized by the supraspinatus and subscapularis tendons, respectively.[31] The superficial fibers insert at the greater tuberosity while the deep fibers connect distal to the supraspinatus insertion, sending slips anteriorly over the biceps tendon.[29] The coracohumeral ligament varies in thickness, but appears more developed than the fibers of the superior glenohumeral ligament.[29] Finally, the transverse band (or "transverse ligament") connects the 2 divisions and resists their separation during the pull of their respective dynamizing muscles.

The tendon of the biceps long head courses between the greater and lesser tubercles, passing through the rotator cuff interval that is formed by the 2 divisions of the coracohumeral ligament (see Figure 2).[9,32] This tendon dives into the capsule on its way to inserting at the supraglenoid tubercle, representing 1 opening of the capsule. This rotator cuff interval is described as a triangular space bordered superiorly by the anterior fibers of the supraspinatus tendon, inferiorly by the superior border of the subscapularis tendon, medially by the corocoid process and laterally by the long head of the biceps tendon. The floor of the rotator interval is comprised of the coracohumeral ligament (CHL), superior glenohumeral ligament (SGHL), and joint capsule.[29,32] The rotator interval plays a role in resisting inferior translation of the humeral head, just as Jost et al suggested that the CHL and the SGHL are primarily responsible for inferior stabilization.[29] Histologically, the rotator interval contains unorganized collagen and an occasional congenital defect between the supraspinatus and subscapularis tendons, each contributing to anteroinferior and multidirectional glenohumeral instability.[32] Conversely, patients with frozen shoulder can demonstrate a CHL that is comprised of thickened, dense, highly vascular, pinkish bands of fibrous scar tissue in the absence of the rotator interval.[33] The contracted CHL consists of a dense matrix of type III collagen composed mainly of fibroblasts and myofibroblasts, lending to GHJ motion loss in the directions of flexion and external rotation.[33]

The anteroinferior ligament and capsule (see Figure 2) serves as the primary restraint to anteroinferior glenohumeral dislocation and exhibits higher peak strains at the glenoid insertion when compared to the humeral insertion.[34] The synovial membrane lines the fibrous capsule and secretes synovial fluid into the joint cavity, creating a normal synovial volume of 20–40 mL of fluid in the GHJ. The inferior portion of the fibrous capsule is redundant in order to allow considerable rotatory and translatory movement associated with overhead elevation (see Figure 3). A synovial lining covers this axillary recess, along with the anterior and posterior bands of the inferior glenohumeral ligament. A loss in synovial fluid creates the potential for adhesions within this recess, accompanied by a reduced synovial fluid volume to 2–4 mL and subsequent adhesive capsulitis. In addition, the size of this recess appears to influence surgical outcomes, as evidenced by a positive correlation between decreased capsular capacity and painful GHJ limitations after rotator cuff repair.[35]

The glenoid labrum is a fibrocartilage ring that circumferentially attaches to the bony rim of the glenoid fossa (see Figure 4). Nishida et al described 2 fibrocartilage layers within the labrum. The most superficial layer is found at the articular surface and contains chondrocytes that are more suited for compressive load tolerance. Conversely, the deep collagen layer provides cushioning and stabilization. Additionally, the fibrocytic

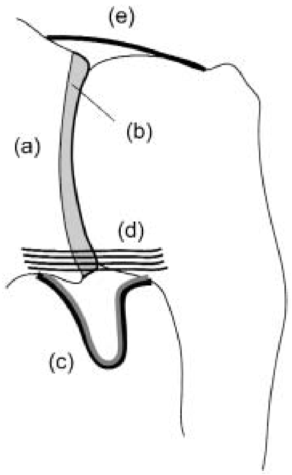

Figure 3. Redundant Glenohumeral Capsule. (a) Scapular glenoid neck and limbus; (b) Glenoid labrum; (c) Inferior glenohumeral capsular recess; (d) Inferior anterior glenohumeral ligament; (e) Superior glenohumeral capsule.

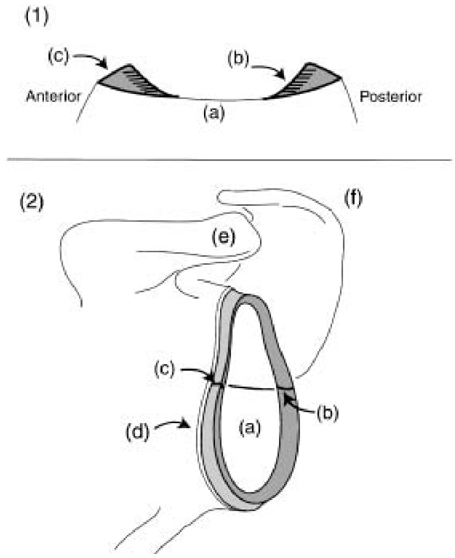

Figure 4. Glenoid Labrum. (1) Inferior Cross-Sectional View: (a) Glenoid fossa; (b) Chondrocytic articular surface; (c) Deep collagenous layer; (2) Anterior Oblique View: (a) Glenoid fossa; (b) Chondrocytic articular surface; (c) Deep collagenous layer; (d) Glenoid limbus and neck; (e) Coracoid process; (f) Acromion process.

collagenous outer rim resists tensile loading produced by glenohumeral movement.[36] The labral attachment to the glenoid bony rim (limbus) varies at different zones of the labrum. The inferior labrum is firmly attached to the limbus, while the superior labrum potentially demonstrates a loose attachment, predisposing it to disruption.[37] In addition, the attachment of the anterior labrum appears to be variable, lending it to compromise during micro- and macrotraumatic events.[38]

The glenohumeral capsule, ligaments, and numerous cuff tendons variably insert into the labrum.[39] For example, variations in the biceps long head insertion at the supraglenoid tubercle create differences in subsequent labral lesions. The more the biceps tendon inserts into the labrum versus the limbus or tubercle, the higher the potential it poses for superior labral lesion. In addition to increasing GHJ surface area contact, the labrum promotes stability by creating negative pressure within the GHJ.[40,41] The introduction of a small opening (vent) through the labrum appears to increase GHJ mobility as a consequence of reduced negative pressure in the joint.[42] Thus, either labral tears or surgically induced venting could produce increased laxity in the joint, meriting protective stabilization.[43]

The glenohumeral joint capsule is reinforced by the insertion of the rotator cuff muscles. These muscles include the supraspinatus, infraspinatus, teres minor, and the subscapularis.[4,44] These muscles contribute largely to the overall dynamic stability of the GHJ through concavity compression,[42] and weakness or imbalance in any of these muscles may cause changes in elevation chain function.[43] Therefore, the function of these muscles must be addressed during any shoulder stabilization routine.

Musculature

No discussion about the shoulder complex would be complete without including the clinical implications of muscles in the shoulder region. The deltoid is considered the most important mover and dynamic inferior stabilizer of the GHJ, although pathology of the deltoid is rare.[38] This reduced injury potential is likely related to the fibrous bands originating from the anterior corner of the acromion and proceeding through the middle portion of the deltoid, apparently providing structural support for the forces sustained during elevation.[45] While deltoid activity can elevate the greater tubercle into the acromion, the latissimus dorsi functions to decrease this compression within the acromiohumeral interval, meriting latissimus dorsi activation during the treatment of chronic bursitis.

The scapulothoracic primary movers, including the rhomboids, serratus anterior, and the trapezius, all contribute to scapular control and stability.[3] Scapular control is essential to scapulohumeral coordination and scapulothoracic instability can emerge out of performance deficits demonstrated by any of these muscles. The ability of the rotator cuff to move and dynamically stabilize the GHJ is largely dependant upon the ability of the scapular muscles to provide the GHJ with a stable base at the scapulothoracic joint. Consequently, clinicians should include scapular stabilization in the treatment of numerous shoulder afflictions.

The external insertions of the supraspinatus and infraspinatus tendons are predisposed to compression by external structures (such as the acromion) as they approach the greater tubercle in an inclined direction. Conversely, the internal insertions demonstrate a vertical course toward the deep aspects of the greater tubercle, lending them to shear, tension, and or compression loading. Additionally, these fibers appear to be susceptible to bone bruises when compression loaded in subjects younger than 35 years old. Each of these impingement behaviors will demonstrate unique clinical pictures and merit different management strategies (see Figure 5).[46]

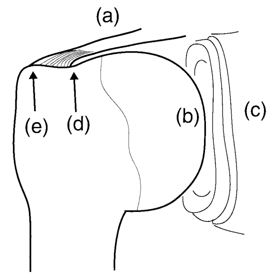

Figure 5. Rotator Cuff Insertions. (a) Supraspinatus tendon approaching the insertion into the greater tubercle of the humerus; (b) Humeral head; (c) Glenoid limbus, fossa, and accompanying labrum; (d) Internal insertion of the supraspinatus; (e) External insertion of the supraspinatus.

Defining the functions of the rotator cuff muscles has remained controversial. Cooperatively, the entire cuff system constrains the humeral head during elevation[38] and compresses the humeral head into the glenoid fossa for stability.[42,43,47] Individually, the infraspinatus primarily acts as an external rotator, whereas the supraspinatus is a primary abductor and a secondary external rotator. Consequently, resisted abduction will be the most painful clinical test for supraspinatus tendopathies, often followed by resisted external rotation. Itoi et al divided the supraspinatus into anterior, middle, and posterior sections. Based on evaluations of the ultimate load/stress and modulus of elasticity, the anterior strip appeared to be the most biomechanically significant for accepting loads.[48] However, select authors have suggested that the role of the supraspinatus is overemphasized.

While the popular belief is that this small muscle keeps the humeral head from migrating cranially during elevation, Halder et al suggested that the supraspinatus is less effective in superior stabilization of the GHJ when compared to the latissimus and teres minor muscles.[38] Thompson et al proposed that the main function of the supraspinatus is in the early range of abduction, and reported that increasing activation of the supraspinatus actually initiates an upward migration of the humeral head.[49] In addition, Halder et al suggested that the supraspinatus was ineffective at providing inferior stabilization when compared to the lateral deltoid and the coracobrachialis.[38] Wuelker et al found that supraspinatus activity actually increased GHJ friction and increased acromiohumeral interval pressure by 8%.[50] Based on these studies, abduction activities initiated by the supraspinatus should be delayed with impingement patients in order to reduce the risk of any symptom provocation associated with increased interval pressure. Furthermore, lesions must accompany supraspinatus tears to either the infraspinatus or subscapularis for active elevation to be compromised.[50] This may explain why patients with isolated supraspinatus tears are still able to elevate their shoulders.

Historically, the supraspinatus has been evaluated with isometric abduction testing in the "empty-can" position, where the shoulder is abducted and internally rotated. However, Sharkey demonstrated that the infraspinatus is more active than the supraspinatus during the "empty can" test and therefore challenged the test's validity for evaluating isolated supraspinatus activity.[51] Additionally, investigators demonstrated an increase in infraspinatus activity during elevation with internal rotation, and increased subscapularis activity during elevation with external rotation.[52] Furthermore, Otis suggested that the rotator cuff (especially the infraspinatus) is most important for elevation during the first 30–60° of abduction, the subscapularis is most important during elevation over 60° of abduction. Consequently, the best method for strengthening the subscapularis may be resistive training internal rotation prepositioned at 60° abduction.[53]

The subscapularis is the most powerful muscle of the rotator cuff. The subscapularis tendon, which completely covers the lesser tubercle, primarily acts to internally rotate the shoulder. Shoulder adduction is produced by the latissimus dorsi, pectoralis major, teres major, and teres minor when the shoulder is situated in the resting position (arm at the side). Conversely, the subscapularis can serve as an adductor when the shoulder is prepositioned in abduction greater than 30°. Therefore, an isolated subscapularis tendopathy will produce pain during resisted internal rotation, while resisted adduction is pain-free when the shoulder is positioned at the patient's side. Finally, the superior fibers of the subscapularis are subject to impingement within the acromiohumeral interval during flexion elevation. Equally, the inferior fibers are at risk for impingement against the coracoid process when the individual internally rotates the shoulder in a horizontally adducted position (as witnessed during a volleyball slam or a tennis serve). Therefore, subscapularis must be considered as a potential cause of a patient's shoulder impingement, meriting specific tests that suggest its involvement.

The subscapularis serves as an important anterior stabilizer, especially when eccentrically activated during functional movements. While this stabilization is provided through both active and passive constraint, any failure in the musculotendinous unit could compromise shoulder stability. Although the insertion of the superior tendon demonstrates the greatest thickness and highest tensile load-to-failure, it appears to be the most frequent failure point, closely followed by the midsubstance of the inferior tendon. Anteriorinferior dislocation or a tension load imposed by external rotation and or extension can injure these regions.[38]

The anatomical variation of long head of the biceps (LHB) proximal insertion has been well described.[54–56] Approximately 50% of the tendons are attached to the supraglenoid tubercle, whereas 25% are attached only to the labrum and 25% are attached to both supraglenoid tubercle and the labrum.[54] This variability lends to inconsistency in tensile and shear loading properties within the tendon and labrum, as well as differences in the lesions produced during macrotraumatic events. Additionally, the LHB shares fibrous connection to the superior and inferior glenohumeral ligaments as a component in the periarticular fiber system.[57] Furthermore, Jost et al describes anterior support to the LHB tendon from the coracohumeral and superior glenohumeral ligaments.[29]

The LHB courses through the intertubercular groove, acting as a guide for glenohumeral elevation.[58] In essence, the LHB prevents superior translation of the humeral head into the acromiohumeral interval, thus stabilizing the GHJ (see Figure 6).[37,43,59] Levy et al suggested that the LHB functions minimally in isolated shoulder motion when elbow and forearm motion is controlled, and therefore the LHB function at the shoulder must be based on the passive tensile role of the LHB tendon or tension associated with elbow and forearm activity.[60]

The long head of the biceps (LHB) is intraarticular but extra-synovial as it is escorted through the GHJ joint capsule by its own synovial sheath. This tenosynovial sheath is often the source of LHB affliction and is most provocative when the tendon is moved. Biceps tenosynovitis can be characterized by fibrosis and collagen degeneration, synovial villous or vascular hyperplasia, lymphocytic-plasmacytic infiltrates, cartilaginous metaplasia, and possible ischemic necrosis.[61] This behavior is related to the structure of the sheath, which presents with a visceral layer attached to the tendon and a parietal layer that is harnessed to surrounding structures by connective tissue. Tendon movement is produced when the patient's shoulder is extended in the

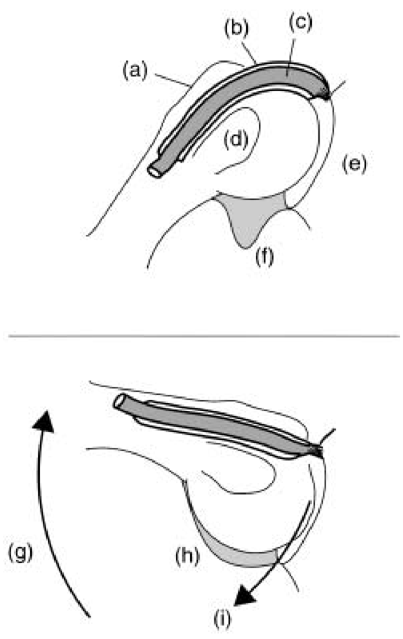

Figure 6. Function of the Biceps Long-Head Tendon during shoulder elevation. (a) Greater tubercle of the humerus; (b) Tenosynovial sheath surrounding the tendon; (c) Biceps long-head tendon coursing through the humeral bicipital groove to its insertion into the glenoid labrum and supra-glenoid tubercle; (d) Lesser tubercle of the humerus; (e) Glenoid; (f) inferior gleno-humeral capsular recess; (g) Elevation of the glenohumeral joint into abduction; (h) Inferior capsular recess stretched under tension loading; (i) inferior arthrokinematic translation of the humeral head.

glenoid plane, thus sliding the visceral layer of the sheath on the stationary parietal layer. This movement can produce the patient's symptoms when the visceral and parietal layers are inflamed, swollen, and irregular,[62] potentially producing pain with the movement as the rough surfaces of the inflamed layers slide across each other.

Suprahumeral Roof

Components of the suprahumeral roof include the coracoacromial ligament, the coracoid and the acromion. Graichen et al reported a difference in subacromial space between males (larger) and females (smaller) at rest and at 30° of abduction, but not at 90° abduction or during muscle activity. Thus, higher levels of elevation and muscle activity increases the variability in subacromial space.[47] Occupying the acromiohumeral interval are the rotator cuff tendons and the subacromiodeltoid bursa. The bursa plays a large role in the gliding mechanism,[63] as it is attached to the greater tubercle of the humerus, supra- and infraspinatus muscles, acromion, coracoacromial ligament, and the inferior acromioclavicular ligament.

The bursa may vary in size with a possible segmental or compartmentalized configuration,[4] thus confounding the role of palpation in the diagnosis of shoulder pain. The acromiohumeral interval can be compressed as the deltoid and rotator cuff are activated, resulting in bursal irritation and subsequent symptoms with any shoulder movement. The bursa is the most densely innervated structure in the area, whose nerve supply arises from the articular branches of the suprascapular and lateral pectoral nerves. The bursa may be involved in the regulation of shoulder movement as evidenced by the populations of free nerve endings, Ruffini endings and Pacinian corpuscles observed in the surrounding capsuloligamentous structures.[63–66] The bursa is often the primary source of pain with traumatic partial rotator cuff tears in patients younger than 40 years old, and as a result of overuse tears in patients older than 40.[67] In addition, a localized bursal reaction is described as a degenerative disorder or the result of acromion distortions.[25,68] Finally, the symptoms associated with chronic bursal irritation may stem from increased substance P and substance P receptor expression in the synovial region.[69]

Vascularization (GHJ)

Branches of the posterior circumflex humeral artery and the suprascapular artery supply the blood flow to the posterior rotator cuff. The anterior circumflex humeral artery and the subscapular and coracoacromial arteries supply the anterior rotator cuff. Hypovascular zones known as "zones of lability" exist in the supraspinatus, infraspinatus, and subscapularis with the supraspinatus having the highest incidence.[70–72] These hypovascular zones create early predilection sites for degeneration and subsequent traumatic tears. The "wringing out" mechanism occurs with the individual's arm at the side, as the humeral head is pushed cranial against the tendon of the rotator cuff.[4] Slight abduction may limit the potential for this "wringing-out," so many exercises in the rehabilitation process should be performed in a position of slight abduction.

BIOMECHANICS

Upper extremity elevation depends on shoulder-complex function. Whereas elevation represents every attempt to lift the upper extremity overhead, an individual can elevate the arm forward through flexion in the parasagittal plane, sideways through abduction in the frontal plane, or any movement between these planes in an oblique direction. In addition, an individual can elevate backward in the parasagittal plane. One can identify several important structural members within the elevation chain: the acromioclavicular joint, or ACJ; the sternoclavicular joint, or SCJ; the glenohumeral joint, or GHJ; the scapulothoracic junction, or STJ; the cervicothoracic junction, or CTJ; and the upper six ribs in the thoracic spine.[1] Dysfunction at any of these sites can perpetuate clinical problems, such as impingement or instability. In addition, movement can be appreciated in the acromiohumeral interval during elevation. Within this space one can appreciate movement between the undersurface of the acromion and the long tendon of the biceps as well as the other soft tissue structures found in the area, such as the subacromiodeltoid bursa and tendons of the supraspinatus or infraspinatus. Each of these members demonstrates a host of unique biomechanical properties that, when combined, produce complex kinematic and kinetic behaviors during functional upper extremity movement. To understand these complex behaviors, one must first analyze the osteokinematic and arthrokinematic performance of each component.

The sternoclavicular joint (SCJ) moves as result of clavicular movement. Osteokinematic clavicular motion is a component of shoulder girdle movement in several planes. The clavicle can swing cranial about a horizontal axis through its proximal end during shoulder girdle elevation, producing arthrokinematic movement at the sternoclavicular joint in relation to the intraarticular disc and sternum.[73] Arthrokinematically, the convex clavicular surface rolls cranial, medial and slightly dorsal while it slides caudal, lateral, and slightly ventral (see Figure 7).[4] Conversely, the clavicle swings into retraction within the transverse plane about a vertical axis through the sternum, where the concave clavicle and intraarticular disc will move in relation to the convex sternum.[73] Here, the concave clavicle and disc will arthrokinematically rock and glide in a posterior, slightly caudal, and slightly medial direction (see Figure 8).[4] Although these behaviors are respectively reversed during shoulder girdle depression and protraction, they are less clinically relevant as patients rarely present with clinical limitations in either direction of movement.

The clavicle demonstrates a curved trajectory upward, backward, and downward during functional upper extremity elevation (Vanderhelm, 1994).[74] More specifically, the clavicle elevates and retracts during functional elevation between 0° and 150°.[1] Conversely, the clavicle produces a relative depression and protraction trajectory during elevation greater than 150°, while never reaching its original starting position (see Figure 9). In addition, functional elevation requires the clavicle to move at the SCJ about a third axis, whereas the clavicle produces a 50° to 70° accessory backward spin (see Figure 9).[74] Although a sellar joint should only allow 2° of freedom (ie, elevation/depression and protraction/retraction), this third degree of freedom is allowed by deformation within the intraarticular disc. Thus, SCJ mechanics violate the traditional view of sellar joint behavior.

In context with the backward spin at the SCJ, Hollinshead discovered that SCJ movements are greater during isolated shoulder girdle elevation versus functional elevation of the entire upper extremity.[73] This author suggested that the difference is associated with the backward spin, in that the capsuloligamentous structures about the SCJ are twisted, thus restraining clavicular elevation or retraction trajectories. While patients can demonstrate normal accessory movement in the SCJ at rest or in a shrugged shoulder girdle position (in absence of the spin), the joint may limit functional upper extremity elevation in relation to a limit of the spin movement. This behavior merits the examination of accessory movement at the SCJ in a position of upper extremity elevation, in that SCJ capsular adaptations can induce a significant loss of upper extremity elevation even if isolated shoulder girdle motion is normal.

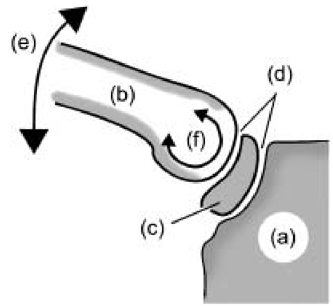

Figure 7. Sternoclavicular Movement in the Frontal Plane during Shoulder Elevation; (a) Sternal manubrium; (b) Clavicle; (c) Sternoclavicular intra-articular disc; (d) Two articular compartments created by the intra-articular disc within the joint; (e) Elevation of the clavicle in the frontal plane; (f) Arthrokinematic rolling of the clavicle on the intraarticular disc during elevation.

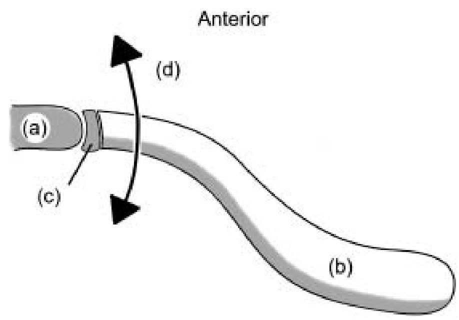

Figure 8. Sternoclavicular Movement in the Transverse Plane during Shoulder Elevation: (a) Sternal manubrium; (b) Clavicle; (c) Sternoclavicular intra-articular disc; (d) Retraction of the clavicle in the transverse plane.

The previously defined clavicular behaviors influence movement at the acromioclavicular joint (ACJ). In addition, movements of the scapula and acromion influences movement at this joint during shoulder girdle movement and upper extremity functional elevation. Moreover, the majority of movement at the ACJ occurs after 90° of upper extremity elevation. This is of great interest to clinicians, as ACJ pain occurs more frequently when the upper extremity is positioned above 90° elevation. This is of great interest to clinicians, as ACJ pain occurs more frequently when the upper extremity is positioned above 90° elevation. Furthermore, the previously mentioned clavicular spin behaviors translate into a spin at the ACJ. However, this spin behavior is rarely greater than 10° at the ACJ, versus the 50° to 70° spin witnessed at the SCJ. This disparity is confusing, because the same osteokinematic spin of the clavicle produces different

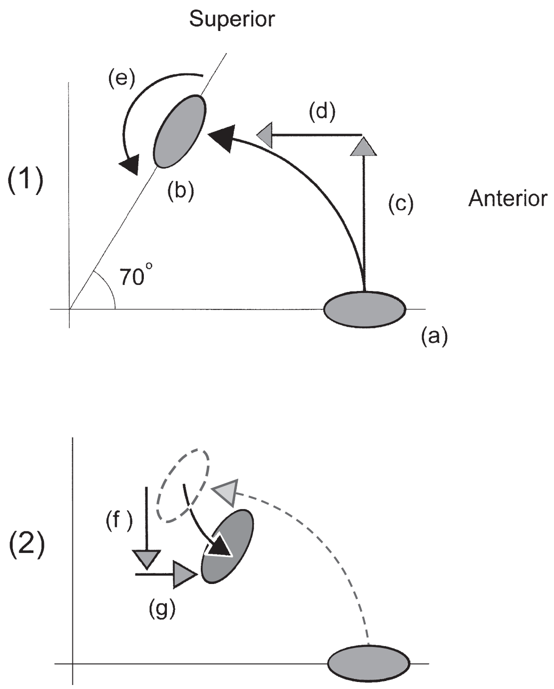

Figure 9. Lateral Cross-Sectional View of the Clavicle. (1) Clavicular Motion during upper elevation 0–150°: (a) Clavicle positioned at rest with arm at the side; (b) Clavicular position when upper extremity is elevated; (c) Clavicular elevation vector; (d) Clavicular retraction vector; (e) Resultant clavicular elevation trajectory; (f) 70° backwards spin of the clavicle. (2) Clavicular Motion during terminal upper extremity elevation between 150–180°: (a) Relative depression vector; (b) Relative protraction vector; (c) Resultant clavicular trajectory.

motion values at the different joints. However, while the clavicle spins relative to a fixed sternum during functional elevation, the same clavicle is spinning relative to a moving acromion. Thus, motion at the ACJ is intimately associated with movement of the scapula at the scapulothoracic junction (STJ).

From an anterior-posterior view, the ACJ is relatively flat, thus producing a relative rocking of the clavicle on the acromion during functional upper extremity elevation. However, the clavicle is convex on a concave acromion from an aerial view. As previously reported, the clavicle retracts during functional upper extremity elevation. As result, the convex clavicle must arthrokinematically slide anterior on the concave acromion during retraction in order to allow functional elevation above 90°.[4] Any limits in this anterior sliding may hinder elevation movement, especially above 90°. Conversely, capsuloligamentous compromise at the ACJ may allow excessive translation and the subsequent sequelae associated with ACJ degeneration, such as deformation and exostosis.[75,76]

Scapular position and movement are essential to total shoulder complex function. The scapula moves as a component of the shoulder girdle on the thoracic wall in a variety of different directions, including upward or downward rotation, protraction or retraction, and elevation or depression. Selected motions of the scapulothoracic junction (STJ) accompany clavicular movements during functional upper extremity elevation. McClure et al conducted in-vivo three-dimensional analyses of scapular movements and found that the scapula upwardly rotates in the frontal plane, posteriorly tilts in the parasagittal plane and externally rotates in the transverse plane in a nonlinear fashion during functional elevation. This behavior was repeated at end-range active external rotation of the glenohumeral joint. However, internal rotation appeared to have little influence on STJ behaviors. McClure et al suggested that the external rotation behavior reduced stress to the anterior glenohumeral joint capsuloligamentous complex during functional elevation, especially in external rotation/abduction as witnessed with the wind-up phase of throwing. The investigators suggested that a limit to this rotation might increase the risk of anterior shoulder laxity and subsequent instability. Finally, they suggested that the posterior tilting promoted humeral clearance in the acromiohumeral interval during elevation, as individuals who suffer from impingement demonstrate reduced posterior tilting.[2,77]

Other investigators have demonstrated similar findings.[1,74,78,79] In addition, Fung et al found that scapular upward rotation and retraction (external rotation) were greatest during abduction elevation (versus flexion elevation). On the other hand, they found that posterior tilting was greatest during flexion elevation. Furthermore, Fung et al found that these behaviors occurred later in the range versus previously documented in-vivo behaviors.[1] This finding suggested that in-vivo shoulder girdle behaviors are initiated by dynamic muscular systems versus the delayed behaviors associated with the passive, isolated capsuloligamentous influence witnessed in this study.

Glenohumeral joint (GHJ) movements participate in the complex angular displacements of the functional “humerothoracic joint”.[80] Historically, glenohumeral movements have been labeled as ball-and-socket kinematics in concert with the relationship of the convex humeral head to the concave glenoid fossa and labrum complex. However, recent investigators have observed translatory behaviors of the humeral head during elevation activities[47,50,81] that are dynamically constrained by the labrum, capsuloligamentous structures, and rotator cuff complex.[19,38,43,82]

The osteokinematic swing associated with GHJ abduction is accompanied by superior, inferior and anterior humeral translation. The humeral head translates superiorly to the superior glenoid fossa within the first 30° of abduction, followed by gradual anterior and inferior translations as the range progresses (see Figure 10).[47,50,81] Inferior translation of the humeral head is constrained by the superior capsule, superior glenohumeral ligament, and coracohumeral ligament when the humerus is at the subject's side in the anatomical resting position.[28] Conversely, the inferior capsuloligamentous complex constrains inferior translation when the GHJ is abducted. Any affliction that triggers inferior capsular adaptive shortening can reduce inferior translation of the humeral head and subsequent GHJ abduction, resulting in a compensatory excess in scapular tilting and possible impingement behaviors in the acromiohumeral interval.[35]

The osteokinematic swing executed during GHJ flexion is accompanied by an arthrokinematic spin and translations of the humeral head. Once again, the humeral head translates superiorly to the superior glenoid fossa during the first 30° of flexion, followed by a gradual posterior and inferior translation as the range progresses (see Figure 11).[50,81] These behaviors are potentially constrained by any member of the entire capsuloligamentous system, as the capsuloligamentous structures twist during the spin movement of the humeral head. However, investigators have demonstrated that the primary physiological constraints to this behavior are the coracohumeral and superior glenohumeral ligaments. Any compromise to these structures, as witnessed after a rotator cuff interval tear, can decrease these controls and produce excessive aphysiological translations and subsequent GHJ instability.[28] On the contrary, adaptive shortening of the posterior capsule can alter the arthrokinematic spin and reduce the inferior translatory behaviors during GHJ flexion, resulting in persistent superior positioning and subsequent impingement in the acromiohumeral interval (see Figure 12).[3,83–85]

Glenohumeral external rotation is best described as an osteokinematic rotation of the humerus about the diaphyseal axis. This movement is accompanied by a posterior rolling and anterior sliding of the humeral head on the glenoid complex when the arm is positioned at the patient's side. This anterior translatory behavior is constrained by both the coracohumeral and superior anterior glenohumeral ligament complex (see Figure 13).[27] Conversely, external rotation performed in a position of GHJ abduction is best described as an

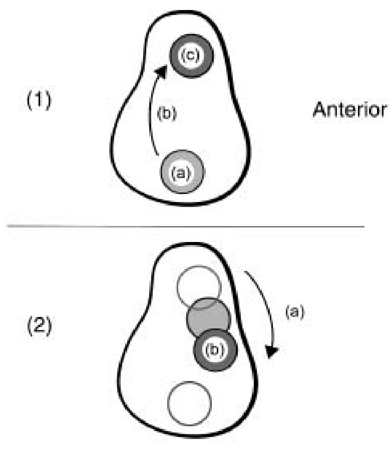

Figure 10. Humeral Head Translation Upon the Glenoid Fossa During Upper Extremity Abduction Elevation: (1) Humeral head translation during the first 30° of abduction elevation: (a) Contact point of the humeral head on the glenoid fossa with the arm at rest; (b) Course of humeral head translation; (c) Glenohumeral contact point with the arm abducted to 30°. (2) Humeral head translation during 30–180° of abduction elevation: (a) Course of humeral head translation; (b) Glenohumeral contact point at end-range abduction elevation.

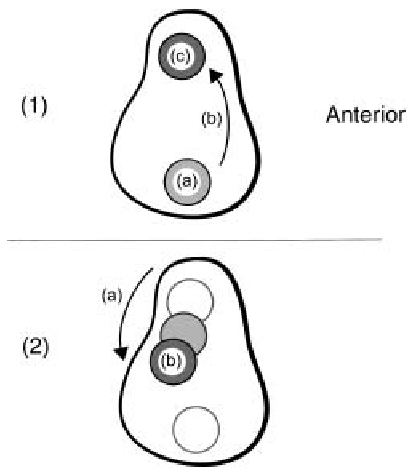

Figure 11. Humeral Head Translation Upon the Glenoid Fossa During Upper Extremity Flexion Elevation: (1) Humeral head translation during the first 30° of flexion elevation: (a) Contact point of the humeral head on the glenoid fossa with the arm at rest; (b) Course of humeral head translation; (c) Glenohumeral contact point with the arm flexed to 30°. (2) Humeral head translation during 30–180° of flexion elevation: (a) Course of humeral head translation; (b) Glenohumeral contact point at end-range flexion elevation.

arthrokinematic spin, due to repositioning of the humeral head with respect to the glenoid complex. The inferior anterior glenohumeral ligament serves as the primary constraint to this particular movement and any adaptive shortening of this structure could limit external rotation in an abducted position (see Figure 13). Additionally, this limitation may require the scapula and shoulder girdle to compensate, as witnessed during the wind-up phase of throwing after Bankhart repair.[27] On the other hand, elongation of this mechanism could increase external rotation during cocking, leading to increased aphysiological motion and risk for rotator cuff lesions, posterior labral impingement, or SLAP lesion (Superior Labrum Anterior-Posterior) in the superior labral quadrant.[86] Finally, the difference in constraints based on changes in GHJ position merits clinical testing for joint limits or laxity in both dependent and abducted positions.

Similar behaviors can be witnessed during internal rotation, where the superior posterior capsule constrains internal rotation in a dependent GHJ position and the inferior posterior capsule limits internal rotation while the GHJ is positioned in abduction. Posterior capsular tightness can limit internal rotation and, as previously mentioned, can result in sustained superior humeral head translation during elevation. Limitations appear to be related to posterior capsular fibrosis and muscular tightness.[87,88] Additionally, progressive limitation appears to be related to repetitive or sustained activity in a functionally external rotated position, such as tennis.[87,89,90] However, as previously discussed normal posterior structures provide little support to the stability of the GHJ in the posterior translatory direction. Rather, posterior stability is afforded by the anterior angulation of the glenoid fossa,[1] the integrity of the glenoid labrum and the support afforded by the anterior inferior glenohumeral ligament complex.[82]

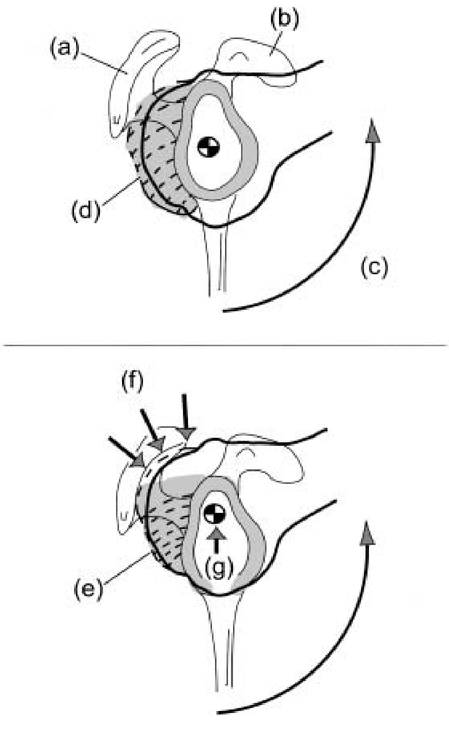

Figure 12. The Diablo Effect; Influence of Posterior Glenohumeral Capsular Tightness on Impingement Behaviors Seen from an Outlet View: (a) Acromion process; (b) Coracoid process; (c) Elevation of the glenohumeral joint into flexion; (d) Tension loading of a normal posterior glenohumeral capsule; (e) Tension loading of an adaptively shortened posterior glenohumeral capsule; (f) Decreased acromiohumeral interval space, resulting in elevated interval pressure and subsequent impingement; (g) Persistent superior positioning of the glenohumeral contact point during elevation.

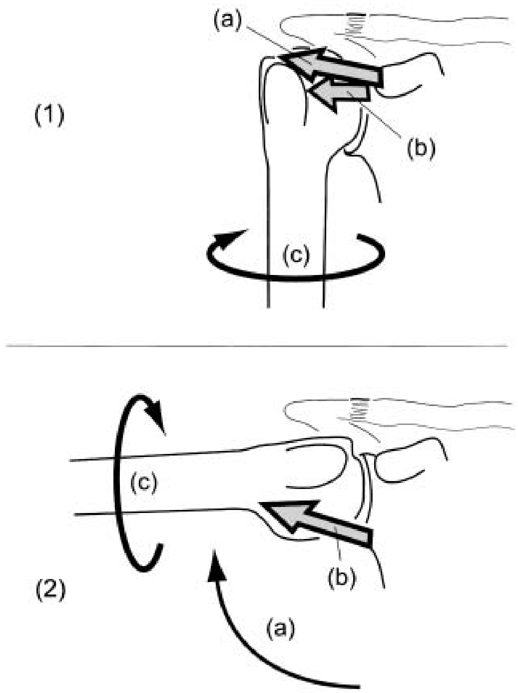

Figure 13. Capsulo-Ligamentous Constraints on Glenohumeral External Rotation: (1) Constraints to External Rotation with the Humerus Positioned at the Subject's Side: (a) Tension loading in the coraco-humeral ligament; (b) Tension loading in the superior glenohumeral ligament; (c) External rotation of the humerus. (2) Constraints to External Rotation with the Humerus Positioned at 90° Abduction: (a) Elevation of the glenohumeral joint to 90° abduction; (b) Tension loading in the inferior glenohumeral ligament complex; (c) External rotation of the humerus.

Glenohumeral joint movement is very complex during functional elevation, due to coupling movements of the joint and movement of scapula. First, elevation in abduction requires external rotation of the glenohumeral joint to maximize humeral contact with the glenoid fossa.[91] Second, the glenohumeral joint moves in concert with the scapulothoracic junction about a functional axis outside the humeral head during upper extremity functional elevation.[80] While, rotator cuff muscle activity appears to persuade humeral head centralization during elevation,[47] scapular movement helps to maintain appropriate length tension relationships in those muscles through full elevation range.[2] This nonlinear behavior is a consequence of concerted functional coordination between the GHJ and STJ, known as "scapulohumeral rhythm".[1,2,92] While the influence that the direction of elevation has on this rhythm is controversial, investigators have historically suggested that this behavior can be best described as a ratio of movement between the GHJ and STJ.[92–95]

Recently, investigators have identified three distinctive phases of elevation, accompanied by different scapulohumeral rhythm behaviors occurring in each of the various phases.[74,92] During the setting phase of elevation (0° to 60°) the scapula seeks a stable position under the humerus, so to provide a more secure base for the rolling humeral head. The movement ratio that is witnessed during this phase is approximately 6:1 to 7:1 (GHJ:STJ). Throughout this arc, the scapula "wiggles" as it attempts to establish an optimal position. However, because the upper extremity weighs more than the scapula; the scapula tends to tip or wing if not sufficiently controlled by activity of the serratus anterior (especially during eccentric activity associated with a return from an elevated position).

During the elevation phase (60° to 130°), the scapulohumeral complex produces three-dimensional motion around the previously mentioned helical oblique axis outside of the humeral head. The glenoid fossa is appropriately positioned under the humeral head during this phase and the subsequent movement ratio is approximately 1:1. However, this ratio changes again to 5:1 during the end-range phase (130° to 180°).

Controversy can be witnessed regarding the impact that resisted movement has on the scapulohumeral rhythm. While select investigators have suggested that an increase in STJ involvement can be observed earlier in the elevation range of motion when the movement is resisted,[92,93] others have suggested that resistance has no impact on the rhythm.[78] Additionally, McQuade et al found that shoulder muscle fatigue appeared to significantly alter scapulohumeral rhythm by decreasing scapulothoracic movement during elevation.[96] Clinically, disturbances in this rhythm can be linked to impingement, instability, and elevation limits.[2,97,98] Additionally, attaining full GHJ abduction does not insure normal functional elevation. Thus, clinicians should use an elevation preposition when mobilizing the glenohumeral joint to ensure full restoration of functional elevation.[99]

SUMMARY

Distinctive anatomical features prevail in the shoulder complex, lending to specific pathological conditions. Clinical conditions in the shoulder complex are multifactoral, and both anatomical and biomechanical disturbances participate in the development of affliction. The sternocalvicular, acromioclavicular, glenohumeral, and scapulothoracic joints must all participate in function of the shoulder complex, as each biomechanically contributes to functional movements and clinical disorders witnessed in the shoulder region. Clinicians are encouraged to consider the anatomical and biomechanical distinctions in this region when examining and diagnosing disorders of the shoulder.

Many painful conditions in the shoulder region share similar clinical features, creating a diagnostic challenge and potential confusion for the clinician. A careful examination that implements specific testing procedures can lead a clinician to effective diagnosis of the painful shoulder. Once diagnosed, a clinician should consider specific management options when attempting to eradicate the patient's symptoms. Clinical examination, differential diagnosis, and management options will be considered in Part II of this series.

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Appendix: Continuing Medical Education Questions

1. All of the following clavicular movements are involved in upper extremity elevation less than 150°, except:
   a. Backward Spin
   b. Elevation
   c. Protraction
   d. Retraction
2. Which ligament system is most responsible for stabilizing the acromioclavicular joint in the frontal plane (ie, . . . in the cranial-caudal direction)?
   a. Acromioclavicular ligaments
   b. Coracoacromial ligament
   c. Coracoclavicular ligaments
   d. Coracohumeral ligaments
3. What percentage of the humeral head is in contact with the glenoid fossa, in absence of the glenohumeral labrum?
   a. 30%
   b. 40%
   c. 50%
   d. 60%
4. All of the following structures serve as components of the rotator cuff interval, except:
   a. Coracohumeral ligament
   b. Infraspinatus tendon
   c. Subscapularis tendon
   d. Superior glenohumeral ligament
5. Which of the following ligaments associated with the glenohumeral joint are frequently underdeveloped?
   a. Coracohumeral ligament
   b Inferior glenohumeral ligament
   c. Middle glenohumeral ligament
   d. Superior glenohumeral ligament
6. The glenohumeral joint capsule is reinforced by the tendons of all of the following muscles, except:
   a. Infraspinatus
   b. Subscapularis
   c. Supraspinatus
   d. Teres Major
7. Your patient produces severe pain during resisted shoulder abduction, along with minimal pain during resisted external rotation. Which of the following tendopathies would be most likely responsible for your patient's pain?
   a. Biceps Tendinitis
   b. Infraspinatus Tendinitis
   c. Subscapularis Tendinitis
   d. Supraspinatus Tendinitis
8. All of the following muscles are adductors while the arm is positioned at the patient's side, except for:
   a. Latissimus dorsi
   b. Pectoralis major
   c. Subscapularis
   d. Teres Major
9. Which of the following tendons are considered intra-articular but extrasynovial as it courses in proximity of the glenohumeral joint?
   a. Biceps Tendinitis
   b. Infraspinatus Tendinitis
   c. Subscapularis Tendinitis
   d. Supraspinatus Tendinitis
10. All of the following statements are true regarding the subacromiodeltoid bursa, except:
    a. It is often the 1° source of pain with traumatic rotator cuff tears in patients younger than 40 years.
    b. It is the most densely innervated structure in the glenohumeral region
    c. It may be involved in the neurological regulation of shoulder movements
    d. It's size and compartmental configuration are predictable and consistent across patients.
11. Which of the following joints includes an intra-articular disc that creates two joint compartments?
    a. Acromioclavicular joint
    b. Glenohumeral joint
    c. Scapulothoracic joint
    d. Sternoclavicular joint
12. During which of the following upper extremity motions is scapular posterior tilting most prevalent?
    a. Abduction elevation
    b. Extension elevation
    c. Flexion elevation
    d. Internal rotation
13. The coracohumeral ligament serves as a principle constraint to all of the following movements, except:

a. Glenohumeral abduction
b. Glenohumeral external rotation
c. Glenohumeral flexion
d. Glenohumeral inferior translation with the arm at the patient's side.

14. All of the following structures are essential to posterior glenohumeral joint stability except:
a. Anterior angulation of the glenoid fossa
b. Anterior-inferior glenohumeral ligament complex
c. Integrity of the glenoid labrum
d. Posterior glenohumeral capsule

15 What is the approximate scapulo-humeral movement ratio produced between the glenohumeral joint and scapulothoracic complex at 40° of arm elevation?
a. A ratio of 1 : 1
b. A ratio of 7 : 1
c. A ratio of 3 : 1
d. A ratio of 5 : 1

Answers

1. c
2. c
3. a
4. b
5. c
6. d
7. d
8. c
9. a
10. d
11. d
12. c
13. a
14. d
15. b