Shoulder Kinematics and Biomechanics

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Alper Yataganbaba, Erman Ceyhan, and Gazi Huri

After the human race evolved to be bipedal, the scapulohumeral complex also adapted. The bone continuity required in the weight-bearing joints is compromised to perform more complex movements with the upper limb and increase the range of motion. This adaptation in bony structures of shoulder complex increased the importance of soft tissue in joint stability [1, 2]. Thus, more unstable but the most flexible joint in our body has been formed. This is called "mobility-stability trade-off" [3].

The shoulder complex consists of four joints: glenohumeral joint (GH), acromioclavicular joint (AC), sternoclavicular joint (SC) joint, and scapulothoracic (ST) joint.

The GH joint is the main component of the shoulder complex. It connects the humerus and the scapula and is the joint with the widest range of motion in the human body. The mismatch between the humeral head and the relatively smaller glenoid creates instability, which provides a wide range of motion [4]. The GH joint can perform 180° of vertical abduction and 40° of vertical adduction (a), 180° of flexion and 55° of extension in the sagittal plane (b), 130° of horizontal abduction and 40° of horizontal adduction (c), 70° of internal rotation and 90° of external rotation movements around the long axis of the humerus (d). The glenohumeral joint also allows translation in all directions, which also increases the shoulder range of motion [5] (Fig. 4.1).

Although the shoulder complex constitutes most of the upper limb, they are connected to the axial skeleton by a single joint, the sternoclavicular (SC) joint [6]. Keeping the shoulder complex steady in the trunk is done mainly with muscle strength than this single joint. The sternoclavicular joint is a plane synovial joint that allows elevation/depression, protraction/retraction, and axial rotation movements. The position of the lateral end of the clavicle defines elevation/depression and protraction/retraction movements; the rotation is around the long axis of the clavicle. Besides, the medial end of the clavicle can translate in the anterior/posterior, superior/inferior, and medial/lateral directions on the sternum. Stability is provided by a synovial capsule, joint disc, and three major ligaments [6, 7]. Since the clavicle is connected laterally to the scapula with the acromioclavicular (AC) joint, the SC joint is also involved in the movement of the scapula [8, 9].

The acromioclavicular joint is the synovial plane joint between the lateral end of the clavi-

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A. Yataganbaba
Hacettepe University School of Medicine,
Department of Orthopaedics and Traumatology,
Ankara, Turkey

E. Ceyhan
Department of Orthopaedics and Traumatology,
Ankara City Hospital, Ankara, Turkey

G. Huri (✉)
Department of Orthopaedics and Traumatology,
Hacettepe University School of Medicine,
Ankara, Turkey

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Fig. 4.1 Glenohumeral Joint movements

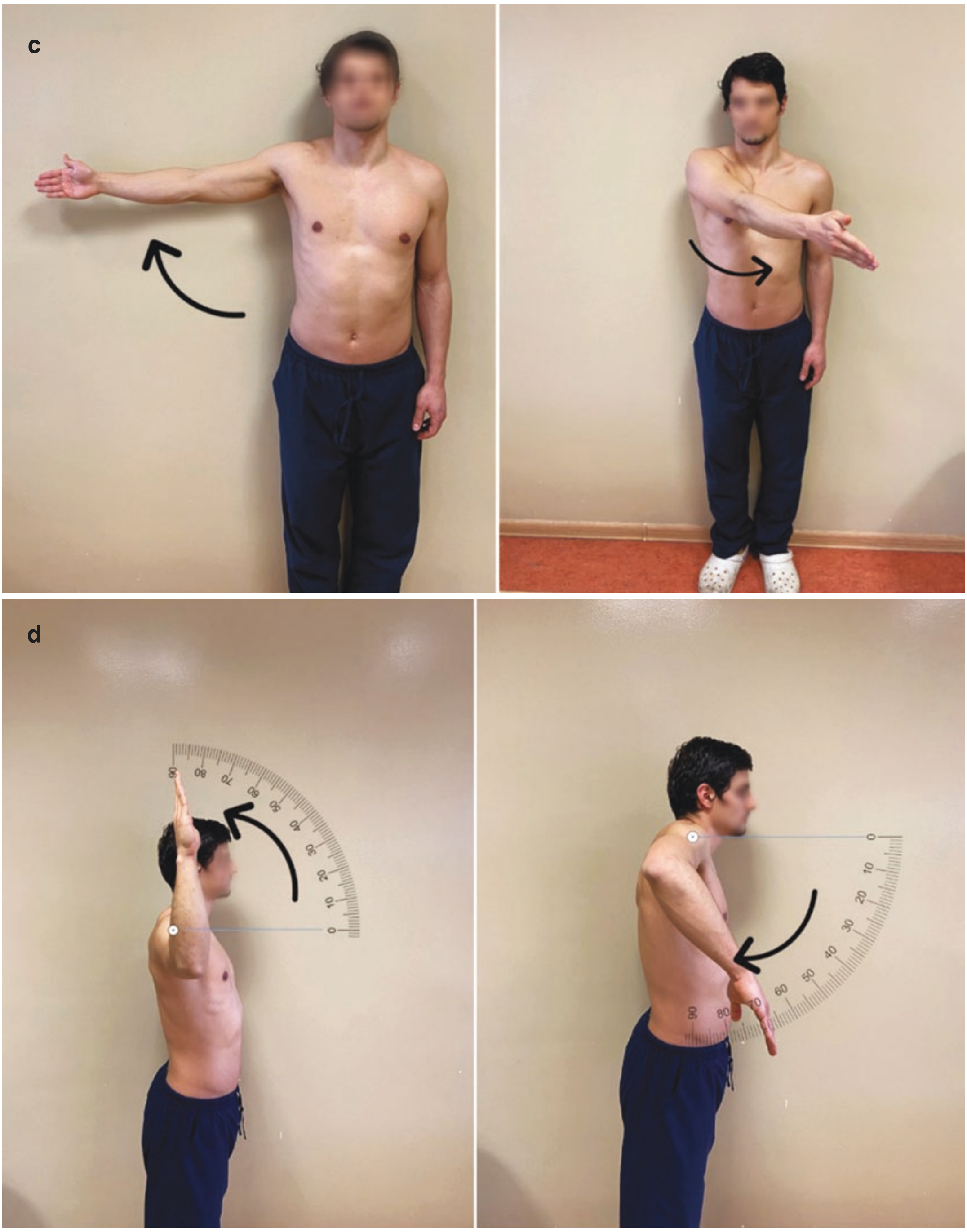

Fig. 4.1 (continued)

cle and the acromion. Similar to the SC joint, stability is ensured by capsule, ligaments, and joint disc [10]. The acromioclavicular joint helps scapula move in harmony with the thorax that changes shape during shoulder movements [11]. It also allows the forces applied to the upper limb to be transferred to the trunk through the clavicle and are more susceptible to injuries. Joint movements are limited because the joint surfaces between the scapula and the clavicle are incongruent. The number of studies describing the movements of this joint is limited.

The scapulothoracic joint forms the connection between the scapula and thorax. Still, the ST joint is not a real joint where the bone segments are connected by fibrous, synovial, and cartilage tissue. Thus, the ST joint is often referred to as "functional joint" in the literature [12]. Accordingly, the shoulder is mainly kept stable on the thorax by muscle contractions. The scapula is attached to the clavicle with an AC joint. Therefore, every movement of the scapula affects the AC joint and SC joint [12–14]. The scapula is located on the thorax between the second and seventh ribs. It is positioned in 35–45° internal rotation, 10–15° anteriorly tilted, and 10° upward rotation [8]. The glenohumeral joint forms two-thirds of the total range of motion of the shoulder, and scapula movements create one third. The regular movement of the scapula includes three components: upward and downward rotation around a horizontal axis perpendicular to the plane of the scapula (a), abduction and adduction (b), elevation and depression(c). During these movements, protraction and retraction occur with the help of the clavicle and acromioclavicular joint [15, 16] (Fig. 4.2).

The subacromial space, which is part of the glenohumeral joint, can also be considered another "functional joint." The movements of this joint are essential in shoulder functions [12].

The shoulder complex allows more complicated movements than other parts of the body as different types of joints work together in harmony. This large range of motion is allowed by a balanced interaction between static and dynamic stabilizers.

4.1 Shoulder Stability

Stability is the state that remains unchanged in the presence of forces that would change the current situation [17]. Shoulder stability can be analyzed in two parts: glenohumeral stability and scapulothoracic stability.

4.1.1 Glenohumeral Stability

Glenohumeral stability is that the humeral head remains in the glenoid and maintains its anatomic alignment during and after shoulder movements. Glenohumeral joint instability has been the most studied shoulder problem since the time of Hippocrates [18]. The stabilization of the joint is analyzed in two parts: static stabilization and dynamic stabilization [19].

4.1.1.1 Static Stabilization

Bony Static Stabilizers

Although the continuity between the humeral head and glenoid is low, bony structures are essential in ensuring shoulder stability. During rest, the inferior surface of the humeral head touches only a small area in the inferior part of the glenoid. Only 30% of the humeral articular surface is in contact with the glenoid articular surface at any time [20, 21]. Abduction increases the glenohumeral contact, and the pressure in the joint decreases [22]. When the pressure increases at the glenohumeral contact point, the humeral chondral surface can penetrate the glenoid chondral surface up to 1.2 mm. However, it is still controversial in which movements the pressure increases [23].

The humeral head forms the distal joint surface. The humeral head faces medially, superiorly, and posteriorly with regard to the humeral shaft and the condyles. The humeral head is retroverted on average 19° (range 9–31°) and inclined on average 41° (range 34–47°); head radius measures 23 mm (range 17–28 mm), and medial and posterior head center offsets are on average 7 mm (range 4–12 mm) and 2 mm (range 1–8 mm), respectively [24, 25].

Fig. 4.2 Scapular movements

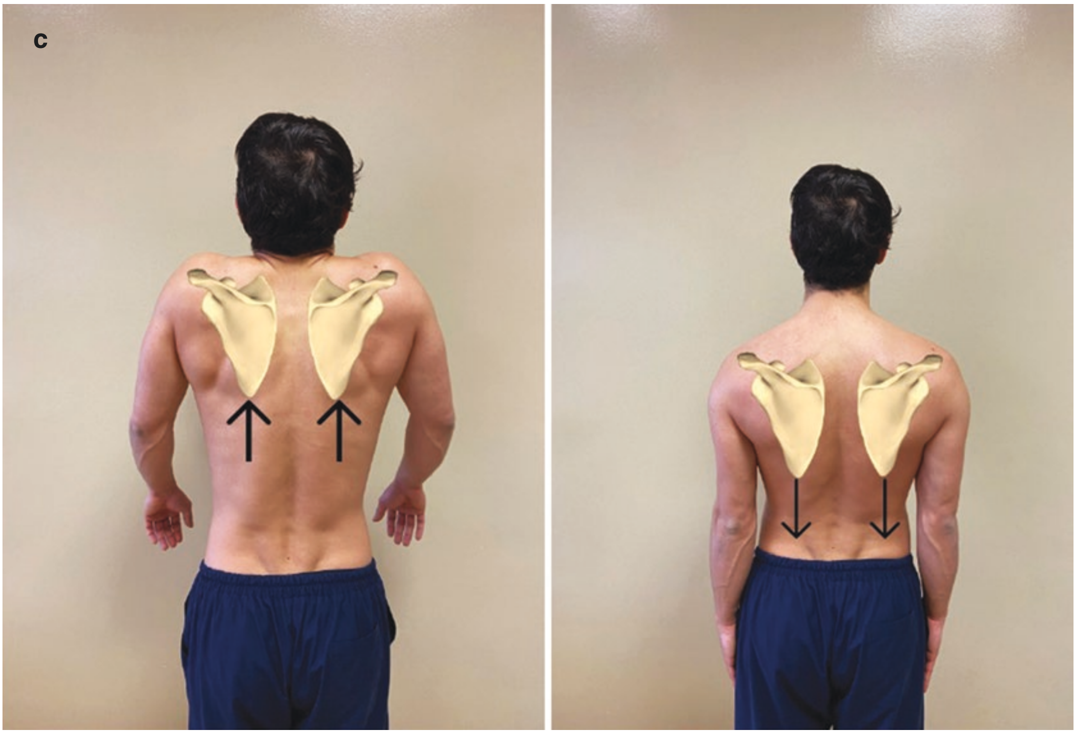

Fig. 4.2 (continued)

Since the scapula is in internal rotation in the resting position, humeral retroversion increases the congruence of the glenohumeral joint by directing the humeral head toward the glenoid. Increased retroversion also increases the amount of external rotation of the humerus while decreasing its internal rotation. This mechanism explains the increased humeral retroversion of the dominant shoulders of the overhead athletes that have forced external rotation of the humerus during pitching [26, 27].

The shape of the glenoid fossa, which forms the proximal part of the joint, is also crucial in glenohumeral stability. The glenoid is a shallow socket that holds the humeral head; its mean depth is 2.5 mm on the anteroposterior direction and 9 mm in the superior-inferior direction. Therefore, different amounts of displacing forces must be applied to dislocate the shoulder in different directions [28, 29]. It is retroverted on average, 1.23° (range 9.5° of anteversion to 10.5° of retroversion), and inclined superiorly, on average 4.2° (range, 7° of inferior inclination to 15.8° of superior inclination) [30]. More than 10° of anteversion and more than 15° of retroversion is related to increased anterior and posterior instability, respectively [31–33]. Friedman and Kessler reported that its bending radius is greater than the humeral head radius in 93% of examined joints; the remainders have the glenoid and humeral head with the same bending radius [34].

Moroder et al. and Peltz et al. showed that the loss in glenoid concavity is related to glenohumeral instability. And patients with traumatic or atraumatic shoulder instability have a flatter glenoid cavity with a higher radius of curvature than healthy controls [35–37]. Weishaupt et al. mentioned that the dysplastic glenoid could also cause shoulder instability due to bone defects in the posterior glenoid rim. They defined three different glenoid forms according to bone defects in the posterior glenoid rim: pointed form (without any deficiency), rounded glenoid deficiency (“lazy J” form), and the triangular bony deficiency (“delta” form) [38, 39].

Bone loss is also an important factor in shoulder instability. It usually occurs traumatically. In most cases, forced abduction and external rotation force cause the humeral head to dislocate anterior-inferiorly [31]. Most important bony lesions that result in instability occur after traumatic events and involve the anterior-inferior glenoid rim (Bony Bankart lesion) and the posterolateral aspect of the humeral head (Hill-Sachs lesion).

Bony Bankart lesions are significant if they involve more than 20% of the length of the glenoid. In this case, if the correct soft tissue repair is not performed, there is a high probability of recurrence. If Bony Bankart involves more than 50% of the glenoid, there will be more than a 30% reduction in shoulder stability [40]. Bony Bankart lesions are classified according to Bigliani et al.: type I, a displaced avulsion fracture with attached capsule; type II, a medially displaced fragment mal-united to the glenoid rim; type III, an erosion of the glenoid rim lower than 25% (III A) and more than 25% (III B) [41]. The PICO method suggested by Baudi et al. could be used to calculate glenoid bone defect [42].

Hill-Sachs lesion occurs after anterior shoulder dislocation due to a compression fracture involving the posterior-lateral part of the humeral head. The effect of the lesion on shoulder stability depends on the size and location. There are different classification methods. Calandra classification, which uses arthroscopy to measure the depth of the lesion, is the most frequently used method [43]. Apart from this, classification can be made according to radiography or magnetic resonance imaging [44, 45].

It is necessary to evaluate bone defects that cause instability in glenoid and humerus together and not to ignore injuries in soft tissue other than bone defects [46]. Glenoid track concept and its association with the concept of “engaging” and “non-engaging” lesions showed that the relationship between the humerus and glenoid lesions determines stability [47, 48].

Posterior shoulder dislocations are much rarer. It usually occurs after direct trauma or seizure. It usually occurs after direct trauma or seizure. In this case, a compression fracture occurs in the anterior superior of the humeral head (Reverse Hill-Sachs Lesion or McLaughlin lesion), and another fracture may occur in the posteroinferior rim of the glenoid (Reverse Bankart Lesion) [49–51].

Soft Tissue Static Stabilizers

Soft tissue static stabilizers include glenoid labrum, glenohumeral capsule, glenohumeral ligaments, rotator interval, negative intracapsular pressure, and adhesion cohesion mechanism.

Glenoid Labrum

The glenoid labrum is a triangular section ring around the glenoid rim, deepening the relatively flat glenoid cavity. The upper part is more mobile than the lower part, which is more tightly attached to the glenoid rim [52]. The superior part joins the structure of the biceps anchor, and the long head of the biceps tendon.

The glenoid labrum increases the depth of the glenoid cavity by 50% and increases its congruity with the humeral head and contributes to the negative pressure required for shoulder stability [28]. It increases the contact surface between the humerus and the glenoid by 2 mm anteroposteriorly and 4.5 mm supero-inferiorly [53].

The negative pressure in the glenohumeral joint is 32 mmHg. This pressure is particularly effective against traction force, while it is less effective against shear forces [54]. The contribution of negative pressure to joint stability is higher in the hanging arm position, while it decreases with shoulder abduction [55]. Loss of intracapsular negative pressure can manifest itself as an anterior translation of the humeral head. The labrum creates an attachment site around the glenoid rim for the glenohumeral ligaments and joint capsule. It also acts as an anti-shear bumper during mid-range movements [21].

When defining lesions in the labrum, it is necessary to analyze anatomical variants such as sublabral foramen, meniscoid labrums, and cord-like middle glenohumeral ligament do not require surgery [56].

The most common glenoid labrum injury is Bankart lesion. It accompanies 90% of traumatic anterior shoulder instability [57]. It is defined as a detachment of the anteroinferior aspect of the labrum and capsule. It occurs due to the detachment of the middle glenohumeral ligament and inferior glenohumeral ligament from the glenoid. Despite its frequency, it cannot be considered as an isolated cause of instability [58].

Green and Christensen classified Bankart lesions in five arthroscopic types: type 1 refers to the entire labrum; type 2 is a simple detachment of labrum with no other significant lesions; type 3 is an intra-parenchymal labrum tear; type 4 and

5 are complex tears with significant or complete degeneration of inferior glenohumeral ligament, respectively [59]. This classification also has a prognostic value: type 4 and 5 lesions have a high chance of recurrent instability after arthroscopic Bankart procedure of 87%.

Another lesion involving the anteroinferior aspect of the labrum is the ALPSA lesion (anterior labroligamentous periosteal sleeve avulsion). The anterior labroligamentous complex rolls up in a sleeve-like fashion and becomes displaced medially and inferiorly on the glenoid neck [60].

The redislocation rate in ALPSA lesions and the probability of engaging the Hill-Sachs lesion are higher than those of Bankart lesions. Besides, the external rotation limitation developed after ALPSA lesion repair is another crucial problem [61].

Specular lesions can be described for the posterior aspect of the labrum. Reverse Bankart lesion involves the posterior labrum and the posterior band of the inferior glenohumeral ligament. POLPSA is the posterior labroligamentous sleeve avulsion. In chronic conditions, Bennett lesions may occur (an extra-articular calcification along the posteroinferior glenoid neck close to the posterior band of the glenohumeral ligament) [62, 63].

Reverse Bankart lesion is frequent in athletes, such as rugby players, with a 20% incidence reported in a study of 142 elite rugby player shoulder arthroscopy [64]. The injury mechanism could be traced to a direct blow to the anterior and lateral aspects of the shoulder, while the arm is adducted; a rare mechanism of injury is a posterior blow to the arm while holding a tackle shield [65].

Concerning superior labrum, a prevalent lesion in throwing overhead athletes is SLAP (superior labrum anterior and posterior) tear. This lesion is described for the first time by Snyder et al. [66]. Snyder classified SLAP tears into four types. Type 2 and type 4 are more likely to create instability as they involve both the labrum and the long head of the biceps.

Moreover, SLAP lesions are common in contact sports. Funk and Snow have reported a 35% incidence of SLAP tears, arthroscopically diagnosed, in 51 rugby players' shoulders [67].

Capsuloligamentous Structures

Capsuloligamentous structures include joint capsule and glenohumeral ligaments (superior, middle, and inferior). There are many cadaveric and clinical studies investigating the biomechanical properties of these structures.

The constitutional trait of laxity facilitates extensive motion in multiple planes and may be essential to athletic performance. On the other hand, capsular stretching is noted along with a Bankart lesion is up to 28% of patients with recurrent anterior instability [68].

Superior and middle glenohumeral ligaments, together with coracohumeral ligament, long head of the biceps, and a thin layer of capsule, help to form rotator interval, and they will be treated in detail later.

The inferior glenohumeral ligament is also called the inferior glenohumeral ligament complex (IGHLC). It comprises three parts: two thicker bands on anterior and posterior and a thinner recess. During the abduction and external rotation, extension IGHLC moves anteriorly, forming a restraint to anterior translation of the humeral head.

During adduction, flexion, and internal rotation, IGHLC moves posteriorly, forming a restraint to posterior translation. IGHLC suffers from initial plastic deformation during the initial dislocation, but the damage becomes more critical after several episodes [69]. The lesion could more frequently occur at the glenoid insertion (anteroinferior glenoid rim) and in the middle part or at the humeral insertion [70].

Capsular stretching is often noted along with a Bankart lesion in up to 28% of patients with recurrent anterior instability [68]. The posterior capsule can also be injured; repetitive subluxations may lead to posterior instability by causing posterior capsular redundancy and increased joint volume.

The Rotator Interval

The rotator interval is a triangular space in the anterosuperior of the shoulder. It was first described by Neer in 1970 [71]. It creates resistance against extreme flexion, extension, adduction, and external rotation movements, limits inferior translation of the humeral head during adduction, and limits posterior translation of the humeral head during flexion or external rotation with abduction [72].

Furthermore, the synovial fluid provides to generate adhesion cohesion mechanism. The force formed between the wet surfaces of the humeral head and the glenoid contributes to stability [4].

4.1.1.2 Dynamic Stabilization

Dynamic stabilization provides a wide range of motion while securing stability during the normal function of the joint. There is a delicate balance between stability in the shoulder and range of motion. The muscles surrounding the shoulder and the neuromuscular balance between them ensure the dynamic stability of the joint. The muscles surrounding the shoulder and the neuromuscular balance between them provide the dynamic stability of the joint.

Proprioception

We know that capsuloligamentous structures also contribute to shoulder stability with their sensorimotor properties in addition to their mechanical functions. There are mechanoreceptors, especially in the anterior-inferior of the glenohumeral joint capsule. Proprioceptive information obtained from these structures contributes to shoulder stability by coordinating motor movements, reflexes, and joint stiffness.

As a result of the injuries in these structures, the decrease in proprioceptive information causes shoulder instability [73, 74]. Besides direct injury, capsular laxity has also been shown to cause a decrease in proprioception, leading to instability [75, 76].

Repairing of the capsuloligamentous structures restores the mechanical functions and tension of these tissues [77]. Retention allows joint capsule and ligamentous structures to sense mechanical stimulation and to facilitate proprioceptive feedback [74, 78].

Rotator Cuff Muscles

The rotator cuff is the common name of the structure consisting of muscles and tendons that contributes to shoulder stability. The rotator cuff consists of four muscles. These are supraspinatus (SSP), infraspinatus (ISP), teres minor (TM), and subscapularis (SSC).

Rotator cuff muscles provide fine control of shoulder movement. They play an essential role in dynamic stability, as well as contribute to proprioception [21].

Rotator cuff muscles compress the humeral head toward the glenoid and make an essential contribution to dynamic stabilization during shoulder movements. While symmetric rotator cuff contraction provides concavity compression, asymmetric contractions during shoulder movements rotate the humeral head. Joint reaction force decreases in rotator cuff tears [29, 79]. This stabilizing effect depends on the force couple formed by coordinated activation of the anterior and posterior fibers of the rotator cuff [80]. They act as an anti-shear force with the help of their mechanoreceptors. During the abduction, the rotator cuff tendon acts as a depressor for the humeral head and balances the pull of the deltoid muscle superiorly. Since this balance is disrupted after rotator cuff tears, the humeral head may be migrated superiorly [81]. A 50% reduction in rotator cuff force increases anterior dislocation by 46% and posterior dislocation by 31% [82].

The SSC is larger than the other three rotator cuff muscles and alone creates as much force as the sum of SSP, ISP, and TM [83]. The attachments of the muscles can be as tendons or muscle bodies [84, 85]. Therefore, the symptoms vary depending on the location and size of the rupture [86].

Long Head of the Biceps

The long head of the biceps (LHB) is a secondary stabilizer with a predominant role in the rotator cuff or capsuloligamentous deficiency. This tendon, originating from the supraglenoid tubercle and passing through the bicipital groove, acts as an anterior stabilizer during external rotation. During the late throwing phase, LHB reduces anterior translation, helping to prevent excessive torsion of the glenohumeral joint with a flexing elbow. These concepts can explain why type II or IV SLAP lesions are widespread in throwing athletes. Also, patients with rotator cuff insufficiency have hypertrophy in the tendon due to increased tension [87].

4.1.2 Scapulothoracic Joint Stability

The contribution of the scapula to upper extremity movements is better understood, especially in the last two decades [88]. The scapula provides a base to support the glenohumeral joint for regular upper limb movements [89, 90]. Since the scapulothoracic joint is not a real joint, its stability is provided only by dynamic stabilizers. The agonist, antagonist, and synergist contraction of the muscles adhering to both the thorax and the scapula ensures scapulothoracic joint stability. Scapular muscles dynamically coordinate the position of the glenoid, helping to create an effective glenohumeral joint movement. This harmonious relationship between the scapula and the humerus is called "scapulohumeral rhythm" [90, 91].

Upper and lower trapezius muscles, the serratus anterior and rhomboids (major and minor) are the structures that contribute most to scapulothoracic stability [15, 92].

Trapezius, together with the serratus anterior, initiates the upward rotation and posterior tilt movement of the scapula. Lower fibers of the trapezius contribute to the stability of the scapulothoracic joint during the descending of the arm from maximum elevation [15].

The serratus anterior muscle pulls the scapula toward the thoracic wall and makes a protraction movement. It provides stability, especially during abduction and pushing or punching type activities [91].

The rhomboids (major and minor) are especially active during adduction and retraction. They control the medial border of the scapula. It is quite active during swimming strokes and pulling [88]. It also takes part in the overhead throwing, both by reducing the stress on the anterior structures by fully retracting the scapula and braking by contracting eccentrically during the follow-through phase of pitching [93, 94].

Most abnormal biomechanics and overuse injuries in the shoulder girdle can be attributed to scapulothoracic joint instability [95, 96]. Alterations in joint movements due to weakness in scapular stabilizing muscles are called scapular dyskinesis [15, 97].

4.2 The Thrower's Shoulder

Throwing consists of six stages: the windup, early cocking, late cocking, acceleration, deceleration, and follow-through. During throwing, large muscle groups work together [98]. The transition between late cocking and acceleration is critical, and most of the injuries occur in this segment. During the late cocking, the shoulder is in abduction, and external rotation, the anterior capsule, and the coracohumeral ligament are under tension. Repetitive stress may cause stains or tensile failure in these structures, causing anterior shoulder instability [99, 100]. When the shoulder is in the 90°–90° position, the posterosuperior rotator cuff can be trapped between the greater tuberosity and the glenoid labrum, causing internal impingement. Shear forces also act on the posterosuperior labrum and biceps anchor in this position [101, 102]. In late cocking, structures in the posterior contract, when leading from late cocking to acceleration, the opposite happens. The anterior structures contract rapidly, allowing energy to be transferred to the ball. In acceleration, mainly the pectoralis major, latissimus dorsi, triceps, and serratus anterior muscles contract. The rotator cuff contracts during deceleration. During follow-through, the posterior capsule and the posterior rotator cuff are under eccentric stress. In repetitive stress, posterior rotator cuff failure, thickening in the capsule, and decrease in compliance may occur [103, 104].

References

1. Rockwood CA, Matsen FA, Wirth MA, Lippitt SB, Fehringer EV, Sperling JW. Rockwood and Matsen's the shoulder. Philadelphia, PA: Elsevier; 2017.
2. Arias-Martorell J. The morphology and evolutionary history of the glenohumeral joint of hominoids: a review. Ecol Evol. 2018;9:703–22. https://doi.org/10.1002/ece3.4392.

3. Veeger HEJ, van der Helm FCT. Shoulder function: the perfect compromise between mobility and stability. J Biomech. 2007;40:2119–29. https://doi.org/10.1016/j.jbiomech.2006.10.016.
4. Terry GC, Chopp TM. Functional anatomy of the shoulder. J Athl Train. 2000;35:248–55.
5. Karduna AR, Williams GR, Williams JL, Iannotti JP. Kinematics of the glenohumeral joint: influences of muscle forces, ligamentous constraints, and articular geometry. J Orthop Res Off Publ Orthop Res Soc. 1996;14:986–93. https://doi.org/10.1002/jor.1100140620.
6. Dempster WT. Mechanisms of shoulder movement. Arch Phys Med Rehabil. 1965;46:49–70.
7. Spencer EE, Kuhn JE, Huston LJ, Carpenter JE, Hughes RE. Ligamentous restraints to anterior and posterior translation of the sternoclavicular joint. J Shoulder Elb Surg. 2002;11:43–7. https://doi.org/10.1067/mse.2002.119394.
8. Ludewig PM, Phadke V, Braman JP, Hassett DR, Cieminski CJ, LaPrade RF. Motion of the shoulder complex during multiplanar humeral elevation. J Bone Joint Surg Am. 2009;91:378–89. https://doi.org/10.2106/JBJS.G.01483.
9. Fung M, Kato S, Barrance PJ, Elias JJ, McFarland EG, Nobuhara K, et al. Scapular and clavicular kinematics during humeral elevation: a study with cadavers. J Shoulder Elb Surg. 2001;10:278–85. https://doi.org/10.1067/mse.2001.114496.
10. Saccomanno MF, Ieso DE, C, Milano G. Acromioclavicular joint instability: anatomy, biomechanics and evaluation. Joints. 2014;2:87–92. https://doi.org/10.11138/jts/2014.2.2.087.
11. Teece RM, Lunden JB, Lloyd AS, Kaiser AP, Cieminski CJ, Ludewig PM. Three-dimensional acromioclavicular joint motions during elevation of the arm. J Orthop Sports Phys Ther. 2008;38:181–90. https://doi.org/10.2519/jospt.2008.2386.
12. Levangie PK, Norkin CC. Joint structure and function: a comprehensive analysis. Philadelphia: F.A. Davis Company; 2011.
13. Peat M. Functional anatomy of the shoulder complex. Phys Ther. 1986;66:1855–65. https://doi.org/10.1093/ptj/66.12.1855.
14. Bigliani LU, Codd TP, Connor PM, Levine WN, Littlefield MA, Hershon SJ. Shoulder motion and laxity in the professional baseball player. Am J Sports Med. 1997;25:609–13. https://doi.org/10.1177/036354659702500504.
15. Roche SJ, Funk L, Sciascia A, Ben KW. Scapular dyskinesis: the surgeon's perspective. Shoulder Elb. 2015;7:289–97. https://doi.org/10.1177/1758573215595949.
16. Ben KW, Sciascia A. Current concepts: scapular dyskinesis. Br J Sports Med. 2010;44:300–5. https://doi.org/10.1136/bjsm.2009.058834.
17. Myers JB, Wassinger CA, Lephart SM. Sensorimotor contribution to shoulder stability: effect of injury and rehabilitation. Man Ther. 2006;11:197–201. https://doi.org/10.1016/j.math.2006.04.002.
18. Wang VM, Flatow EL. Pathomechanics of acquired shoulder instability: a basic science perspective. J Shoulder Elb Surg. 2005;14:2S–11S. https://doi.org/10.1016/j.jse.2004.10.002.
19. Abboud JA, Soslowsky LJ. Interplay of the static and dynamic restraints in glenohumeral instability. Clin Orthop Relat Res. 2002:48–57. https://doi.org/10.1097/00003086-200207000-00007.
20. Soslowsky LJ, Flatow EL, Bigliani LU, Mow VC. Articular geometry of the glenohumeral joint. Clin Orthop Relat Res. 1992;285:181–90.
21. Lugo R, Kung P, Ma CB. Shoulder biomechanics. Eur J Radiol. 2008;68:16–24. https://doi.org/10.1016/j.ejrad.2008.02.051.
22. Warner JJ, Bowen MK, Deng XH, Hannafin JA, Arnoczky SP, Warren RF. Articular contact patterns of the normal glenohumeral joint. J Shoulder Elb Surg. 1998;7:381–8. https://doi.org/10.1016/s1058-2746(98)90027-1.
23. Massimini DF, Warner JJP, Li G. Glenohumeral joint cartilage contact in the healthy adult during scapular plane elevation depression with external humeral rotation. J Biomech. 2014;47:3100–6. https://doi.org/10.1016/j.jbiomech.2014.06.034.
24. Poppen NK, Walker PS. Normal and abnormal motion of the shoulder. J Bone Joint Surg Am. 1976;58:195–201.
25. Robertson DD, Yuan J, Bigliani LU, Flatow EL, Yamaguchi K. Three-dimensional analysis of the proximal part of the humerus: relevance to arthroplasty. J Bone Joint Surg Am. 2000;82:1594–602.https://doi.org/10.2106/00004623-200011000-00013.
26. Kronberg M, Broström LA, Söderlund V. Retroversion of the humeral head in the normal shoulder and its relationship to the normal range of motion. Clin Orthop Relat Res. 1990:113–7.
27. Reagan KM, Meister K, Horodyski MB, Werner DW, Carruthers C, Wilk K. Humeral retroversion and its relationship to glenohumeral rotation in the shoulder of college baseball players. Am J Sports Med. 2002;30:354–60. https://doi.org/10.1177/03635465020300030901.
28. Howell SM, Galinat BJ. The glenoid-labral socket. A constrained articular surface. Clin Orthop Relat Res. 1989;243:122–5.
29. Lippitt SB, Vanderhooft JE, Harris SL, Sidles JA, Harryman DT 2nd, Matsen FA 3rd. Glenohumeral stability from concavity-compression: a quantitative analysis. J Shoulder Elb Surg. 1993;2:27–35. https://doi.org/10.1016/S1058-2746(09)80134-1.
30. Churchill RS, Brems JJ, Kotschi H. Glenoid size, inclination, and version: an anatomic study. J Shoulder Elb Surg. 2001;10:327–32. https://doi.org/10.1067/mse.2001.115269.
31. Di Giacomo G, Piscitelli L, Pugliese M. The role of bone in glenohumeral stability. EFORT Open Rev. 2018;3:632–40. https://doi.org/10.1302/2058-5241.3.180028.

32. Bradley JP, Forsythe B, Mascarenhas R. Arthroscopic management of posterior shoulder instability: diagnosis, indications, and technique. Clin Sports Med. 2008;27:649–70. https://doi.org/10.1016/j.csm.2008.06.001.
33. Brewer BJ, Wubben RC, Carrera GF. Excessive retroversion of the glenoid cavity. A cause of non-traumatic posterior instability of the shoulder. J Bone Joint Surg Am. 1986;68:724–31.
34. Friedman R, An Y, Chokeski R, Kessler L. Anatomic and biomechanical study of glenohumeral contact. J Shoulder Elb Surg. 1994;3:S35.
35. Moroder P, Ernstbrunner L, Pomwenger W, Oberhauser F, Hitzl W, Tauber M, et al. Anterior Shoulder instability is associated with an underlying deficiency of the bony glenoid concavity. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc North Am Int Arthrosc Assoc. 2015;31:1223–31. https://doi.org/10.1016/j.arthro.2015.02.009.
36. Moroder P, Haniel F, Quirchmayr M, Schulz E, Eppel M, Matis N, et al. Effect of glenoid concavity loss on shoulder stability- a case report in a professional wrestler. BMC Musculoskelet Disord. 2016;17:357. https://doi.org/10.1186/s12891-016-1210-9.
37. Peltz CD, Zauel R, Ramo N, Mehran N, Moutzouros V, Bey MJ. Differences in glenohumeral joint morphology between patients with anterior shoulder instability and healthy, uninjured volunteers. J Shoulder Elb Surg. 2015;24:1014–20. https://doi.org/10.1016/j.jse.2015.03.024.
38. Weishaupt D, Zanetti M, Nyffeler RW, Gerber C, Hodler J. Posterior glenoid rim deficiency in recurrent (atraumatic) posterior shoulder instability. Skelet Radiol. 2000;29:204–10. https://doi.org/10.1007/s002560050594.
39. Inui H, Sugamoto K, Miyamoto T, Yoshikawa H, Machida A, Hashimoto J, et al. Glenoid shape in atraumatic posterior instability of the shoulder. Clin Orthop Relat Res. 2002:87–92. https://doi.org/10.1097/00003086-200210000-00014.
40. Piasecki DP, Verma NN, Romeo AA, Levine WN, Bach BRJ, Provencher MT. Glenoid bone deficiency in recurrent anterior shoulder instability: diagnosis and management. J Am Acad Orthop Surg. 2009;17:482–93. https://doi.org/10.5435/00124635-200908000-00002.
41. Bigliani LU, Newton PM, Steinmann SP, Connor PM, Mcllveen SJ. Glenoid rim lesions associated with recurrent anterior dislocation of the shoulder. Am J Sports Med. 1998;26:41–5. https://doi.org/10.1177/03635465980260012301.
42. Baudi P, Righi P, Bolognesi D, Rivetta S, Rossi Urtoler E, Guicciardi N, et al. How to identify and calculate glenoid bone deficit. Chir Organi Mov. 2005;90:145–52.
43. Shibayama K, Iwaso H. Hill-Sachs lesion classification under arthroscopic findings. J Shoulder Elb Surg. 2017;26:888–94. https://doi.org/10.1016/j.jse.2016.10.017.
44. Rowe CR, Zarins B, Ciullo JV. Recurrent anterior dislocation of the shoulder after surgical repair. Apparent causes of failure and treatment. J Bone Joint Surg Am. 1984;66:159–68.
45. Richards RD, Sartoris DJ, Pathria MN, Resnick D. Hill-Sachs lesion and normal humeral groove: MR imaging features allowing their differentiation. Radiology. 1994;190:665–8. https://doi.org/10.1148/radiology.190.3.8115607.
46. Di Giacomo G, Itoi E, Burkhart SS. Evolving concept of bipolar bone loss and the hill-Sachs lesion: from “engaging/non-engaging” lesion to “on-track/off-track” lesion. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc North Am Int Arthrosc Assoc. 2014;30:90–8. https://doi.org/10.1016/j.arthro.2013.10.004.
47. Burkhart SS, De Beer JF. Traumatic glenohumeral bone defects and their relationship to failure of arthroscopic Bankart repairs: significance of the inverted-pear glenoid and the humeral engaging hill-Sachs lesion. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc North Am Int Arthrosc Assoc. 2000;16:677–94. https://doi.org/10.1053/jars.2000.17715.
48. Shaha JS, Cook JB, Rowles DJ, Bottoni CR, Shaha SH, Tokish JM. Clinical validation of the glenoid track concept in anterior Glenohumeral instability. J Bone Joint Surg Am. 2016;98:1918–23. https://doi.org/10.2106/JBJS.15.01099.
49. Fronek J, Warren RF, Bowen M. Posterior subluxation of the glenohumeral joint. J Bone Joint Surg Am. 1989;71:205–16.
50. McLaughlin HL. Posterior dislocation of the shoulder. J Bone Joint Surg Am. 1952;24 A:584–90.
51. Goudie EB, Murray IR, Robinson CM. Instability of the shoulder following seizures. J Bone Joint Surg Br. 2012;94:721–8. https://doi.org/10.1302/0301-620X.94B6.28259.
52. Cooper DE, Arnoczky SP, O’Brien SJ, Warren RF, DiCarlo E, Allen AA. Anatomy, histology, and vascularity of the glenoid labrum. An anatomical study. J Bone Joint Surg Am. 1992;74:46–52.
53. Clavert P. Glenoid labrum pathology. Orthop Traumatol Surg Res. 2015;101:S19–24. https://doi.org/10.1016/j.otsr.2014.06.028.
54. Warner JJ, McMahon PJ. The role of the long head of the biceps brachii in superior stability of the glenohumeral joint. J Bone Joint Surg Am. 1995;77:366–72. https://doi.org/10.2106/00004623-199503000-00006.
55. Halder AM, Kuhl SG, Zobitz ME, Larson D, An KN. Effects of the glenoid labrum and glenohumeral abduction on stability of the shoulder joint through concavity-compression : an in vitro study. J Bone Joint Surg Am. 2001;83:1062–9. https://doi.org/10.2106/00004623-200107000-00013.
56. Rao AG, Kim TK, Chronopoulos E, McFarland EG. Anatomical variants in the anterosuperior aspect of the glenoid labrum: a statistical analysis of seventy-three cases. J Bone

Joint Surg Am. 2003;85:653–9. https://doi.org/10.2106/00004623-200304000-00011.

57. Owens BD, Nelson BJ, Duffey ML, Mountcastle SB, Taylor DC, Cameron KL, et al. Pathoanatomy of first-time, traumatic, anterior glenohumeral subluxation events. J Bone Joint Surg Am. 2010;92:1605–11. https://doi.org/10.2106/JBJS.I.00851.
58. Brand RA. Recurrent dislocation of the shoulder joint. Clin Orthop Relat Res. 2008;466:520–1. https://doi.org/10.1007/s11999-007-0105-3.
59. Green MR, Christensen KP. Arthroscopic Bankart procedure: two- to five-year followup with clinical correlation to severity of glenoid labral lesion. Am J Sports Med. 1995;23:276–81. https://doi.org/10.1177/036354659502300304.
60. Neviaser TJ. The anterior labroligamentous periosteal sleeve avulsion lesion: a cause of anterior instability of the shoulder. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc North Am Int Arthrosc Assoc. 1993;9:17–21. https://doi.org/10.1016/s0749-8063(05)80338-x.
61. Lee BG, Cho NS, Rhee YG. Anterior labroligamentous periosteal sleeve avulsion lesion in arthroscopic capsulolabral repair for anterior shoulder instability. Knee Surg Sports Traumatol Arthrosc. 2011;19:1563–9. https://doi.org/10.1007/s00167-011-1531-z.
62. Ciccone WJ 2nd. Arthroscopic posterior labral repair and capsular shift with a lateralized posterior portal. Arthrosc Tech. 2013;2:e323–6. https://doi.org/10.1016/j.eats.2013.05.005.
63. Van Tongel A, Karelse A, Berghs B, Verdonk R, De Wilde L. Posterior shoulder instability: current concepts review. Knee Surg Sports Traumatol Arthrosc. 2011;19:1547–53. https://doi.org/10.1007/s00167-010-1293-z.
64. Badge R, Tambe A, Funk L. Arthroscopic isolated posterior labral repair in rugby players. Int J Shoulder Surg. 2009;3:4–7. https://doi.org/10.4103/0973-6042.50875.
65. McDonough A, Funk L. Critical reflection of the advanced rehabilitation of an elite rugby league player sustaining a posterior Bankart lesion. Phys Ther Sport Off J Assoc Chart Physiother Sport Med. 2013;14:60–7. https://doi.org/10.1016/j.ptsp.2012.01.002.
66. Snyder SJ, Karzel RP, Del Pizzo W, Ferkel RD, Friedman MJ. SLAP lesions of the shoulder. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc North Am Int Arthrosc Assoc. 1990;6:274–9. https://doi.org/10.1016/0749-8063(90)90056-j.
67. Funk L, Snow M. SLAP tears of the glenoid labrum in contact athletes. Clin J Sport Med Off J Can Acad Sport Med. 2007;17:1–4. https://doi.org/10.1097/JSM.0b013e31802ede87.
68. Rowe CR, Patel D, Southmayd WW. The Bankart procedure: a long-term end-result study. J Bone Joint Surg Am. 1978;60:1–16.
69. Robinson CM, Dobson RJ. Anterior instability of the shoulder after trauma. J Bone Joint Surg Br. 2004;86:469–79. https://doi.org/10.1302/0301-620x.86b4.
70. Bigliani LU, Pollock RG, Soslowsky LJ, Flatow EL, Pawluk RJ, Mow VC. Tensile properties of the inferior glenohumeral ligament. J Orthop Res Off Publ Orthop Res Soc. 1992;10:187–97. https://doi.org/10.1002/jor.1100100205.
71. Neer CS 2nd. Displaced proximal humeral fractures. I. Classification and evaluation. J Bone Joint Surg Am. 1970;52:1077–89.
72. Frank RM, Taylor D, Verma NN, Romeo AA, Mologne TS, Provencher MT. The rotator interval of the Shoulder: implications in the treatment of Shoulder instability. Orthop J Sport Med. 2015;3:2325967115621494. https://doi.org/10.1177/2325967115621494.
73. Riemann BL, Lephart SM. The sensorimotor system, part I: the physiologic basis of functional joint stability. J Athl Train. 2002;37:71–9.
74. Tibone JE, Fechter J, Kao JT. Evaluation of a proprioception pathway in patients with stable and unstable shoulders with somatosensory cortical evoked potentials. J Shoulder Elb Surg. 1997;6:440–3. https://doi.org/10.1016/s1058-2746(97)70050-8.
75. Allegrucci M, Whitney SL, Lephart SM, Irrgang JJ, Fu FH. Shoulder kinesthesia in healthy unilateral athletes participating in upper extremity sports. J Orthop Sports Phys Ther. 1995;21:220–6. https://doi.org/10.2519/jospt.1995.21.4.220.
76. Blasier RB, Carpenter JE, Huston LJ. Shoulder proprioception. Effect of joint laxity, joint position, and direction of motion. Orthop Rev. 1994;23:45–50.
77. Rokito AS, Birdzell MG, Cuomo F, Di Paola MJ, Zuckerman JD. Recovery of shoulder strength and proprioception after open surgery for recurrent anterior instability: a comparison of two surgical techniques. J Shoulder Elb Surg. 2010;19:564–9. https://doi.org/10.1016/j.jse.2009.09.010.
78. Lephart SM, Warner JJ, Borsa PA, Fu FH. Proprioception of the shoulder joint in healthy, unstable, and surgically repaired shoulders. J Shoulder Elb Surg. 1994;3:371–80. https://doi.org/10.1016/S1058-2746(09)80022-0.
79. Parsons IM, Apreleva M, Fu FH, Woo SLY. The effect of rotator cuff tears on reaction forces at the glenohumeral joint. J Orthop Res Off Publ Orthop Res Soc. 2002;20:439–46. https://doi.org/10.1016/S0736-0266(01)00137-1.
80. Thompson WO, Debski RE, Boardman ND 3rd, Taskiran E, Warner JJ, Fu FH, et al. A biomechanical analysis of rotator cuff deficiency in a cadaveric model. Am J Sports Med. 1996;24:286–92. https://doi.org/10.1177/036354659602400307.
81. Mura N, O'Driscoll SW, Zobitz ME, Heers G, Jenkyn TR, Chou S-M, et al. The effect of infraspinatus disruption on glenohumeral torque and superior migration of the humeral head: a biomechanical study. J Shoulder Elb Surg. 2003;12:179–84. https://doi.org/10.1067/mse.2003.9.

82. Wuelker N, Korell M, Thren K. Dynamic glenohumeral joint stability. J Shoulder Elb Surg. 1998;7:43–52. https://doi.org/10.1016/s1058-2746(98)90182-3.
83. Keating JF, Waterworth P, Shaw-Dunn J, Crossan J. The relative strengths of the rotator cuff muscles. A cadaver study. J Bone Joint Surg Br. 1993;75:137–40.
84. Cleeman E, Brunelli M, Gothelf T, Hayes P, Flatow EL. Releases of subscapularis contracture: an anatomic and clinical study. J Shoulder Elb Surg. 2003;12:231–6. https://doi.org/10.1016/s1058-2746(02)00035-6.
85. Collin P, Lädermann A, Le Bourg M, Walch G. Subscapularis minor--an analogue of the Teres minor? Orthop Traumatol Surg Res. 2013;99:S255–8. https://doi.org/10.1016/j.otsr.2013.03.003.
86. Collin P, Matsumura N, Lädermann A, Denard PJ, Walch G. Relationship between massive chronic rotator cuff tear pattern and loss of active shoulder range of motion. J Shoulder Elb Surg. 2014;23:1195–202. https://doi.org/10.1016/j.jse.2013.11.019.
87. Pagnani MJ, Deng XH, Warren RF, Torzilli PA, O'Brien SJ. Role of the long head of the biceps brachii in glenohumeral stability: a biomechanical study in cadavera. J Shoulder Elb Surg. 1996;5:255–62. https://doi.org/10.1016/s1058-2746(96)80051-6.
88. Paine R, Voight ML. The role of the scapula. Int J Sports Phys Ther. 2013;8:617–29.
89. Voight ML, Thomson BC. The role of the scapula in the rehabilitation of shoulder injuries. J Athl Train. 2000;35:364–72.
90. Ben KW, Ludewig PM, McClure PW, Michener LA, Bak K, Sciascia AD. Clinical implications of scapular dyskinesis in shoulder injury: the 2013 Consensus statement from the "scapular summit". Br J Sports Med. 2013;47:877–85. https://doi.org/10.1136/bjsports-2013-092425.
91. McClure PW, Michener LA, Sennett BJ, Karduna AR. Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo. J Shoulder Elb Surg. 2001;10:269–77. https://doi.org/10.1067/mse.2001.112954.
92. Smith J, Dietrich CT, Kotajarvi BR, Kaufman KR. The effect of scapular protraction on isometric shoulder rotation strength in normal subjects. J Shoulder Elb Surg. 2006;15:339–43. https://doi.org/10.1016/j.jse.2005.08.023.
93. Digiovine NM, Jobe FW, Pink M, Perry J. An electromyographic analysis of the upper extremity in pitching. J Shoulder Elb Surg. 1992;1:15–25. https://doi.org/10.1016/S1058-2746(09)80011-6.
94. Provencher CMT, Makani A, McNeil JW, Pomerantz ML, Golijanin P, Gross D. The role of the scapula in throwing disorders. Sports Med Arthrosc. 2014;22:80–7. https://doi.org/10.1097/JSA.0000000000000023.
95. Moseley JBJ, Jobe FW, Pink M, Perry J, Tibone J. EMG analysis of the scapular muscles during a shoulder rehabilitation program. Am J Sports Med. 1992;20:128–34. https://doi.org/10.1177/036354659202000206.
96. Kuhn JE, Plancher KD, Hawkins RJ. Scapular winging. J Am Acad Orthop Surg. 1995;3:319–25. https://doi.org/10.5435/00124635-199511000-00002.
97. Burn MB, McCulloch PC, Lintner DM, Liberman SR, Harris JD. Prevalence of scapular dyskinesis in overhead and nonoverhead athletes: a systematic review. Orthop J Sport Med. 2016;4:2325967115627608. https://doi.org/10.1177/2325967115627608.
98. Ben KW, Wilkes T, Sciascia A. Mechanics and pathomechanics in the overhead athlete. Clin Sports Med. 2013;32:637–51. https://doi.org/10.1016/j.csm.2013.07.003.
99. Kuhn JE, Bey MJ, Huston LJ, Blasier RB, Soslowsky LJ. Ligamentous restraints to external rotation of the humerus in the late-cocking phase of throwing. A cadaveric biomechanical investigation. Am J Sports Med. 2000;28:200–5. https://doi.org/10.1177/03635465000280021001.
100. Mihata T, McGarry MH, Neo M, Ohue M, Lee TQ. Effect of anterior capsular laxity on horizontal abduction and forceful internal impingement in a cadaveric model of the throwing Shoulder. Am J Sports Med. 2015;43:1758–63. https://doi.org/10.1177/0363546515582025.
101. Gelber JD, Soloff L, Schickendantz MS. The Thrower's shoulder. J Am Acad Orthop Surg. 2018; https://doi.org/10.5435/JAAOS-D-15-00585.
102. Burkhart SS, Morgan CD, Ben KW. The disabled throwing shoulder: spectrum of pathology Part I: pathoanatomy and biomechanics. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc North Am Int Arthrosc Assoc. 2003;19:404–20. https://doi.org/10.1053/jars.2003.50128.
103. Werner SL, Gill TJ, Murray TA, Cook TD, Hawkins RJ. Relationships between throwing mechanics and shoulder distraction in professional baseball pitchers. Am J Sports Med. 2001;29:354–8. https://doi.org/10.1177/03635465010290031701.
104. Thomas SJ, Swanik CB, Higginson JS, Kaminski TW, Swanik KA, Bartolozzi AR, et al. A bilateral comparison of posterior capsule thickness and its correlation with glenohumeral range of motion and scapular upward rotation in collegiate baseball players. J Shoulder Elb Surg. 2011;20:708–16. https://doi.org/10.1016/j.jse.2010.08.031.