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A comprehensive, integrated study of the clavicle: Its topographical anatomy, biomechanical architecture and function; pathological anatomy of mid-shaft fractures and the decision-making process for a surgical approach when planning an intramedullary implant:

Part 6 Scapular Dyskinesis and Acromiohumeral Impingement resulting from Frustum formation

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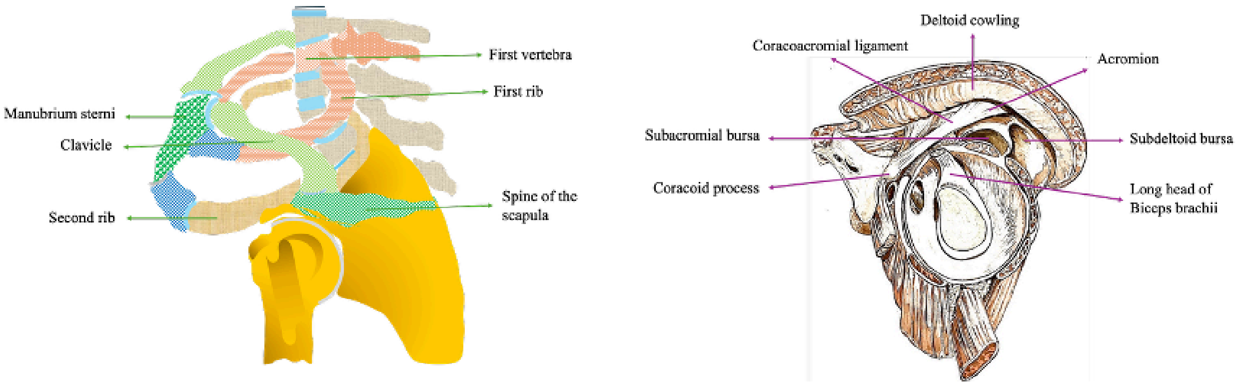
Highlights: Persistent shoulder ptosis due to malunion of the clavicle leads to “winging” and “scapular dyskinesis.” The resulting adverse involuntary kinematics of the scapula, with or without pain, influence the kinematics of the glenohumeral joint. The mechanical aetiology of scapular winging and dyskinesis requires a mechanical solution.

In an unattended clavicle fracture malunion, the eccentricity of the acromiohumeral synsarcosis hastens impingement injury to the rotator cuff and the long tendon of the Biceps brachii. The inflamed subacromial bursa becomes the source of pain. Prevent malunion of clavicle fractures, so that the subacromial space remains concentric in both protracted and retracted positions of the scapula throughout elevation of the arm.

Graphic abstract:



Keywords: Clavicle fracture, Clavicle malunion, Scapular winging, Scapular dyskinesis, Subacromial impingement, Rotator cuff, Cuff tear, Biceps brachii tendinosis, Subacromial bursitis

1.0 Cleidoscapular relationship:

The clavicle is the steering rod of the shoulder complex, and the scapula is the intermediary linkage, allowing normal motion at the glenohumeral articulation. It is a beam spanning the thoracic aperture, between the manubrium sterni and the acromion, without a column supporting it. It hangs from the craniocleidal musculature– the Occipitocleidal trapezius and the Sternocleidomastoid muscles —acting like a derrick, from which the scapula hangs. In turn, the scapula suspends the load of the upper extremity. The line of the ground reaction forces transmitted to the distal end of the upper extremity via the vertebral column to the clavicle and the scapula across the locomotor system is called the kinetic chain. All planar movements of the clavicle and the scapula are initiated at the hand in the form of a task through the central nervous system, with the participation of multiple links and joints of the upper extremity. However, the clavicle’s best performance provides precision at the glenohumeral articulation to complete the task successfully.

The clavicle is a conjunctive linkage within the pectoral girdle mechanism; it cannot be moved voluntarily, independent of the other links connected with it. The scapulae, on either side of the vertebral column helps generate powerful abduction-rotation at the glenohumeral articulation. During arm elevation or swinging, with or without weight in the hand, the clavicle becomes a dynamic cantilever rooted at the sterno-costoclavicular joint.

The scapula is a well-designed anatomical link to translate cogently and congruently as a slider on the ellipsoid proximal half of the rib cage. The filler muscle layers and the areolar tissue between them contain a thin film of lubricating tissue fluid, forming a synsarcosis. It is well-adapted to perform concentric translation in all planes, without leaving the thoracic surface, except for anterior to posterior tilting in the sagittal plane and swivelling around a vertical axis.

Just preceding the “setting phase”, the scapula and the clavicle receive kinematic input from the humeral head. Musculoskeletal sensory receptors and proprioceptors provide a sense of belonging and cohesion among the three linkages at their articulations. The scapula swivels, rotating the glenoid fossa posteriorly by 10 degrees, bringing it underneath the humeral head, and positioning the acromion over the humeral head, thereby maintaining congruence of the acromioclavicular synsarcosis(Kapandji, 2007). Adjusting plane of the acromion provides concentric motion without collision against the greater tuberosity of the humeral head. At an incremental velocity, the clavicle takes over control to steer the scapula, producing a combined three-planar amplifying motion at the sternoclavicular joint. The motion at the acromioclavicular joint, differentiating between low- and high-speed demands at the glenohumeral articulation, toggles in three planes and adjusts the scapula. With its limited range of motion, the acromioclavicular joint refines scapular motion to maintain continued glenohumeral congruence.

Ultimately, the clavicle articulates with the central axial mast, the vertebral column, through the manubrium sterni, the first costal cartilage and the rib solely at the first thoracic vertebra. The costal cartilage of the first rib forms a fibrous joint (*synarthrosis*) with the manubrium sterni and continues at the costochondral junction with the bony rib(Collin & Cox, 2016). No movement occurs at the synarthroses or the costochondral junctions, providing a stable bilateral foundation to the pectoral girdle.

The first thoracic vertebra resembles a cervical vertebral body in structure and possesses long, thick spinous process, frequently as prominent as that of the seventh cervical vertebra(Baron & Tunstall, 2016). It has a round superior facet for articulation with the whole facet on the head of the first rib. The head of the first rib articulates with the body and transverse process of the first thoracic vertebra, forming simple synovial joints. There are limited gliding movements at the costovertebral joints.

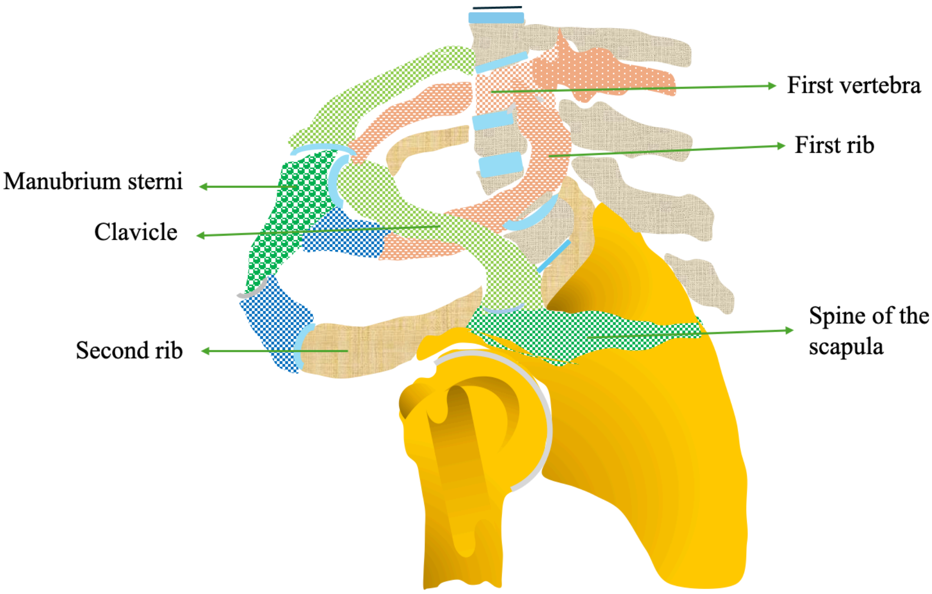


Figure 1. Inner and outer circles of the pectoral girdle. The outer consists of the manubrium sterni, clavicles, and the scapulae with their musculature attached to the cranium and spinous processes; the inner made up of the manubrium, first ribs and the first thoracic vertebra. The manubrium is the key bone joining the two (created in PowerPoint by the author).

Thus, the manubrium sterni indirectly attaches the clavicle to the first thoracic vertebra through the first rib, forming inferior and superior circles of the pectoral girdle mechanism between the appendicular and the axial skeleton, thereby providing additional mobility and stability to the pectoral girdle (**Fig. 1**).

Apparently, this evolutionary arrangement is part of the postcranial descent of the pectoral girdle. The first rib costovertebral articulation participates in the function of the pectoral girdle at the zenith of forward flexion, with the rostral and caudal motion of the sternum. During high reaches of arm abduction, there is contralateral lateral flexion and lordotic unfolding of the thoracic spine, with movement of the first rib similar to the bucket handle, accompanying the sternum.

The clavicle is the master link at the foundation of the upper extremity. Anatomical and biomechanical disturbances of the clavicle will alter the orientation of the scapula and scapulothoracic congruence, thereby, affecting the transmission of regular forces to the scapula, undermining the mechanical performance of the scapulothoracic synsarcosis and glenohumeral kinematics. The scapulothoracic joint, devoid of the capsular and ligamentous constraints, masks biomechanical dysfunction of the clavicle and the upper extremity. At low loads and elevation speeds, despite significant deformation of the clavicle and a frustum formation, the scapula acts as an excellent buffer, against gross glenohumeral kinematic disturbances.

In evidence-based medicine, the minimal kinematic dysfunction at the glenohumeral articulation is often reported as "statistically insignificant." Several outliers with lower-than-average scores are often ignored. They become clinically irrelevant to a learner of evidence-based medicine in clinical practice, and the outcome of the clavicle malunion becomes a long-term patient-based problem. Hence, the appeal lies not in evidence-based statistics but in the plea to address the state of an individual's malunited clavicle before the onset of associated delayed mechanical and neurovascular complications. The scapula and the soft tissues compensate relatively well following healing of minimal to moderate clavicle fracture displacements. A mechanically significant three-dimensional malunion results in acromiohumeral impingement and functionally relevant scapular winging and dyskinesis.

2.0 Scapular dyskinesis:

The dyskinesis (*Gk. Dys means bad, impairment, abnormal, ill, unfavourable, or painful. Gk. Kinesis (noun) means involuntary reaction or movement resulting from an external stimulus; non-directional movement in response to a stimulus*(Avis et al., 1983). The rate of response *(movement)* depends on the strength of the stimulus. Here, the stimulus refers to malunion or malposition that leads to malfunction.

Malunion of the clavicle alters the anatomical relationship between the scapula and the thoracic wall, resulting in mechanical "scapular winging." The resulting kinematic disturbance is "scapular dyskinesis" with or without pain. It is a borrowed descriptive term, used initially in relation to the glenohumeral joint and the subacromial impingement disorders. It is essential to distinguish the pain of scapular dyskinesis from deep regional pain arising in the anterior aspect of the shoulder by ruling out neurovascular compromise in the infraclavicular fossa due to the clavicle's malunion during arm elevation. Deep-seated ache may be due to irritation or oscillatory traction of the brachial plexus, with paresthesia during forceful hyperabduction or even at rest due to the weight of the arm.

The position, stability and motion of the scapula primarily depend on the anatomy, orientation and motion of the clavicle; so, do the normal anatomy of the scapulothoracic and acromiohumeral synsarcoses. The interaction of several muscle force couples, altogether keep the scapula congruent on the thorax at an angle to the coronal and the median planes of the vertebral column to maintain the concentric relationship between the humeral head and acromion. Malunion of the clavicle can cause significant malposition of the scapula and, hence, the orientation of the glenoid fossa, affecting the kinematics of the glenohumeral joint(Andermahr et al., 2006; Edelson, 2003). Combined linear and angular deformity of the clavicle causes scapular winging, dyskinesis and dysfunction of the entire pectoral girdle. With shoulder ptosis, there is a loss of ipsilateral shoulder height and width, with measurable reductions in strength, power and endurance at the glenohumeral joint, and a disturbed 2:1 ratio of scapulohumeral rhythm. Therefore, following a malunited clavicle, the resulting shoulder ptosis and a shortened clavicle are not benign conditions.

2.1 Mechanism and consequences of winging and scapular dyskinesis:

Typically, the dorsolateral scapula on the thorax lies between the second and the seventh ribs, with anterior tilt. The glenoid fossa is retroverted and laterally facing, with a slight cranial tilt. Bracing is the voluntary pulling of the scapulae posteriorly towards the median plane *(retraction)*, bringing the shoulders to military position, and hugging is the voluntary pulling the shoulders forward *(protraction),* reducing the width between the two shoulders. Shrugging is the voluntary elevation of both the shoulders, causing the scapulae to translate superiorly in the coronal plane, with or without protraction and slight turning of the inferior angles away from the median plane.

Following a malunited clavicle fracture, the resting scapula in protraction (*hugging pose*) shows ventral translation along the convex ellipsoid curvature of the ribcage, in excessive anterior tilt, and the inferior angle pulled away from the median plane, with or without mechanical winging (*lifted off the thoracic wall at an angle, creating a three-dimensional pyramidal prismatic space under the inferior angle*). The glenoid faces anteriorly, laterally, and slightly caudally, depending on the degree of scapular malposition from its typical dorsolateral position, with ptosis of the shoulder complex. The retraction (*bracing pose*) of the scapula is dorsal translation around the thoracic wall, pulled medially by the rhomboids, with a posterior tilt of the scapular blade; the inferior angle is either vertical or slightly rotated towards the median plane.

Scapular dyskinesis is an observable, functionally involuntary adverse movement of the scapula due to its malposition, with or without pain, during elevation of the humerus. It is characterised by the lifting of the inferior angle and/or the vertebral border of the scapula from the thoracic wall, known as "winged scapula."(Kuhn et al., 1995). The Occipitocleidal trapezius and inferior head of the Trapezius, together with the Serratus anterior, form a force couple that rotates the inferior angle of the scapula on the thoracic wall and tilts it posteriorly(Kibler & Sciascia, 2015; Speer & Garnett, 1994). At the same time, on reversal of the motion, the inferior head of the Trapezius controls the inferior angle of the scapula, bringing it back to its resting position.

In clavicle fractures, shortening with anterior-posterior displacement of the fragments, the Rhomboids pull the vertebral border towards the median plane and superiorly, rotating the glenoid face anteriorly, with anterior tilting of the scapula, holding it protracted obliquely on the thorax(Kim et al., 2019). In addition, the shortened clavicle pulls the coracoid process anteriorly and inferiorly, and frequently its apex directed end-on, anteriorly and medially, depending on the degree of shoulder ptosis, thereby fixing the scapula in its new orientation. The ventral displacement of the scapula from its dorsolateral position or protraction disrupts shoulder biomechanics, muscle-length tension relationship and altered muscle firing of the periscapular muscles due to ineffective length of the clavicle, reducing strength and imbalance: weakness of the Serratus anterior and the lower Trapezius, overactivation of the Occipitocleidal trapezius, causing instability, and altered scapulohumeral rhythm.

Malrotation of the lateral fragment reduces the normal posterior tilt and the angular deformity alters the open and closed-packing state of the sterno-costoclavicular and acromioclavicular joints producing dysfunctional kinematics, and load distribution along deformed clavicle length. Associated with this is anterior facing of the glenoid fossa, and anterior translation and the lateral tilt of the acromion, which reduce the subacromial space. The Pectoralis minor, working with the Serratus anterior and the short head of the Biceps brachii, holds the scapula in anterior tilt, thereby lifting its inferior angle from the thorax.

Usually, as the arm elevates, the humeral head remains at a distance and moves parallel to the arch formed by the acromion and the coracoacromial ligament. However, scapular winging results in incongruency of the scapulothoracic synsarcosis and the scapular dyskinesis, which prevents normal posterior tilting of the scapula, causing the head of the elevating humerus to collide against the acromion. Additionally, during repetitive overhead activity, with an altered scapulohumeral rhythm, reduced strength and power lead to early fatigue, dragging the scapula along the thoracic wall, as the key findings of scapular dyskinesis. Prolonged compressive friction between the muscle layers of the scapulothoracic synsarcosis can cause inflammation of the intermuscular planes, producing crepitus and pain.

2.2 Clinical and biomechanical literature review:

A mean shortening of 21.1 mm is associated with shoulder ptosis, upper extremity weakness, early fatiguability, periscapular pain, and scapular winging at rest, with worsening of the malalignment towards end range of humeral abduction(Ristevski et al., 2013). This computed tomography study revealed a 24.3 mm anterior translation of the acromion on the clavicle. The inferior and superior angles of the scapula had shifted by 5.9 and 9.9 mm, respectively. The anterior tilt of the scapula changed by 4.2 degrees compared with the contralateral side. The acromion follows the acromial fragment of the clavicle without an equal amount of scapular ventral translation around the thorax, which varies with loss of length and angular deformity of the clavicle. As a result of excessive anterior tilt, during the “setting phase,” the scapulothoracic and clavicle group of large muscles would require greater input effort to reset the inclination of the scapula to initiate the movement at the glenohumeral articulation.

In a study of displaced mid-shaft fractures, a longitudinal telescoping range of 21-76 mm developed delayed scapular dyskinesis compared to those with a range of 20-53 mm without scapular dyskinesis(Shields et al., 2015). Of these patients, 8% of operated cases (1 out of 12) and 67% of conservatively treated patients (8 out of 12) who developed scapular dyskinesis were assessed using the SICK Scapula Rating Scale (*Scapular malposition, Inferomedial border prominence, Coracoid pain and malposition, and unfavourable painful Kinematics of the scapula*). Range of motion and abduction strength were similar between the two groups. However, the dominant side clavicle fractures, and females developed scapular dyskinesis(Shields et al., 2015). The study did not consider the effects of the clavicle malunion, scapular dyskinesis and associated winging on the application of brassiere in the female patients.

In a 6-year follow-up study only 20 patients out of 119 in the conservatively treated group showed a significantly higher Quick Dash score than the 20 operatively fixed fractured clavicles(Pradel et al., 2021). The conservative group had 10, and only three of the operated cases had scapular dyskinesis. On plain radiographic and ultrasound measurements, the study considered a clinical shortening of more than 8% as an indication to restore the length of the clavicle, for the restitution of clavicle-scapula angle to normalize shoulder kinetics, preventing scapular malposition attended with dyskinesis. The scapulothoracic angle (*degree of winging*) is noticeably higher in the conservatively treated cases than in surgically treated clavicle fractures(Koç et al., 2022).

In a cadaveric study, to clarify the cause of shoulder pain and dysfunction in cases of clavicle fracture malunion with graded longitudinal shortening of 12, 24 and 36 mm, the winging of the scapula increased in a stepwise fashion with shortening of the clavicle, reorienting the glenoid fossa, acromioclavicular and sternoclavicular joints(Hillen et al., 2012). On average, the protraction of the scapula increased by 20 degrees, the inferior angle rotated by 12 degrees on the clockface, and posterior tilt decreased by 7 degrees. The graded shortening of the clavicle affected kinematics at the sternoclavicular joint but not at the acromioclavicular joint. Over the full range of arm elevation, the movements of the scapula changed progressively relative to the amount of shortening of the clavicle. The malposition of the resting scapula remained relatively unchanged.

There are several aetiologies in the differential diagnoses of the “winging of scapula” and “scapular dyskinesis,”. Therefore, carefully evaluate the static and dynamic mechanical lifting of the inferior angle of the scapula, with or without lifting of its vertebral border. Distinguish the causes by applying clinical tests, such as scapular assistance test and the scapular retraction test(Roche et al., 2015). Objectively test various scapulothoracic and craniocleidal muscles with electromyography. It is essential to rule out traction injury to the C5, C6 and C7 nerve roots associated with clavicle fractures, particularly during high-velocity motorbike injuries. A healthy nerve can be pulled safely up to 2% of its original length without neuropraxia. This helps to diagnose missed isolated traction injury of the long thoracic and accessory nerves during dynamic displacement of the lateral fragment of the clavicle due to centrifugal force acting on the shoulder in dragging accidents, causing distraction of the fractured fragments. Consider a computed tomography scan, including the first costovertebral articulation, to rule out subluxation or dislocation as a long-term cause of deep shoulder and dorsocervical pain. Every displaced clavicle fracture sustained during a high-velocity accident is potentially a floating shoulder because, without the restraining capsule and ligaments holding the scapulothoracic synsarcosis the muscles can stretch far more than the nerves and the vessels.

The clinical signs of scapular winging and dyskinesis following the clavicle’s malunion are mechanical and require mechanical correction. Intensive physical therapy and bone remodelling in the young can help, but surgical restoration of the anatomy and biomechanical architecture of the clavicle is imperative to prevent commonly known complications and biomechanical deficits. Before planning surgical management of a malunited clavicle fracture, it is crucial to consider differential diagnoses for the signs and symptoms of scapular dyskinesis and investigate further to reach a final diagnosis. Not forgetting that fracture displacement is a dynamic triplane three-dimensional deformity, and imaging is a static observation despite the availability of a revolving animated three-dimensional reconstruction in all planes. It is still not patient-specific enough to dynamically reorient multiplanar and multiaxially displaced fractured fragments to restore the biomechanical architecture and animate deforming muscular forces as in the living.

3.0 Eccentricity of the acromiohumeral synsarcosis and impingement:

The Deltoid muscle completely covers the acromiohumeral synsarcosis on its three sides. It is the most important muscle acting on the glenohumeral joint. It has three main components: anterior, lateral and posterior. The anterior part originates from the anterior and superior surfaces of the acromial third of the clavicle, the lateral from the acromion, and the posterior from the whole of the inferior border of the scapular spine, opposite the Trapezius. Each part has a specific function in various proportions and stages of arm elevation in sagittal, scapular and coronal planes **(see Part 1 of the series).**

3.1 Boundaries and contents of acromiohumeral space:

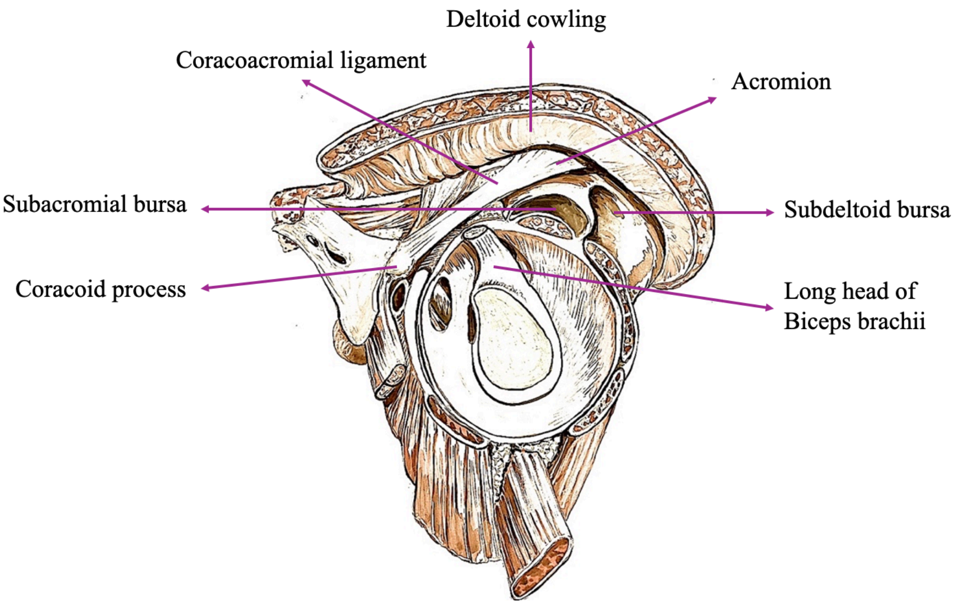


Figure 2. Artwork illustrating acromiohumeral synsarcosis underneath the deltoid cowling. Modified from Gray’s Anatomy

The acromiohumeral synsarcosis (**Fig. 2**) is bounded by the deep surface of the Deltoid, which forms a cowling over the shoulder joint. The osseous-fibrous coracoacromial arch deep to it, is formed anteriorly by the coracoid process, superiorly by the coracoacromial ligament and the acromioclavicular joint, superior and posteriorly by the undersurface of the acromion and adjacent part of the scapular spine. It is bounded inferiorly by the articular surface of the humeral head, lesser and greater tuberosities, and transverse ligament bridging the bicipital groove for the passage of the tendon of long head of the Biceps brachii muscle. More medially, it is bounded by the superior edge of the glenoid tubercle and labrum. From anterior to posterior, the tendon of the Subscapularis muscle inserts on the lesser tuberosity, and tendons of the Supraspinatus, Infraspinatus and Teres minor muscles inserts on the three facets of the greater tuberosity. The tendons of these four muscles fuse edge-to-edge close to their insertion, forming the rotator cuff. The anatomical arrangement of the rotator cuff serves an important function of dynamically holding down and stabilizing the humeral head against the glenoid during arm elevation, in conjunction with the Deltoid muscle(Curtis et al., 2006). The contraction of the rotator cuff and the scapulothoracic muscles, through proprioceptive activity, balances and co-ordinate dynamic movements at the glenohumeral joint for normal scapulohumeral rhythm(Warner et al., 1992).

3.2 Extrinsic and intrinsic spaces of the acromiohumeral synsarcosis:

Structurally, the rotator cuff divides the acromiohumeral synsarcosis into an extrinsic and an intrinsic space. The extrinsic space lies between the superficial surface of the rotator cuff and the undersurface of the coracoacromial arch, extending up to the acromial angle. It is occupied by a serosal sac, lined with the synovial membrane, which contains a thin lubricating film— functioning as a secondary synovial articulation —facilitating movement between the coracoacromial arch and the subjacent Supraspinatus muscle(Lambert, 2016). The sac often extends laterally beneath the Deltoid muscle, forming a subdeltoid bursa covering part of the greater tuberosity. Inflammation of the subdeltoid/subacromial serosal sac filled with transudate is called subacromial bursitis.

A thick fibrous layer covering the rotator interval extending from the lateral edge of the coracoid process splits to cover both the superficial and deep surfaces of the rotator cuff tendons and inserts into the lesser and greater tuberosities of the humerus(Harryman et al., 1992). The deep surface of the rotator cuff blends with the glenohumeral capsule and various ligaments of the glenohumeral joint. The tendon of the long head of the Biceps brachii enters the glenohumeral joint, running medially and anteriorly over the humeral head at an angle, and inserts into the supraglenoid tubercle and adjacent glenoid labrum on either side of it. The intracapsular course of the tendon remains outside the synovial cavity of the joint. The extrinsic or intrinsic space of the acromiohumeral synsarcosis do not communicate with the synovial cavity of the glenohumeral joint.

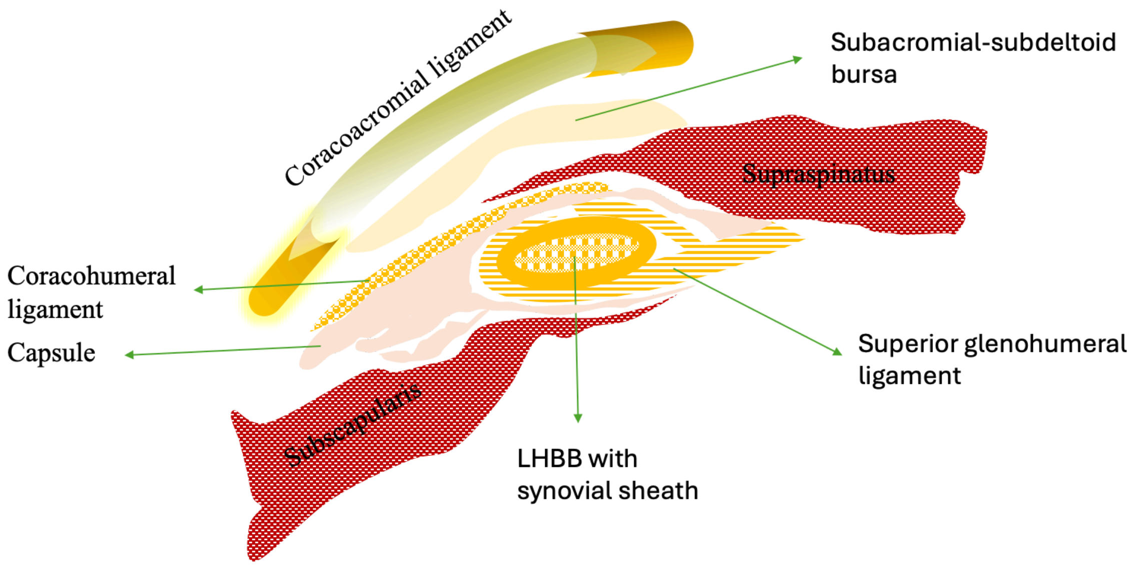


Figure 3. Illustration showing extrinsic and intrinsic spaces at the rotator interval, above and within the layers beneath the rotator cuff (created in PowerPoint by the author).

In the triangular rotator interval between the Subscapularis and Supraspinatus tendons, the extra-synovial intracapsular tendon of the long head of the Biceps brachii is superficially covered by the coracohumeral ligament and on its deep aspect lies the superior glenohumeral ligament (**Fig. 3**). Fibres of both the ligaments insert on the lesser tuberosity close to the opening of the bicipital groove(Ferrari, 1990). The strong circular fibres of the capsular layer intermingle with the tendinous fibres of the Supraspinatus and Infraspinatus muscles, forming a roof over the long tendon of the Biceps brachii continues into the superficial layer of the anterior capsule(Gohlke et al., 1994). It spans the rotator interval, serving as its floor, covering the underlying long tendon of the Biceps brachii. The anterior fibres of the Supraspinatus tendons cross the bicipital groove, with an additional insertion point on the lesser tuberosities in 10 out of 30 cadaveric specimens(Kolts, 1992).

3.3 Relationship of long tendon of the Biceps brachii to the Supraspinatus:

The variable presence of an accessory slip of the Supraspinatus tendon bridging across the bicipital groove to the lesser tuberosity, reinforcing the transverse ligament, is a critical anchor, as the tear usually begins at the greater tuberosity, giving the rupture a Y-shaped appearance. The long head of the Biceps brachii has an intricate relationship with the expanded insertion of the Supraspinatus as it enters the intracapsular intrinsic space, wrapped in layers of the capsule and Supraspinatus tendon(Burkhead et al., 2009; Clark & Harryman, 1992). The tendon anchored at the bicipital groove in a fibrous sleeve is analogous to the tine of a belt buckle **(for details see Part 3 of the series).**

The coracoid process lies at the base of the triangular rotator interval, and the transverse humeral ligament lies at the apex over the intertubercular groove. From an anterior extra-articular view, the coracohumeral and superior glenohumeral ligaments reinforce the floor of the interval formed by the anterior capsule. The middle glenohumeral ligament crosses over laterally deep to the Subscapularis tendon, blending into the deep layers of its articular surface. In an intraarticular view, at the superior edge of the rotator interval lies the superior glenohumeral ligament, and deep to the subscapularis at the inferior edge is the middle glenohumeral ligament. In a resting state of the glenohumeral joint, the intracapsular extra-synovial tendon of the long head of the Biceps brachii lies deep to the superior glenohumeral ligament and floor of the rotator interval.

In the extrinsic space of the acromiohumeral synsarcosis, the superficial surfaces of the Supraspinatus and infraspinatus tendons impinge on the coracoacromial arch during arm elevation. Simultaneously in the intrinsic space, the obliquely oriented long tendon of the Biceps brachii sustains shear injury against the undersurface of the anterior-superior capsule, coracohumeral and superior glenohumeral ligaments (**Fig. 4**).

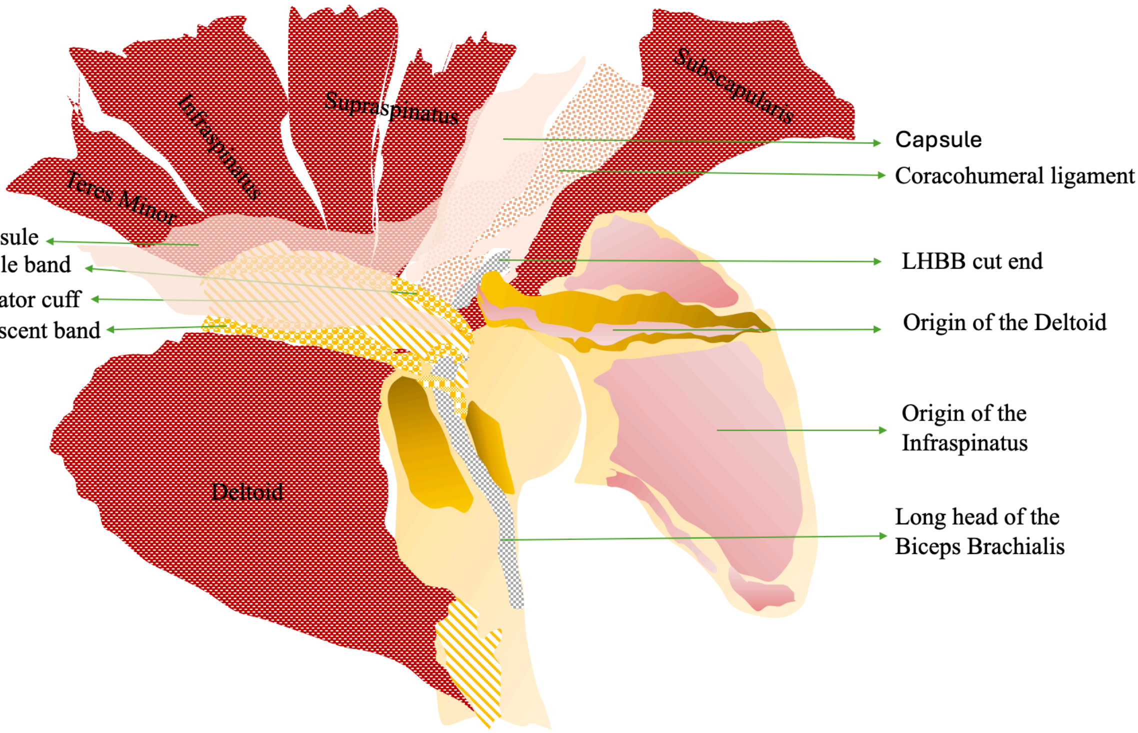


Figure 4. An exploded view of the intrinsic space (created in PowerPoint by the author).

During overhead abduction beyond 90 degrees, with external rotation of the humerus, the tendon of long head of the Biceps brachii is fixed between its insertion at the supraglenoid tubercle and fibro-tendinous retaining sling at the intertubercular groove. The tendon normally wipes against the capsuloligamentous structures with minimal shear, protected by the covering synovial sheath.

3.4 Mechanism for the development of extrinsic and intrinsic injury and dual pathology of the rotator cuff and Biceps tendon:

With an overhead load and repetitive high-velocity throwing movements, the long tendon of the Biceps brachii acts like a stationary tight rope, and the humeral head slides like a pulley along the tendon instead of the tendon sliding on a stationary pulley(Burkhead et al., 2009). During abduction and external rotation of the humerus, the tightened tendon wipes harshly back and forth against the overlying capsular structures like a windscreen wiper. The synovial sleeve twists and untwists, causing inflammatory kissing lesions. Over time, the undersurface of the capsuloligamentous surface is frayed, initiating intrinsic lesions, opposite to the wearing of the superficial surface of the rotator cuff in the extrinsic space.

With progressive wear due to unrelenting high-velocity overhead activities, the rotator cuff and the capsuloligamentous structures get thin at their insertion sites, deepening from both sides, establishing a definitive tear. In addition, the concentric contraction that compress and stabilizes the humeral head against the glenoid, and the tensile stretch due to rapid eccentric contraction of the rotator cuff following the culmination of each act of a thrower, which start as microtears, develop into a full-fledged rupture. A tear can develop gradually over years, or a significant rupture may occur suddenly due to an eccentric contraction during a forceful throw.

Early fraying of the long tendon of the Biceps brachii adjacent to the bicipital groove is visible on arthroscopy when the elbow is flexed, relaxing the long tendon of the Biceps brachii and pulling it towards the joint space, where the tendon has been rubbing the most(Carvalho et al., 2020; Ditsios et al., 2012). There is often a relationship between the tears of the long tendon of the Biceps brachii and those of the Supraspinatus and Subscapularis tendons(Beall et al., 2003). In the extrinsic space, most of the contact of the moving humeral head and the surrounding structures during arm elevation occurs against the prestressed coracoacromial ligament and the apex of the acromion, with forward flexion, adduction and internal rotation against the lesser tuberosity, which receives the insertions of the Subscapularis muscle tendon, coracohumeral and superior glenohumeral ligaments, initiating the tear simultaneously. Thus, the extrinsic rotator cuff lesion occurs due to impingement and the intrinsic one because of the 'wiper-effect'.

Simultaneous intrinsic and extrinsic rotator cuff lesions exacerbate shear injury to the tendon of the long head of the Biceps brachii along its course in the rotator interval to the bicipital groove. The tendon sheath develops tenosynovitis, with or without inflammatory fluid. With the constant intrinsic injury, there is continuous fraying and thinning of the capsuloligamentous structures, with the peeling away of the Supraspinatus and Infraspinatus tendons at their insertions on the greater tuberosity. The peeling progresses with each episode of the intrinsic strike of the greater tuberosity against the anterior-superior-posterior labral edge of the glenoid fossa during their concentric contraction. In the malunion of the clavicle with a significant frustum formation, as the medially and inferiorly protracted scapula cannot rotate normally on its anterior-posterior axis, the glenoid fossa fails to face cranially, while remaining non-concentric under the humeral head, cause dual pathology of the Supraspinatus and long tendon of the Biceps brachii.

This fixation of the scapula, due to length shortening of the clavicle, angulation and anterior rotation of the lateral fragment, increases asymmetry of the acromiohumeral space with the acromion closing onto the head of the humerus. A relative shortening of more than 10% and increased anterior rotation of the clavicle is unfailingly associated with impingement, decreased forward flexion, and early, prolonged acromiohumeral contact on external rotation of the humerus at 90 degrees of abduction in conservatively treated patients. An unattended clavicle fracture malunion with an eccentricity of the acromiohumeral synsarcosis hastens the injury to the rotator cuff tendons and the long tendon of the Biceps brachii. Delayed surgical intervention in such cases results in poor outcomes(George et al., 2015; Van Scoy et al., 2023).

4.0 Setting in of the adhesive capsulitis as "frozen shoulder":

Following a deep angular frustum, there is a definitive loss of acromiohumeral concentricity. The enduring contact between the humeral head and the coracohumeral ligament, at the apex and the lateral edge of the acromion causes symptoms arising from the superior aspect of the rotator cuff. During the early phase, transudation of fluid filling up the subdeltoid and subacromial bursae, with recurrent frictional injury, is a defensive strategy to protect the rotator cuff. However, in the late stages, the uncorrected malunion with anterior-superior coracohumeral impingement involving structures in the floor of the rotator interval results in decreased strength and instability of the glenohumeral articulation due to pseudo-laxity of the anterior capsular tissues. Over time, an extrinsic lesion of the rotator cuff, with increasing reactive inflammatory fluid formation in the subacromial bursa, results in chronic bursitis. The eccentricity of the acromiohumeral synsarcosis, increasing contact of the humerus with apex of the acromion during forward flexion with persistent friction injury, result in inflammation and adhesive fibrosis at the rotator interval, which limits both the external rotation and forward flexion of the humerus. This limitation of the external rotation and forward flexion, with stiffness and painful restriction of the other glenohumeral movements, establishes the pathophysiology of adhesive capsulitis, followed by tissue contractures, commonly known as frozen shoulder(Codman, 1934; Warner, 1997).

The shoulder complex can present with global pain in cases of malunited clavicle fracture. The anterior-superior shoulder pain is due to compromise of the extrinsic space of the acromiohumeral synsarcosis. Superior-lateral pain radiating along the tendon of the long head of the Biceps brachii muscle is due to pathology of the intrinsic space. The pain due to the inflammatory pathology in the shoulder complex can radiate to the wrist, following Hunter's law of articular innervation. The dyskinesis of the acromiohumeral synsarcosis restrict the motion of the glenohumeral joint. And the restricted motion of the glenohumeral articulation in one plane always limits the motion in the other two planes(Debski et al., 1999). The limitation occurs because of shared tension and slackness of the capsuloligamentous structures, which struggle to stabilize and centralize the moving articular surfaces to maintain equilibrium under the simultaneous action of various force couples acting on the linkages and the joints of the pectoral girdle.

5.0 Advanced changes in acromiohumeral synsarcosis with shoulder ptosis:

In an uncorrected clavicle malunion, there is fixation of the anteriorly protracted glenoid fossa, a laterally tilted acromion, and an anteriorly tilted body of the scapula, with varying degrees of winging. The accompanying shoulder complex ptosis leads to the pseudo-laxity of the anterior-superior capsule and ligaments, associated with anterior instability, and variable inferior gravitational shift of the humeral head. In addition to reducing the gap between the undersurface of the acromion and the greater tuberosity, there is closure of the coracohumeral gap, causing impingement of the coracoid tip on the rotator interval. The severity depends on the degree of angular displacement of the fracture fragments and mispositioning of the coracoid, with internal or external rotation of the humeral head during underhand forward flexion and overhead athletic activities.

Compromised congruency and concentricity of the acromiohumeral synsarcosis result in uneven loading of the articular surfaces of the humerus and the glenoid. There is a constant effort by the craniocleidal, scapulothoracic and scapulohumeral muscles to maintain an equilibrium among them, optimizing motion at the sternoclavicular, acromioclavicular, and scapulothoracic articulations to achieve maximum kinematic functions from the glenohumeral joint in all planes. An increased global effort of the shoulder complex is required for even simple activities due reduced strength and early fatigue, leading to delay in task-specific outcomes.

When the compensatory efforts fail, the dyskinesis of the scapulothoracic synsarcosis becomes clinically visible. Post-traumatic chronic impingement in the extrinsic space, fraying of the Supraspinatus and the capsuloligamentous structures, atrophy of the rotator cuff musculature due to pain and disuse, and tendinosis of the long tendon of the Biceps brachii due to its altered path of excursion during loaded arm elevation become relentless and clinically significant. The eccentric gliding movement at the acromiohumeral synsarcosis generates pathological shear forces between layers, reducing the efficiency of the glenohumeral articulation. These changes results from a single malfunctioning linkage, the malunited clavicle, in the power transmission system of the ipsilateral shoulder complex.

The entire pectoral girdle is affected bilaterally, with the midline origins of the Trapezius and Rhomboids on the medial half of the superior nuchal line and spinous processes of the cervical and thoracic vertebral column. There is anterior or lateral shoulder pain, with or without radiation to the arm, and chronic pain at the scapulothoracic synsarcosis over the long term. These symptoms may accompany irritation or compression of neurovascular structures in the thoracic aperture, infraclavicular fossa or within the axillary sheath, accompanying upper back pain with referred arm pain via Kuntz's nerve, depending on the degree of malunion and dysfunctional kinematics of the first costovertebral joint during extreme abduction to deliver high velocity projectile. Whether altered movements of the first rib result in degenerative changes in the costovertebral articulations remains unreported, if the high velocity projectile delivery continues.

6.0 Acromiohumeral and coracohumeral impingement mechanism following malunion of the clavicle fracture:

The condition of acromion striking against the insertion of the rotator cuff on the tuberosities of the humerus, causing shoulder pain, chronic subacromial bursitis and partial tearing of the rotator cuff' is the original description of the term "impingement syndrome"(Neer, 1972). Impingement from the Latin *impingere* to drive at, strike at; *im* means on + *pangere* means to fasten, drive in, strike. Impinge means to encroach, infringe, collide (with), or strike. Accordingly, following the malunion of the clavicle, it is the acromion that encroaches on the space of the acromiohumeral synsarcosis. Anterior superior impingement by the apex of the acromion causes the wearing of the rotator cuff and tendon of the long head of the Biceps brachii at the rotator interval. The humeral head strikes it each time the humerus is elevated. The definition applies well to the condition of posttraumatic symptoms arising out of malunion of the clavicle.

Usually, the centre of the coracoacromial arch aligns with the glenoid fossa, maintaining a concentric relationship with the circumference of the humeral head. When the difference in their radii of curvatures remains uniform throughout the excursion of the humeral head, the concentricity enhances the stability of the glenohumeral articulation(Codman, 1934). In the presence of a malunited clavicle, the acromiohumeral synsarcosis becomes eccentric, and the severity of acromial-related symptoms depends on the preexisting anatomy of the acromion, whether it is flat, curved or hooked at the apex(Bigliani et al., 1991). These acromial changes are acquired rather than developmental, and rotator cuff pathology correlates well with age(Gill et al., 2002; Lee et al., 2001; Yazici et al., 1995). Older patients are more likely to have curved and hooked acromia. Therefore, the shoulder pain must be carefully assessed after ruling out pre-existing causes, differentiating from recently developed symptoms because of the clavicle fracture.

Scapular protraction and scapulothoracic asynchrony, due to clavicle malunion, result in anterior translation of the humeral head relative to the glenoid fossa reducing dynamic stabilization of the glenohumeral joint and causing fatigue, impingement, microtrauma, and subsequently, attrition of the rotator cuff tendons(Paley et al., 2000). The protraction of the acromion and mispositioning of the scapular body produce a deficit of internal rotation of the humerus, leading to a greater arc of external rotation, encouraging early acromion contact with the humeral tuberosities(Burkhart et al., 2003). Muscle fatigue during overhead repetitive activity leads to the progressive protraction of the acromion and intrinsic impingement. With protraction of the scapula, as the glenoid faces anteriorly and inferiorly, the humeral head is inferiorly displaced, requiring greater force-couple effort during the "setting phase", significantly increasing the arc and duration of external rotation, thereby increasing shear and torsional forces right at the onset of the movement(Burkhart et al., 2003; Ristevski et al., 2013).

The oblique course of the long tendon of the Biceps brachii over the top of the humeral head, corresponding to the retroversion angle of the humeral head, is 45 degrees relative to the intercondylar line of the distal humerus(Burkhead et al., 2009; Habermeyer et al., 1987). Like the clavicle, the humerus has a phylogenetic and developmental relationship with the angular course of the long tendon of the Biceps brachii as it passes over its head(Burkhead et al., 2009). These parallels between the clavicle and humerus are related to the inversion of the sagittal and coronal diameters of the thoracic cage from side-to-side flattening to front-to-back flattening, resulting in retroversion of the humeral head to redirect the hand from a quadrupedal forelimb to perform new functions upon acquiring bipedalism. Consequently, the dorsolateral placement of the scapula forms an angle of

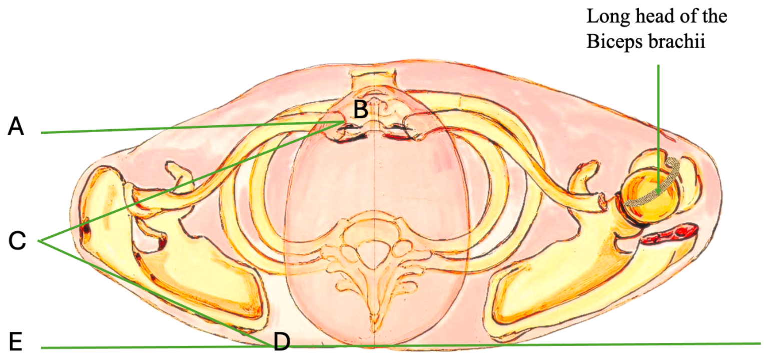


Figure 5. Artwork - Oblique orientation of the Long head of the Biceps brachii; Angles ABC 20 degrees, BCD 60 degrees, and CDE 30-35 degrees.

30-35 degrees to the rear coronal plane and 60 degrees to the plane of the clavicle (**Fig. 5**). This configuration brought the tendon of the Biceps brachii into a 45-degree relative to the intercondylar plane of the distal humerus in an anterior to posterior direction, aligning in the scapular plane(Burkhead et al., 2009; Hitchcock & Bechtol, 1948).

Malunion of the clavicle with shortening, malrotation of its diaphysis, posterior-superior angulation, and malposition of the scapula alter the relationship of the long tendon of the Biceps brachii with the retroverted head of the humerus, displaced with the glenoid, the intercondylar line of the distal humerus, and the eccentrically placed coracoacromial arch. The angular shift of the tendon over the top of the humeral head influences the shear forces at the interface between the tendon and the circular fibres of the capsule, associated ligaments, and the Supraspinatus tendon during abduction and external rotation of the humerus, causing them to rub harshly against each other and leading to wear of the tendon and chronic painful tendinosis due to the wiper-effect. Tenotomy with extracapsular distal tenodesis is a standard surgical procedure for relieving symptoms from the tendon injury due to the impingement. The procedure does not deteriorate the shoulder function(Burkhead et al., 2009). In an uncorrected malunion, without complete remodelling of the biomechanical architecture of the clavicle, how the tenotomy alters the decelerating effect of the Biceps brachii and its stabilizing force to centralize the humeral head on the glenoid during movements, other than the enhanced activity of already adversely affected rotator cuff, in the presence of shoulder ptosis, scapular dyskinesis and impingement, remains unclear.

The symptoms of coracoid impingement and Biceps brachii tenosynovitis at the rotator interval will be similar. The normal distance between the coracoid tip and the humerus is 8.6 mm(Gerber et al., 1985). Reducing this distance to less than 6.7 mm in cases of scapular protraction will cause coracoid impingement, and there are variations in the morphology of the coracoid process to consider(Bhatia et al., 2007; Zhang et al., 2022). The degree of misorientation of the coracoid in cases of malunited clavicles treated conservatively or surgically would influence the severity of coracohumeral impingement symptoms **(for details see part 4 of the series).** Extracapsular impingement presents with pain and tenderness over the anterior acromion and coracoacromial ligament, as well as at the insertion of the Supraspinatus muscle tendon.

The normal acromiohumeral interval with an intact rotator cuff on an anterior-posterior radiographic view is equivalent to the normal thickness of the cuff, which is about 6.0 mm(F. Matsen & Lippitt, 2004). In cases of clavicle malunion with shoulder pain, in addition to anterior-posterior views, consider Garshey and Zanca radiographic views; arthrography; magnetic resonance imaging; computed tomography and angiography, where indicated; or ultrasonography to establish differential diagnoses. There is a lack of corroborating dynamic imaging studies to demonstrate the mechanism of impingement following clavicle malunion, to show side-to-side differences, and to prove the effect of age-related changes in the anatomy of the acromion and the symptoms generated by the malunited clavicle. An arthroscopic examination will help assess both extrinsic and intrinsic spaces of the acromiohumeral synsarcosis, the site of impingement during various stages of abduction with external rotation of the humerus, starting from its displaced position relative to the glenoid, in all the planes. Alternatively, perform dynamic [1]biplanar arthrography under anaesthesia, to rule out eccentricity of the acromiohumeral synsarcosis and impingement. At the same time, check stability, dynamic subluxation and eccentric movements at the glenohumeral joint, and observe dyskinesis of the scapulothoracic synsarcosis and scapular winging.

The net resultant equilibrium of the force couples acting on the links and joint, capsule and ligaments, inertia between the tissue layers, and atmospheric pressure effectively stabilises the shoulder complex. As the glenoid and upper lateral border of the scapula sag with ptosis of the shoulder tip, there is passive abduction of the humerus with relaxation of the rotator interval and the superior joint capsule. This resembles the passive abduction seen in patients with a high body mass index, who cannot rest the arm straight up and down beside the body. The anteriorly facing glenoid fails to support the humeral head adequately. When the regular supporting Trapezius, Rhomboids and the Serratus anterior cannot stabilize the scapula, the medial border of the scapula is more prominent than the lateral border(F. A. Matsen et al., 1994). In addition to normal articular surface geometry and joint reaction forces, the functional geometric properties of the normal scapulothoracic relationship are greatly enhanced with an appropriate degree of protraction and retraction coincident with the elevating arm when the articular surfaces are compressed against each other to maintain centrality during translation(Soslowsky et al., 1992). These stabilizing forces maintaining articular geometry are challenged when shoulder ptosis with frustum formation is left for long time.

The subacromial space should remain concentric in both protracted and retracted positions of the scapula; otherwise, with protraction, the subacromial height decreases and increases with retraction(Solem-Bertoft et al., 1993). On retraction of the acromion, the height of the subacromial space increases because of the posterior tilt and retracted position of the scapular body, produced by the middle and inferior heads of the Trapezius and the Rhomboids. The measured height of the subacromial space between the undersurface of the acromion and uppermost margin at the peak of the greater tuberosity of the humeral head is 10-15 mm on an anterior-posterior radiographic view(Flatow et al., 1994). Such baseline measurements can help assess the acromiohumeral space following conservative management of clavicle fractures.

In summary, concentricity and congruence between the acromion and the humeral head throughout arm elevation in all planes are paramount to prevent impingement. A clavicle fracture, which has been completely restored anatomically and biomechanically, it elevates, rotates posteriorly, and retracts, with the scapula tilting posteriorly, lifting the apex of the acromion simultaneously, maintaining 2:1 scapulohumeral rhythm as the humerus abducts higher. If the clavicle malunion with frustum formation is benignly left to its fate, the synchrony of the clavicle and scapula will be in disarray.

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[1] Similar to the arthrography examination of the hip joint in the developmental dysplasia of the hip.

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