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

Part 3 Articular Anatomy of the Pectoral Girdle

Gandhi, Harjeet Singh, MD, FRCS, FRCSC, MSc (Biomed. Eng)

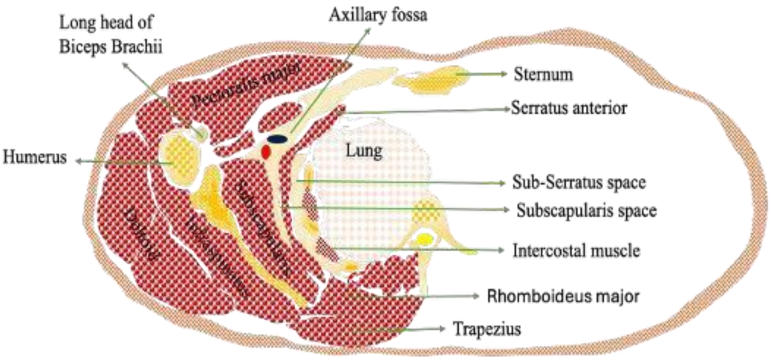
Orthopaedic surgeon, Honorary Staff, Hamilton Health Sciences, Hamilton, ON, Canada

Email: harjeetg52@yahoo.co.uk

Highlights: The bilateral clavicle articulates with the axial skeleton directly at the clavicular fossae of the manubrium sterni, indirectly to the first thoracic vertebra through the first rib, and soft tissue connectivity via the scapulothoracic synsarcosis, completing the pectoral girdle system.

The dual compartments of the sternoclavicular articulation offer multiplanar and multiaxial kinematic properties. In the presence of normal biomechanical architecture of the clavicle, the scapulothoracic synsarcosis enhances the versatility of the pectoral girdle and, along with a healthy acromiohumeral synsarcosis, provides uniform scapulohumeral rhythm and powerful overhead movements.

Graphic abstract:



Keywords: Clavicle anatomy, Pectoral girdle, Sternoclavicular joint, Acromioclavicular joint, Scapulothoracic synsarcosis, Acromiohumeral synsarcosis, Human anatomy

1.0 Articulations of the clavicle:

The medial end of the clavicle articulates with the clavicular fossa of the manubrium sterni, and the lateral end with the acromion. At the medial end, the clavicle has a secondary articulation with the first costal cartilage and, rarely, at the lateral curvature, it has an accessory articulation with the coracoid process. The articular surface of the secondary articulation between the first costal cartilage and the part of inferior circumference of the sternal end extends to the adjacent metaphysis of the clavicle. It is free of capsular and ligamentous attachments, assisting in the axial rotation of the clavicle(Standring, 2016).

With maximum dorsal rotation of the clavicle on its longitudinal axis, the variably shaped and sized posteriorinferior conical tubercle at its sternal end overhangs the clavicular fossa posteriorly. It engages with the first costal cartilage, acting like a cam, and passively raises the acromial end higher towards the end of the abduction movement. Even though the tubercle does not have a well-defined articular surface, the cam action is enabled due to the lax inferior and superior capsules pivoting on the tightened posterior capsule.

Ossification of the costoclavicular ligament resulting in costoclavicular synostosis, often encountered in females over the age of 50 years, produces an exophytic bony ledge(Standring, 2016). The reported incidence of costoclavicular synostosis ranges from 1.44% to more than 10%(Paraskevas et al., 2019). The coracoclavicular articulation, often a pseudarthrosis, is phylogenetically vestigial(Singh et al., 2011).

2.0 Sterno-costoclavicular articulation (Sternoclavicular joint):

The sterno-costoclavicular joint is a diarthrodial synovial dual-compartment articulation with an intervening intraarticular disc. The prismoid medial end of the clavicle is much larger than the available manubrial articular surface, known as the clavicular fossa. Consequently, the articular surfaces of the clavicles, on either side of the median plane, rise much above the clavicular fossae in their resting position, bordering the jugular notch, resulting in incongruent sterno-costoclavicular joints. The extension of the clavicular fossa over the first costal cartilage partly compensates for this incongruence during elevation of the clavicle. Therefore, it forms a compound Sternocostoclavicular articulation involving three elements. The joint surface at the sternal end of the clavicle is reminiscent of a saddle shape, being concave in one plane and convex in the other (**Fig. 1**).

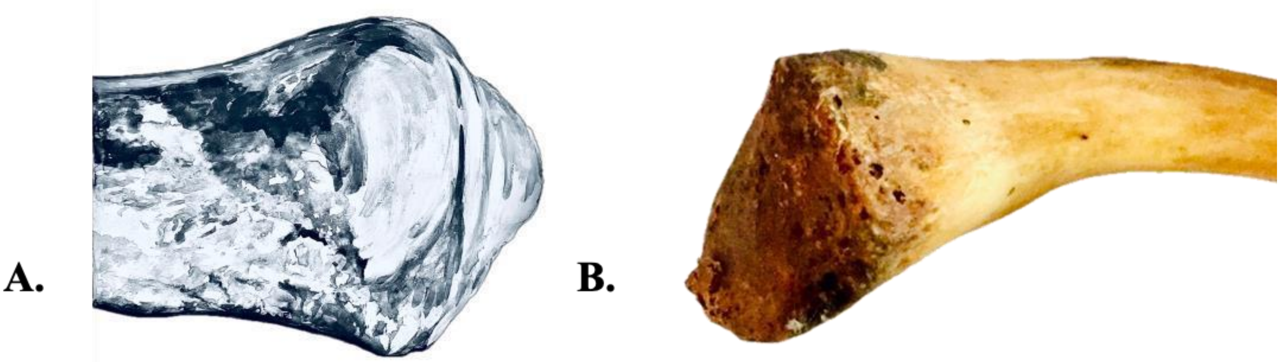


Figure 1. A. Artwork showing a saddle-shaped covering of healthy articular cartilage on the sternal articular end; **B.** without the articular cartilage.

In architectural engineering, the orthogonal arrangement of the concavo-convex surface of a saddle is called a hyperbolic paraboloid. The geometric relationship between two opposing curves fused back-to-back or side-byside enhances strength and stability of the structure. In the construction of the sterno-costoclavicular joint in conjunction with the intraarticular disc, the saddle shape increases the concentricity of the articulating surfaces and stabilizes its multiplanar and multiaxial kinematics(Kapandji, 2005).

2.1 Sternal end articular surface and the intra-articular disc:

The articular surface at the sternal end of the clavicle has a significantly thicker layer of fibrocartilage compared to the shallow socket of the manubrium sterni(Standring, 2016). The fibrocartilage covers approximately 67% of the anteroinferior aspect of the clavicle's sternal end articular surface(Lee et al., 2014; Van Tongel et al., 2012). Less than half the inferior part of the articular surface articulates with that of the clavicular fossa of the manubrium sterni(Renfree & Wright, 2003). The complete or perforated intra-articular disc, attached to the posterior and superior articular margins of the clavicle, divides the sterno-costoclavicular joint cavity into two, forming twin synovial joints. The thick periphery of the disc is continuous with the fibrous capsule and ligaments inferiorly, medially, superiorly, and posteriorly. It is also attached inferiorly to the first costal cartilage near the manubrium sterni.

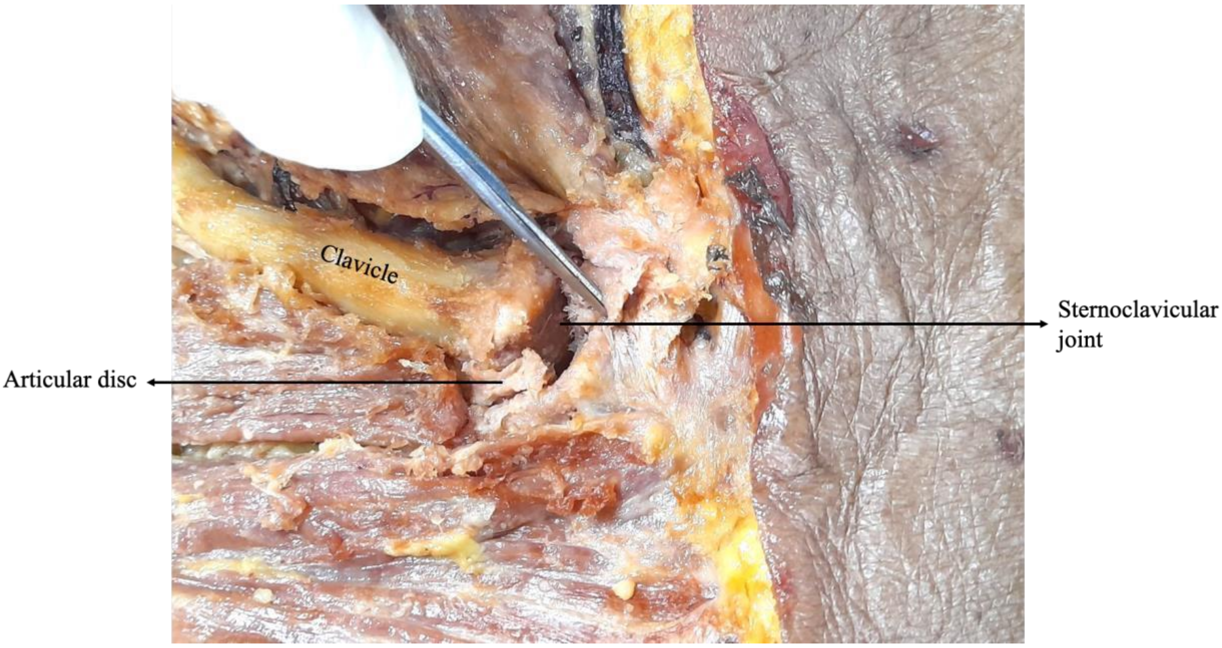


Figure 2. The author's dissection exposes the bare surface of the sternal end articular surface of the clavicle and the torn intra-articular disc.

The average diameter of the articular disc is 18mm and has a peripheral thickness of 5.4mm, tapering centrally, having appreciable concavities on both sides, resembling a biconcave lens(Lee et al., 2014). In advanced osteoarthritis, with complete loss of the articular cartilage, the disc may disintegrate (**Fig. 2**). The inferior attachment of the articular disc to the first costal cartilage and the capsule prevents subluxation of the medial end of the clavicle over the manubrium(Renfree & Wright, 2003).

2.2 Articular capsule and ligaments:

The capsule is thick on the anterior and posterior aspects of the sterno-costoclavicular joint; however, the posterior capsule is much thicker than the anterior. The posterior capsule attached to the superior and posterior articular margins of the clavicle is taut and firmer than the lax and softer anterior(Van Tongel et al., 2012). The superior and inferior portions of the capsule, made of loose areolar tissue, are much thinner(Standring, 2016). The capsular and extracapsular ligaments of the sterno-costoclavicular joint include— the anterior sternoclavicular, posterior sternoclavicular, interclavicular, and costoclavicular. The articular disc is considered as the intra-articular discal ligament.

The broad band of the anterior sternoclavicular ligament extends from the anterior-superior margin of the clavicle, descending obliquely in the inferior-medial direction, and attaches to the manubrium sterni. It sends an expansion to the first costal cartilage covered by the sternal portion of the Sternocleidomastoid. Its deep surface is related to the intra-articular disc and synovial folds. The posterior sternoclavicular ligament attaches to the superior and posterior articular margins of the clavicle. It passes obliquely in inferior and medial directions, attaching to the superior part of the manubrium sterni. Its deep surface is related to the intra-articular disc and posteriorly to the Sternothyroid muscle.

The interclavicular ligament from one side to the other curves across the sternal notch to attach on the superior aspect of the clavicles. It also sends a few fibres to the upper surface of the manubrium sterni. The cervical fascia merges with the ligament, enclosing a fascial space(Standring, 2016). The tautness of the interclavicular ligament, acting as a suspension band, maintains the articular contact of the clavicle at its inferior aspect of the joint. At the same time, it resists downward displacement of the clavicle against gravity, maintaining shoulder balance(Bearn, 1967).

Figure 3. The author's dissection – The Cleidobrachialis pectoralis reflected from the clavicle, exposing the costoclavicular ligament and Subclavius tendon.

2.3 Costoclavicular ligament:

The rhomboid-shaped costoclavicular ligament is short and thick (**Fig. 3**). It is an inverted cone having two laminae, anterior and posterior. The laminae run in opposite directions in a cruciate fashion, attaching below to the superior surface of the first costal cartilage, medial to the costochondral junction(Kapandji, 2005; Standring, 2016). The longer fibre of the anterior lamina arises medial to the posterior lamina and ascends obliquely in the lateral direction. The shorter fibres of the posterior lamina arise laterally and descend in the medial direction behind the anterior lamina. Both laminae get attached to the inferior surface of the clavicle, close to the sternoclavicular articulation.

The footprint on the clavicle may be either a depression, or an eminence called the costoclavicular fossa or the clavicular tuberosity, respectively. Anteriorly, the ligament complex is related to the origin of the Subclavius muscle tendon, deep fibres of the Cleidobrachialis pectoralis, medially to the capsule of the Sterno-costoclavicular joint and posteriorly lies the Subclavian vein.

2.4 Neurovascular anatomy of the joint:

The sterno-costoclavicular articular fibrocartilage, intra-articular disc and capsular structures receive blood supply from an extensive microvascular anastomosis formed by the internal thoracic artery, the intercostal artery, the Costo-cervical and Thyrocervical arteries(Barbaix et al., 2000). The sternal branches of the Supraclavicular nerve, a branch from the lateral pectoral nerve and filaments from the nerve to the Subclavius muscles innervate the sterno-costoclavicular joint capsule and ligaments(Emura et al., 2025; Standring, 2016). The deep afferent mechanoreceptors of the Subclavius tendon and the action of the muscle have an intimate relationship with the costoclavicular ligament and intra-articular structures because of the shared innervation by the nerve to the Subclavius(Standring, 2016).

3.0 Impact of architectural characteristics of the joint on its kinematics:

Functionally, whether the opposing articular surfaces of the Sterno-costoclavicular joint are reciprocal, like the saddle-shaped first carpometacarpal joint without an intraarticular disc, to be called truly a saddle joint is questionable. There is a lack of complete congruency and concentricity between the corresponding articular surfaces and the intervening space-filling articular disc. Nor is it appropriate to call it “ball and socket” due to the lack of one or the other surface being remarkably convex sitting in a concavity. Indeed, the sternal end articular surface of the clavicle, built up with a thick fibrocartilage layer covering two-thirds of the bony surface, becoming “saddle-shaped”, does provide some degree of concentricity to the lateral side compartment of the joint. The two orthogonal axii corresponding to the concave and convex curves, do tend to allow coronal and transverse plane movements of the clavicle during arm elevation.

The incongruency, along with the flexible intra-articular disc forming dual synovial joint cavities for joint conformity, the laxity of capsuloligamentous structures, the cam effect of the conical posterior articular margin, and the sternocostoclavicular joint— which admits translatory, vertical and horizontal angular movements, as well as limited axial rotation with increasing degree of freedom to the clavicle —render the sterno-costoclavicular articulation a nonconventional type of universal joint. Most importantly, it is the thick and thin parts of the capsule, the strategic arrangement of the ligaments, the peripheral attachments of the intra-articular disc, and the Subclavius muscle that maintain the versatility and stability of the incongruent sternoclavicular joint.

With increasing overhead working load, the incongruency and lack of concentricity of the articular surfaces means that, the thrust of the clavicle’s sternal end against the shallow articular concavity of the clavicular fossa acts like the thrusting end of a pole into the vault box during pole-vaulting. Repetitive axial thrust and conjunct rotation of the clavicle apply shear loads against the clavicular fossa, leading to work- and age-related wear and tear, perforation of the articular disc, and arthrosis, with disintegration of saddle contour of the articular cartilage (**Fig. 2**).

4.0 Kinematics of sterno-costoclavicular joint:

All geometrical axii and planes of a moving body part are relative to a virtual vertical plumbline passing through the centre of gravity and the median plane of the body. In clinical practice, it has become acceptable to consider the movements of the humerus at the glenohumeral joint in all planes and axii as reliable and reproducible, serving as a proxy to the kinematics of the clavicle and those of the sterno-costoclavicular joint. However, the resting state of the clavicle and the humerus are in different orientations to each other; therefore, the kinematics of the humerus cannot be an accurate surrogate of the clavicle’s kinematics at the sterno-costoclavicular articulation, with intervening acromioclavicular joint and the scapulothoracic synsarcosis.

The translatory movements of a freely mobile joint occur between contiguous surfaces, regardless of its surface features. In angular movement between the two spherical surfaces of articulating bones, the angle increases and decreases during extension-flexion and adduction-abduction, moving towards or away from the median plane of the body— the rotation occurs around the central or eccentric longitudinal axis of the bone. The nearly horizontal clavicle, from its resting position, exhibits multiplanar and multiaxial angular movements at the sternocostoclavicular joint, with ascent and descent of the arm in various planes via movements at the acromiohumeral and scapulothoracic synsarcosis and acromioclavicular joint.

During arm elevation, the clavicle's cranial and caudal movements— ascending and descending —in conjunction with protraction and retraction, are accompanied by ventral (anterior) and dorsal (posterior) axial rotation around the mechanical and screw axii (**Fig. 3**). The combination of elevation, retraction and rotation produces a rolling

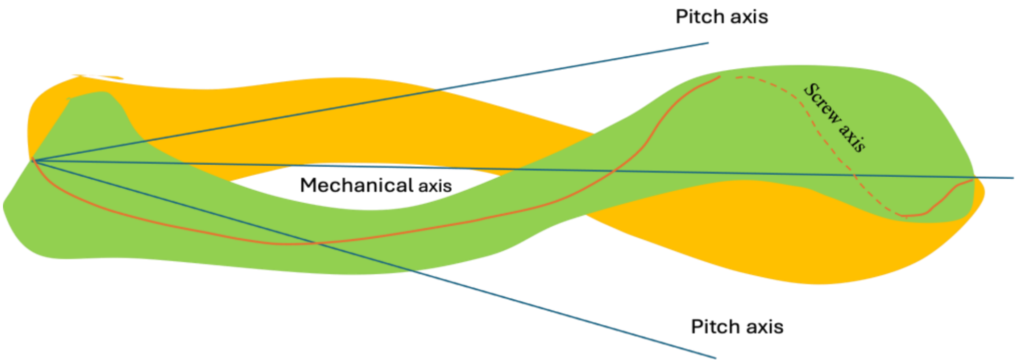


Figure 3. Illustration showing axial rotation of the clavicle around the mechanical axis and the helical screw axis, following the offset between the curves and screw twist (created in PowerPoint).

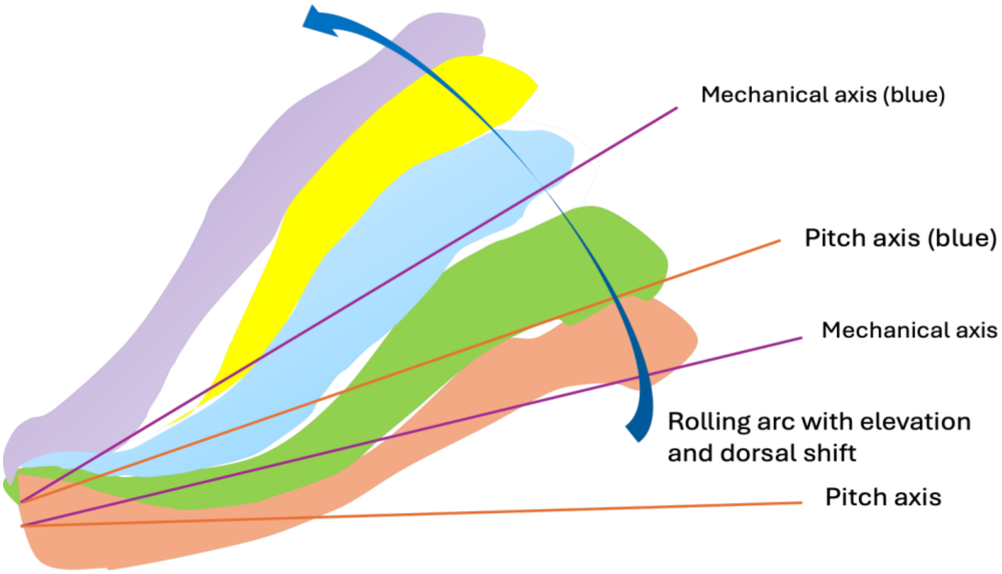


Figure 4. Illustration depicting the rolling motion of the clavicle during arm elevation (created in PowerPoint).

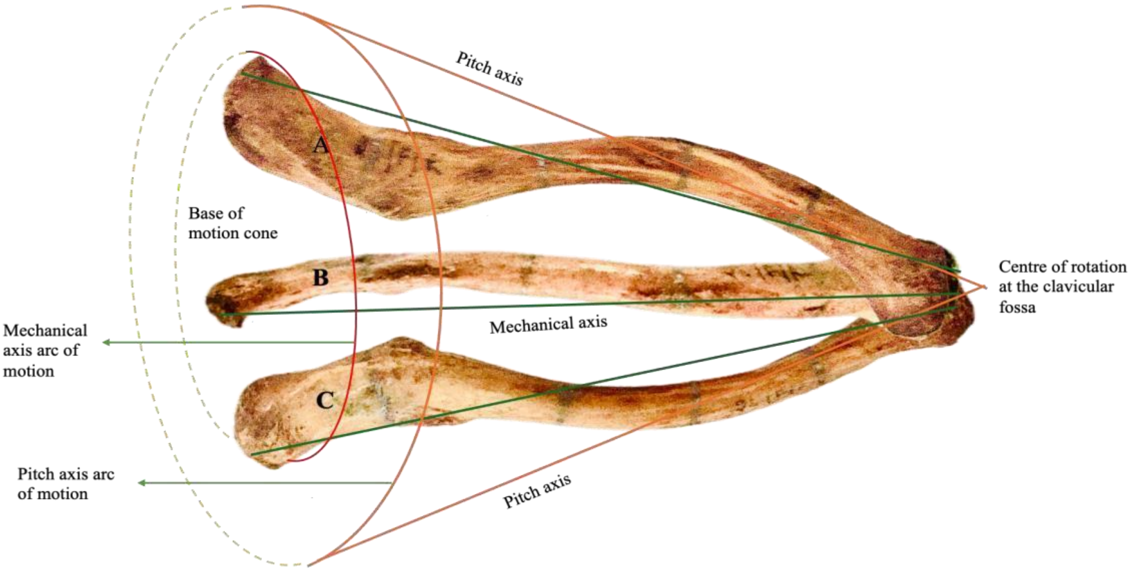


Figure 5 Illustration depicting the rotation of a disarticulated clavicle around the mechanical and pitch axii, forming the motion cone and functional motion arc at the acromial end. Clavicle **B.** shows the anterior surface, **A.** the inferior surface and **C.** the superior surface (created in PowerPoint).

motion around the pitch axis (**Fig. 4**). The circumduction at the sterno-costoclavicular joint, the rolling motion of the articulated clavicle, at its acromial end, circumscribes a conical shape having an asymmetric, oblique and elliptical base with its apex in the clavicular fossa of the manubrium sterni **(Fig. 5)**. In the sagittal plane arm elevation, compared to the coronal plane, the acromial end of the rolling clavicle circumscribes a similar but much smaller arc. The formation of the asymmetric base of the motion cone in an articulated clavicle is due to its anatomical orientation and biplanar offset between the opposing medial and lateral curvatures, laterally concentrated inferior curvature, the associated variable distribution of the diaphyseal torsion angle and the version angle between the proximal and distal articular surfaces; and the torsion angle of the acromion articulating with the clavicle. The setting of the lateral curve offset posterior to the medial curve facilitates rapid dorsal advancement of the clavicle's acromial end, while simultaneously cranking to elevate the scapula with posterior tilt during high-velocity projectile delivery.

The clavicle is not a straight bar or a strut, so its anatomical axis does not follow a straight centreline. It rotates around a straight longitudinal mechanical axis and intrinsic elements following the torsional path around the screw axis of the screw twist, passing through eccentrically placed centroids of the sternal and acromial end articular surfaces. The rolling of the clavicle and the intricate phenomenon of its axial rotational are not an isolated kinematic event. They occur as conjunct motion during arm elevation. Inman and colleague demonstrated the rotational motion from ventral to dorsum in a living subject by placing a Kirschner wire perpendicular to the anterior surface of the clavicle rather than to its longitudinal mechanical axis(Inman & Saunders, 1946).

It is the orientation and degree of laxity of various components of the capsule and ligaments that confer variable degrees of multiplanar and multiaxial motions to the clavicle at the sterno-costoclavicular joint. The movements of the clavicle are more extensive between the clavicle's sternal end articular surface and the intra-articular disc than between the disc and the manubrium sterni(Standring, 2016). Elevation and depression of the clavicle occur at the clavicle and the disc surface. In contrast, protraction and retraction occurs between the disc and articular surface of the manubrium sterni(Barbaix et al., 2000). At the same time, the sternal end of the clavicle glides or translates within the clavicular fossa around the extracapsular fulcrum at the costoclavicular ligament(Kapandji, 2005).

During coronal plane abduction, when the clavicle has achieved full elevation and retracted with accompanying dorsal (posterior) axial rotation, the joint attains a close-packed position. As the sternal end of the clavicle translates anteriorly, the anterior joint capsule, anterior sternoclavicular ligament, and the anterior lamina of the costoclavicular ligament tighten. In response, the sternal end of the clavicle, when pushed against the tightened anterior structures, slides posteriorly. It is the thin and elastic anterior sternoclavicular ligament that accommodates the advancing sternal end, while supported by the thicker posterior capsule. With progressive dorsal axial rotation and rolling *(elevation and retraction)* of the clavicle, the gradual engagement of the posterior inferior conical projection of variable prominence at the sternal end, plays a substantial role in the sterno-costoclavicular articulation, functioning like a cam. Theoretically, the cam mechanism, combined with already maximum elevation of the acromial end, passively provides additional elevation of the clavicle, finalizing the coronal and scapular plane abduction during high velocity projectile delivery.

Approximately 35 degrees of elevation, 10 degrees of depression, 35 degrees of protraction and retraction and 4550 degrees of axial rotation of the clavicle occur at the sterno-costoclavicular joint(Inman et al., 1944). The anterior or ventral axial rotation of 8-10 degrees and posterior or dorsal rotation of 45 degrees are resisted by the capsule and the ligaments. Most of the elevation of the clavicle occurs during 30-90 degrees of abduction of the humerus, and rotation begins after 70-80 degrees of abduction of the humerus(Inman et al., 1944). The elevation and rotation of the clavicle at the sterno-costoclavicular joint allow 40-60 degrees of excursion of the arm relative to the thorax around the sterno-costoclavicular joint(Wood, 1986). The sterno-costoclavicular joint contributes 4 degrees of motion for every 10 degrees of humeral abduction(Renfree & Wright, 2003). Aside from axial rotation, cranial elevation and retraction, equivalent to shrugging, bracing and hugging, can occur independently and conjunctively during the humerus elevation in various proportions depending on the task.

The tension developed in the entire costoclavicular ligamentous complex resists superior translation of the clavicle. The anterior capsule and posterior sternoclavicular ligament resist protraction and retraction of the clavicle. The anterior capsule opposes the retraction, while the anterior sternoclavicular ligament and costoclavicular ligament oppose the protraction. The posterior capsule is considered the principal restraint to anterior and posterior translations(Spencer et al., 2002). However, the costoclavicular ligament is the primary restraint to the movements of the sterno-costoclavicular joint(Kapandji, 2005; Tubbs et al., 2009). At full abduction, with rotation and posterior tilt of the scapula and dorsal rotation of the clavicle, the sterno-costoclavicular joint remains stable due to close packing position of the joint, to carry an overhead load(Standring, 2016).

The restraint caused by the saddle design results in recurrent oblique compression and tensile eccentric loading, which impact the articular disc with overhead weights and high shear forces, due to repetitive translation and rotation of the clavicle, during high-velocity throwing, leading to its rapid degeneration and disintegration. In general populations although not common— over long periods, frequently applied moderate localized pressure due to incongruency —the articular disc and the articular cartilage tend to show age related wear in later decades, causing perforation with a prevalence range of 30 to 56%, as reported in several studies(Barbaix et al., 2000; DePalma, 1963; Van Tongel et al., 2012). The intra-articular disc and synovial lining likely prevent rapid wear of well vascularized articular fibrocartilage, which has healing potential in the early years against 'pestle-mortar' type of rotational and translatory grinding shear forces.

5.0 Acromioclavicular articulation:

The acromioclavicular articulation is a diarthrodial synovial joint between the lateral end of the clavicle and the anteromedial margin of the acromion. A fibrocartilaginous intra-articular disc is rarely present, and when present, it divides the joint cavity wholly or partially into two compartments. It is incomplete inferiorly beyond the second decade of life(Standring, 2016). When complete, it forms two separate synovial articulations. Otherwise, there is only a single layer of the synovial lining.

The joint cavity first becomes evident between the ages of 3 and 5 years(DePalma et al., 1949; Renfree & Wright, 2003; Tiurina, 1985). Only the anterolateral part of the clavicle's acromial end has an oval-shaped articular surface, which make a vertical butt joint with the acromion. Alternatively, the articular surface of the clavicle facing laterally may be directed inferiorly and posteriorly at varying angles, overlapping the matching opposing articular surface of the acromion. The varying angular orientations of the joint, inclined at different degrees to the sagittal plane, range from 20 to 50 degrees(DePalma Anthony F & Edward James, 1957; Renfree & Wright, 2003). These variations can be incongruous in up to 20%(Urist M. R., 1946). The most common type of joint orientation is where the clavicle is overriding, and the least common is where the acromion is overriding. After the age of 17 years, the articular cartilage on the acromial end of the clavicle begins to change, and by the age of 23 years, the existing hyaline articular cartilage of the acromion transforms into fibrocartilage(Tiurina, 1985). An articular capsule, superior and inferior acromioclavicular ligaments, intra-articular disc, and an extra-articular coracoclavicular ligamentous complex with two distinct components, conoid and trapezoid, supports the articulating ends.

5.1 Joint capsule and ligaments:

The superior and inferior acromioclavicular ligaments strengthen the thin fibrous capsule of the acromioclavicular joint. The capsule completely envelops the articular margins on all four sides, which are thicker superiorly and posteriorly than on the anterior and inferior aspects(Stine & Vangsness, 2009). The tendinous aponeurotic fibres of the Occipitocleidal trapezius and Cleidobrachialis deltoideus muscles insert on the acromion and the clavicle by interlacing with parallel fibres of the quadrilateral superior acromioclavicular ligament. This arrangement of the fibres fully covers and reinforces the joint's superior aspect. The reinforced superior acromioclavicular ligament can be as thick as 5.4 mm(Salter et al., 1987). The intra-articular disc attaches to the deep surface of the ligament. The much thinner inferior acromioclavicular ligament is often incomplete. The ligament is attached to the undersurface of the articulating bones adjacent to the articular margins and connects with the intra-articular disc. It forms a part of the ceiling over the subacromial space. Subsequently, the inferior acromioclavicular ligament faces the rotator cuff, particularly the Supraspinatus tendon, in the resting position of the humerus.

5.2 Coracoclavicular ligament complex:

The two-component coracoclavicular ligament complex is unlike any other ligament in the skeletal system because it is entirely extraarticular at a distance from the acromioclavicular joint. The closest structural analogue to it is the extensive interosseous membrane between the radius and ulna in the forearm and the tibia and fibula in the leg. Functionally, the conoid ligament is the key component, acting like a fulcrum to assist the axial rotation of the clavicle. When disrupted, the kinematics of the paired bones— the clavicle and the scapula —are significantly affected in performance and power generation. Therefore, functionally like the ulna and radius, the tibia and fibula, the scapula is the 'sister bone' of the clavicle.

To this anatomical tether can be added the much-ignored importance of the clavipectoral fascia, which blends with the periosteum on the posterior surface of the clavicle and descends to the coracoid process and pectoral fascia, acting like a tensegrity membrane, as the suspensory ligament to the axillary fascia, forming the floor of the axilla. These three structures play subtle yet important biomechanical roles during high-velocity projectile delivery, stabilizing the upper extremity to oppose the centrifugal forces during acceleration and smoothing the deceleration of the returning arm to rest. In a cadaveric biomechanical experiment, the coracoclavicular ligament subtraction by excising or dividing one component at a time could be informative, but it will only provide their passive role in the stability and partially motion-directing function.

The distinctive anatomy and orientation of the coracoclavicular ligamentous complex connecting the clavicle to the scapula has two components, the conoid and the trapezoid **(Fig. 6)**. They are separated by fatty tissue or a bursa(Standring, 2016). Anatomically, the coracoclavicular ligament provides extra-articular reinforcement and

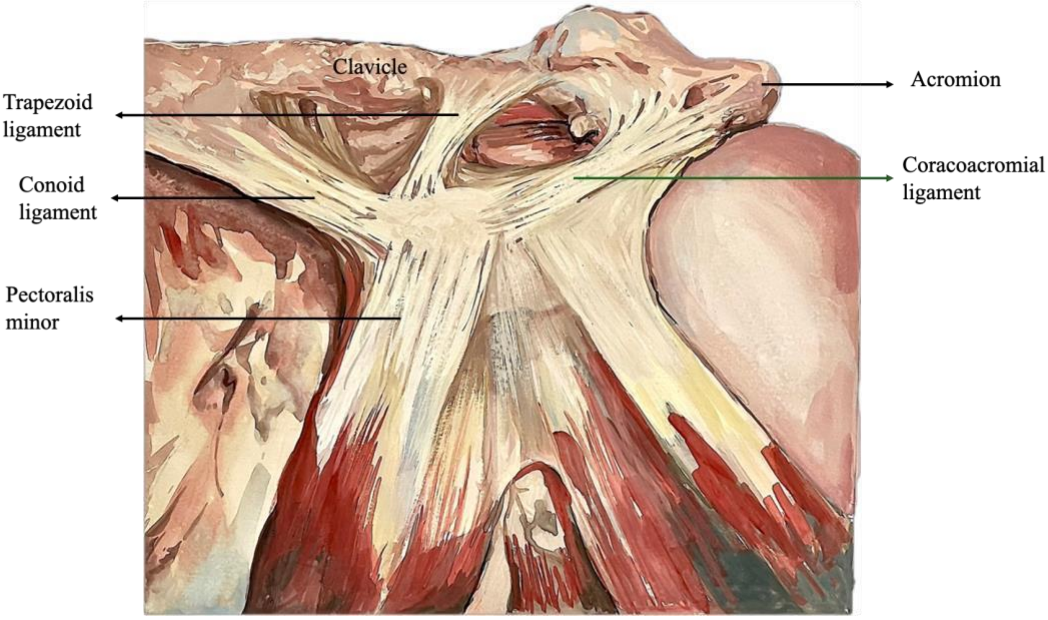


Figure 6. Artwork - schematic drawing of ligaments and other structures attached to the coracoid process.

stability to the acromioclavicular joint, forming the suspensory ligament of the scapula, playing an important role in the kinematics of the clavicle and, indirectly, the upper extremity.

The conical arrangement of fibres forming the thick conoid ligament is medial and posterior to the trapezoid ligament. The apex of the conical ligament is attached to the base of the coracoid process, contiguous to the superior transverse scapular ligament. It extends to the posteromedial surface up to the angulation of the coracoid process. Above, the expanded base of the cone is attached to the conoid tuberosity, edging on the clavicle's posterior border and extending to the trapezoid ridge, directed laterally and anteriorly. The thin quadrilateral fasciculus of the trapezoid ligament is directed obliquely and laterally, anterior to the conoid component. Below, it is attached to the superior surface of the horizontal part of the coracoid process and proximally to the oblique trapezoid ridge on the inferior surface of the clavicle, almost reaching the acromioclavicular articulation. Its anterior border is free, and the posterior border forms an angle with the conoid ligament, which opens medially(Standring, 2016). The coracoclavicular ligamentous complex is related anteriorly to the Subclavius and deep surface of the Cleidobrachialis deltoideus muscle and posteriorly at the posterior border of the clavicle to the Occipitocleidal trapezius muscle insertion on the clavicle.

Biomechanically, the ligament complex, in conjunction with the clavicle, forms a part of the suspension system that enables translation and tilting, protraction and retraction of the scapula at the scapulothoracic synsarcosis. Disruption of the acromioclavicular joint and its extension to the coracoclavicular component(s) affects the kinematics of the sterno-costoclavicular joint, the clavicle's cranking system, scapulothoracic and acromiohumeral synsarcoses and glenohumeral articulation, each to varying degree. The resulting loss of normal upper-extremity suspension reduces performance and power generation in underarm smooth and the overhead high velocity movements.

5.3 Vascular and nerve supply:

The acromioclavicular articulation receives its blood supply from the Suprascapular and Thoracoacromial arteries. Branches from the Suprascapular and Lateral pectoral nerves innervate the joint. A higher density of nociceptors in the inferior acromioclavicular ligament and the capsule forms part of the ceiling of the subacromial space(Borbas et al., 2020; Standring, 2016).

6.0 Kinematics of acromioclavicular articulation:

The acromioclavicular ligaments resist anterior and posterior displacement of the acromioclavicular joint(Standring, 2016). The extraarticular coracoclavicular ligament complex acts like a guy rope, resisting rotation and vertical translation of the clavicle at the joint. The acromioclavicular ligaments resist up to 65% of the forces during daily activities, allowing slight anterior and superior displacements. The conoid ligament helps resist greater loads(Fukuda et al., 1986). The more robust superior acromioclavicular ligament mainly resists dorsal (posterior) axial rotation of the clavicle. The conoid ligament restrains ventral and dorsal axial rotation and displacement of the clavicle at the acromioclavicular joint.

The lengthening and tautness of the conoid ligament, along with ongoing superior displacement and axial rotation of the clavicle intercalated between the manubrium sterni and the acromion, increase the storage of elastic strain energy, which helps in generating nearly 80% of the total torque(Fukuda et al., 1986). The laterally directed oblique fascicles of the trapezoid ligament resist linear axial movement, preventing forceful compression of the clavicle against the acromion(Fukuda et al., 1986). The cumulative compressive and shear forces, during repetitive overhead high-velocity movements, lead to sports- and age-related degenerative changes in the acromioclavicular joint. Depending on the type of activity, the components of the coracoclavicular complex experience an equivalent degree of strain and chronic injury.

The acromioclavicular joint has three degrees of freedom corresponding to three cardinal planes. Subtle variations of planes in which the acromion translates, tilts and swivels will significantly depend on the shape, angle and superior-inferior relationship between the clavicular and acromial facets(Kapandji, 2005). When the clavicle remains stationary, the movements described at the acromioclavicular joint are those of the scapula on the thoracic wall via the acromion. In the transverse plane, the flat acromion projects forward at nearly 90 degrees to the spine of the scapula and the vertical blade of the scapular body. Therefore, the kinematics of the acromioclavicular joint are effectively in a dual orthogonal relationship with the kinematics of the scapulothoracic synsarcosis.

The transverse plane movement of the acromion on the clavicle moves the resting scapula from its coronal plane position in an arc producing protraction and retraction between the coronal and sagittal planes. The acromion translates ventrally (*anterior and medialward as protraction*) and dorsally (*posterior and lateralward as retraction*) on the clavicle, as in hugging and bracing movements of the shoulder around the vertical axis passing through the acromioclavicular joint. The scapular blade when seen from behind translates laterally and medially, away from and towards the vertebral column.

The superior and inferior tilt of the horizontal acromion takes place on the clavicle in the coronal plane around an anterior-posterior axis passing through the acromioclavicular joint, making the scapular blade rotate in the coronal plane. The anterior and posterior tilt of the acromion in the sagittal plane around the mediolateral horizontal axis makes the scapula tilt ventrally and dorsally, facilitating sagittal-plane pitching movements, leaning the superior angle of the scapula anteriorly and posteriorly.

The range of motion at the acromioclavicular joint around various axii varies depending on the orientation and type of facets between the clavicle and the acromion, age-dependent and activity-related degeneration, and experimental methodology. In a two-dimensional radiology-based study, there was 30 degrees of superior tilting of the acromion(Inman et al., 1944). According to a study where Kirschner wires were placed in the spine of the scapula, clavicle and humerus, as the arm was elevated overhead relative to the median and coronal planes, the internal rotation *(protraction)* of the acromion on the clavicle, on average, was 8 degrees, the upward rotation of was 11 degrees, and the dorsal tilt was 19 degrees(Ludewig et al., 2009). The difference in internal and upward rotation across various planes of humerus elevation was dependent on the elevation angle. The acromion is more internally rotated *(protracted)* relative to the clavicle in flexion than in coronal and scapular plane abduction. While the acromion retracts an average of 4 degrees more during forward flexion than abduction.

All studies reporting on the kinematics of the acromioclavicular joint are in conjunction with glenohumeral articulation during elevation of the arm over a varying range of motion. There are no studies examining acromioclavicular joint movements in isolation.

The scapula pivots around the acromioclavicular joint during movements at the scapulothoracic synsarcosis. The acromion glides protracting and retracting in the transverse plane on a vertical axis, abducting-adducting like a hinge in the coronal plane on a horizontal anteroposterior axis, and tilts in the sagittal plane on a mediolateral axis. At the acromioclavicular joint, these movements complement those of the sterno-costoclavicular joint, regulating scapulothoracic movements during abduction, flexion, and extension of the humerus. The acromion translates on the clavicle with ipsilateral mopping movements of the arm in an arc when the clavicle is held in place, and the clavicle translates on the acromion when the contralateral shoulder with torso is rotated forward towards it, and the ipsilateral acromion is fixed in its place.

At the acromioclavicular joint, the dorsal and ventral axial rotation of the clavicle is resisted and limited by the acromioclavicular, conoid and trapezoid ligaments by their very arrangement. The orientation and density of fibres confer tautness and slackness to the fibres, opposing or favouring a particular motion by becoming taut or lax. Density of the fibres is for strength, while laxity allows a range of motion. Under proprioceptive response, during active motion the tightness of the ligaments controls the resultant direction of the motion, adding optimal torque for the best possible performance and energy storage at the tissue level.

The clavicle motion at the acromioclavicular joint is reciprocal to that at the sterno-costoclavicular joint during elevation, as in shrugging. Similarly, there is reciprocal movement of the acromial and sternal ends of the clavicle during retraction and protraction in the transverse plane. Axial rotation of the clavicle cannot occur independently at the acromioclavicular joint. It occurs in conjunction with that of the sterno-costoclavicular joint, when the conoid ligament is taut, acting as a pivoting point (fulcrum), during elevation of the acromial end. The clavicle continues to rotate dorsally as a co-ordinated movement during arm elevation.

The motion of the intercalated clavicle between the sterno-costoclavicular and acromioclavicular joints is guided and restrained by the coracoclavicular ligament complex. The clavicle couples with the scapula at the acromioclavicular joint for the movements of the scapulothoracic synsarcosis and normal performance of the glenohumeral articulation. Therefore, the normal and abnormal functioning of one linkage and movements at the associated joint(s) inevitably affect the other linkage(s).

7.0 Scapulothoracic synsarcosis (A soft compliant articulation):

The Greek 'Skapto' meaning to dig, the spade-like shape of the scapula, and its role in digging among fossorial ancestors hardly applies to dorsolateral position of the scapula in humans. The scapulothoracic synsarcosis, a highly mobile soft-tissue articulation, offers versatile kinematics that enhances the kinetics of the pectoral girdle.

The scapula acts as a sliding link on the 'fixed' stable expansive platform provided by the dorsolateral aspect of the upper thoracic wall. It is suspended by coracoclavicular ligamentous complex and the acromioclavicular articulation at the lateral end of the clavicle, which in turn articulates to the manubrium sterni in the median plane. One-half of the pectoral girdle linkages involve multiple groups of muscles working with the contralateral side. The clavicle is inclined in two planes— elevated and retracted —and features curves and twists to place the scapula in position for normal function of the glenohumeral articulation. When at rest, the two bones form a 60-degree angle, opening medially at the root of the neck and facing the thorax(Kapandji, 2005).

The biomechanical anatomy and triplane kinematics of the scapula constantly orient the glenoid fossa to place it congruently under the translating and rotating humeral head in all three planes, making combinations of angular movements such as abduction-adduction, flexion-extension, and internal-external axial rotation. Hence, the scapula faces the trickiest of all situations with its' flame-shaped glenoid to catch the shifting head of the humerus. Even though the reach of the scapula as a slider is limited, it is exceptionally versatile because of the co-ordination of several muscle groups acting synergistically as agonists and antagonists at various stages of the humeral head movement, keeping track of humeral head's whereabouts. This is a ligament-based proprioceptive phenomenon that collaborates with the musculotendinous sensory apparatus and the articular surfaces. The various groups— the scapulothoracic muscles, the scapulohumeral muscles and the Cleidocranial and Cleidobrachialis muscles — act as force couples, synergistically translating the scapular body in protraction-retraction, superior-inferior direction, and turning clockwise and counterclockwise when seen from behind, along with sagittal anterior-posterior tilt and swivelling of the scapula.

7.1 Structure of scapulothoracic synsarcosis:

The Scapulothoracic synsarcosis is a "false joint" because the articulating bones do not have the covering articular hyaline cartilage or a fibrocartilage layer, and a synovial membrane. The absence of capsuloligamentous structures makes it a highly mobile gliding joint, which allows composite articulating movements between the scapula and the dorsolateral thoracic rib cage. As a result, it is an unusual diarthrodial joint in its rare sense. Areolar tissue and lubricating tissue fluid occupy the spaces between the intervening muscle layers, separating the scapula's costal surface from the underlying rib cage. The curved costal surface of the scapula almost matches the curvature of the ribcage, forming a concentric and congruent articulation. The scapula forms a 30-degree angle to the rear coronal

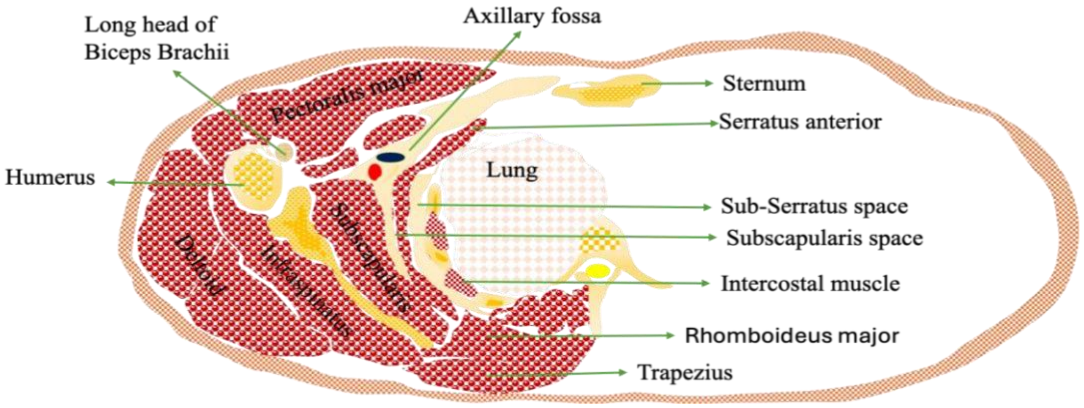


Figure 7. Illustration showing cross-section of the thorax just inferior to the spine of the scapula (created in PowerPoint).

plane, which is open anterolaterally(Kapandji, 2005). When at rest, the scapula overlies the second to the seventh ribs. Its medial border is approximately 6 cm lateral to the thoracic spinous processes, forming an angle of 3 degrees to the sagittal plane(Kapandji, 2005).

The scapulothoracic synsarcosis has two compartments between the osseous elements of the thoracic cage and the deep surface of the scapular body. The superficial space is bounded posteriorly by the costal surface of the scapula and the Subscapularis muscle, and anteriorly by the Serratus anterior muscle in the scapular plane (**Fig. 7**). The expansive Subscapularis muscle fills the entire costal surface of the scapula and contributes to the posterior axillary wall.

The serratus anterior arises by fleshy digitations from the outer surfaces and superior borders of the upper eight to ten ribs, and the fasciae covering the intervening intercostal muscles. Following the contour of the rib cage, the sweeping muscular sheet of the Serratus anterior wraps around the thorax to insert on the vertebral border of the scapula, deep to the Subscapularis, starting from the superior angle and the costal surface of its medial border by musculotendinous fibres to a triangular footprint on the costal surface of the inferior angle. Anterolaterally, the superficial space communicates with intermuscular spaces and the axillary fossa.

The deeper second compartment lies between the Serratus anterior and the ribs, with the intercostal muscles covered by a fascial layer. The space opens medially to the paravertebral muscles, with the overlying Rhomboids and the middle and inferior parts of the Trapezius muscle extending down to the spinous process of the twelfth thoracic vertebra. Anterolaterally, the space is closed by the origin of Serratus anterior digitations from the second to the twelfth ribs. The layers are lubricated with extracellular tissue fluid, providing a wet, sliding surface comparable to a synovial joint.

7.2 Innervation of the scapulothoracic synsarcosis:

The Long thoracic nerve, with root values of C5, C6, and C7, innervates digitations of the Serratus anterior muscle. The Subscapularis receives its nerve supply from the upper and lower subscapular nerves C5 and C6, branches of the posterior cord of the Brachial plexus. The accessory nerve innervates the Trapezius muscle for its motor supply, and the sensory supply comes from C2, C3 and C4. Rhomboids receive a branch of the Dorsal scapular nerve, with root values of C4 and C5.

8.0 Kinematic operations of scapulothoracic synsarcosis:

During abduction and external rotation of the humerus, the three-dimensional movement of the scapula at the scapulothoracic synsarcosis is synergistically conducted motion of the clavicle between the sterno-costoclavicular and acromioclavicular joints in all the three planes(Zuckerman & Matsen, 1989). Successful placing of the hand in a desired position is a conjunct movement of the scapula and clavicle with that of the humerus. Any alteration in the normal function of the clavicle will be associated with the malfunction of the scapula at the scapulothoracic synsarcosis. Such scapular dyskinesis can result in dysfunction of the glenohumeral articulation and ultimately reduce the precision of hand placement in space.

Without the normal conduct of the clavicle, the transmitted axial forces of the kinetic chain will progressively cause 'rickety' movements of the distal segments. Because all skeletal links serve as origin and fixation points for the action of muscles at their insertion points. The origin of a muscle is often far from the centre of rotation on the joint surface. A vector-led line of action to generate an optimal force or torque may act on one or more linkages, often acting simultaneously (*conjunct action*) and less frequently in tandem but as an aide-de-camp (*adjunct action*). Therefore, any alteration in the point of origin, or changes to the length-tension relationship of the muscle fibres, or their point of insertion, would change the length of the moment arm and line of action of a muscle. It would create dysfunctional, frustrated movement at a specific joint, especially if the restriction occurs at the end of the range of motion, limiting the manoeuvre.

For demanding movements and at rest, various force couples stabilize the scapula in a state of equilibrium. During a smooth, speedy and balanced motion, several muscles with synergistic conjunct and adjunct actions act synchronously. The agonists set the scapula in motion, and the antagonists resist initial motion to prevent unregulated movements. Acting simultaneously, the agonists proceed to move the linkage at the articulation. The trajectory of the end effector organ, the hand, moves to the desired position. This coordinated process of a motion must have control, a neuromuscular mechanism at the central nervous system, with each movement of a joint. Such coordination is critical in scapulothoracic synsarcosis because it does not have capsuloligamentous proprioceptors and physical restraint.

The Trapezius and Serratus anterior muscles are prime movers of the scapula(Standring, 2016). The middle and inferior heads of the Trapezius, coupled with the middle and inferior digitations of the Serratus anterior, are key to congruent clockface rotation and simultaneous protraction of the scapula away from the median plane, raising the upper border of the scapula and tilting it posteriorly. Theoretically, during overhead abduction and forward flexion of the arm, the posterior tilt is accompanied by the unfolding of scapular body curvature at the root of its spine, storing elastic strain energy, and assist in its return to the resting state, in conjunction with the dorsal to ventral axial rotation of the elevated clavicle. The Occipitocleidal component of the Trapezius muscle, inserted into the clavicle's superior surface and the convex posterior border of the lateral curvature, in conjunction with the Cleidobrachialis deltoideus, causes ventral axial rotation of the clavicle and steadies it initially, at the beginning of abduction. After this initial antagonism, as the "setting phase", and at the end of abduction, on descent, the two muscles actively reverse the dorsal axial rotation and rolling of the clavicle, assisted by the Cleidobrachialis pectoralis and the elastic strain acquired by the clavicle, during the arm elevation.

During the descent of the elevated humerus, depression of the clavicle and anterior tilt of the scapula with engagement of the Pectoralis minor, the transverse middle fibres of the Trapezius act to return the scapula to its original position, also assisting in repositioning the clavicle. The pectoralis minor, acting at the coracoid process, stabilizes the protracting scapula as a rein to assist the Serratus anterior by its concentric contraction. As the scapula retracts, the Serratus anterior initially acts as an antagonist to stabilize the scapula and coupled with the middle and the inferior heads of the Trapezius, prevent its sudden return to the original position. The pectoralis minor helps guide the scapular motion by its concentric and eccentric contraction during coronal and scapular plane abduction. These force couples, along with solo actors, induce multiplanar and multiaxial motions of the linkages and joints of the pectoral girdle, constantly maintaining an equilibrium based on the principle of tensegrity.

The biomechanical essentials for the operation of a force couple include the moment arm, the line of action, the magnitude of force for equilibrium, and the rate and duration at which it can sustain the tension to attain maximum mechanical advantage. At the molecular level, the contractile mechanism at the level of actin and myosin filaments has led to the concept of muscle tension-length relationship and its graphic bell-shaped representation(Kardong, 2002). The graph illustrates constant tension in a muscle fibre rather than a fixed length of the stimulated muscle. Fixing the same muscle fibre at different lengths following a long bone fracture— either with too much shortening or lengthening with or without angulation —not only affects line of action and changes the length of the moment arm but also alters vectorial properties acting on the linkages and joints. Both shortening and lengthening of a linkage alter the resting actin-myosin overlap, reducing total force at the joint. The correct repositioning of the scapula maintains not only the muscle length-tension relationship but also influences the tension of the glenohumeral capsule and ligaments(Matsen III et al., 2009).

From its insertion on the lateral border of the lesser tuberosity crest of the humerus, the Latissimus dorsi is an internal rotator, adductor, and extensor of the humerus. Indirectly, it rotates the scapula during the abduction of the humerus(Pouliart & Gagey, 2005). The Pectoralis major and Latissimus dorsi, together with the scapulohumeral muscles including Teres major, Subscapularis, Supraspinatus, Infraspinatus and Teres minor, help co-ordinate and stabilize the glenohumeral joint between the scapula and humerus, compressing and fine-tuning the humeral head while the scapula positions the glenoid fossa underneath it, during abduction in coronal and sagittal planes, as the joint has lax capsuloligamentous structures(Lippitt et al., 1993).

In summary, the equilibrium of muscle forces forming a couple as agonists and antagonists through concentric and eccentric contraction, the relative moment arm length of various muscles during the "setting phase", normal actin myosin overlap, and. the balance of tensegrity between the linkages plays a crucial role in generating the normal range of motion and power generation at the scapulothoracic synsarcosis.

9.0 Kinematics of the scapulothoracic synsarcosis:

Technically, the composite movements of the scapula on the thoracic wall surface are multiaxial and multiplanar. They are relative to the median reference plane of the body passing vertically across the vertebral column and the sternum. The plane of Scapulothoracic synsarcosis is at an angle of 30 degrees to the rear coronal plane on the relatively static thoracic frame. It translates smoothly on its surface, like a slider. By anatomical convention, it does not have angular movements like flexion-extension, abduction and adduction as in the case of the limbs moving away from the body, which form an angle with the median plane and other cardinal planes— sagittal, transverse and coronal. When it displaces by sliding away from the median plane with a superior tilt of the acromion, its inferior angle rotates clockwise or counterclockwise around a horizontal axis through the acromioclavicular joint at an angle to the coronal plane.

9.1 Movements of the scapula on the thoracic wall surface:

As the scapula slides along the curved, elliptical surface of the thorax in an arc, most of its costal surface remains in contact with its substratum, engaging several muscle couples that act in equilibrium. The glenoid fossa is steered cranially in posterior or anterior direction, depending on whether the humerus is abducting laterally in coronal and scapular or elevating anteriorly in the sagittal plane. The scapula progresses anteriorly *(protracts)* in an arcuate pathway from its resting dorsolateral 'coronal' plane towards the sagittal plane. The scapula translates back from its advanced position to the dorsolateral station by returning towards the median plane *(retracts)*.

The scapula can be translated vertically in the coronal plane between 5 and 8 cm or more, depending on the height and build of an individual. The angular clockwise *(left scapula)* and counterclockwise *(right scapula)* movement at the inferior angle of the scapula, when seen from behind, can range between 45 and 60 degrees, with lateral displacement of the inferior angle between 10-12 cm from the median plane in the coronal plane during active elevation of the arm, from 0 to 180 degrees(Kapandji, 2005). In the sagittal plane, the scapula tilts from anterior to posterior position, around the medial-to-lateral transverse axis by up to 20 degrees during abduction from 0 to 145 degrees. When the arm is abducted from 0 to 90 degrees in the coronal plane, the swivelling movement around a vertical axis turns the scapula dorsally by 10 degrees to reorient the glenoid fossa laterally in the coronal plane; beyond 90 degrees of abduction, it swivels anteriorly by 6 degrees, only returning to the original resting orientation during adduction(Kapandji, 2005). This biphasic swivelling pattern helps the humeral head to adapt to the coracoacromial arch.

In a recent study with bone pins inserted into the spine of the scapula, during humerus elevation in the scapular plane, the inferior angle of the scapula rotated laterally by 50 degrees, tilted posteriorly by 30 degrees and retracted by 24 degrees(McClure et al., 2001). The movements of the scapula in isolation occur at the acromioclavicular joint when the clavicle is fixed in place so that there is no movement at the sterno-costoclavicular joint. The full clockface scapular movements at the acromioclavicular joint occur only when there are movements at the sternocostoclavicular and the glenohumeral joint. The various local constraints at the sterno-costoclavicular joint and those of acromion at the acromioclavicular joint limit the movement of the clavicle and the clockface movement of the scapula.

9.2 Movements of the scapula at the acromioclavicular joint:

There is limited craniocaudal translation of the scapula in the coronal plane, independent of other elements of the pectoral girdle. Holding the clavicle in place, the scapula moves a little vertically straight up and down, following the elliptical convexity of the thorax with tilting of the acromion at the acromioclavicular joint without movement at the sternoclavicular joint, producing a partial shrug. The clavicle must elevate at the sterno-costoclavicular joint to complete the shrug. The protraction and retraction of the acromion in hugging and bracing movements occur on a vertical axis at the acromioclavicular joint. The most interesting movement of the scapula is tilting (*pitching*) dorsally (*posteriorly*) from its resting ventral (*anterior*) tilt, leaning on the upper dorsal curvature of the thorax. The tilting or pitching movement of the scapula, with the clavicle held down, can be best palpated at the acromioclavicular joint when there is a sagittal plane elevation and depression of the acromion accompanying ascent and descent of the humerus during forward flexion between 80 and 120 degrees, beyond which the thoracic spine exhibits lordotic movement.

During protraction and retraction at the acromioclavicular joint, there is a passive angular movement of widening and narrowing of the angle between the scapula and the clavicle from the resting 60 to 70 degrees on retraction due to the 'wedging' effect of the elliptical cross-section of the thorax. During reversal of retraction, as the clavicle passes the mid-coronal plane of the thorax (*protracts*), the angle between them decreases below 60 degrees(Kapandji, 2005).

The screw axis is located somewhere within a three-dimensional rigid body; the body either translates along it, rotates around it, or produce a conjunct screw motion of rotation and the translation like a machine screw. The pure translatory and rotational movements of the scapula at the acromioclavicular joint follow screw axis movements in different planes with the clavicle held stationary. The screw axis either passes through the acromioclavicular ligaments or through the coracoclavicular ligament attachment on the coracoid process(Sahara et al., 2006). During an open magnetic resonance imaging observation, when the arm is abducted relative to the clavicle, on average, the scapula protracted by 16 degrees, rotated laterally 21.5 degrees on the clockface *(inferior angle and the lateral edge turned laterally)* and tilted dorsally (*posteriorly*) by 22.2 degrees at the acromioclavicular joint(Sahara et al., 2007).

10.0 Conjunctive kinematics of the clavicle at the Sternoclavicular joint:

From its predetermined orientation, the clavicle moves simultaneously in the coronal and transverse planes and around its longitudinal screw axis in varying combinations at the sterno-costoclavicular articulation, during abduction of the humerus in the coronal, scapular and sagittal planes. This composite movement is enabled by the clavicle's toroidal sternal end articular surface, with contouring of the intervening intraarticular fibrocartilage articular disc forming dual compartments and capsuloligamentous structure. The semi-rigid attachment of the clavicle to the coracoid process by the coracoclavicular ligament complex acts as a pivot point for movements of the clavicle between the sterno-costoclavicular and the Acromioclavicular joints. As the conoid ligament elongates and becomes taut during axial rotation of the clavicle, it assists posterior tilting or pitching of the scapula.

Clinically, the humeral elevation in any of the planes is relative to the median plane of the thorax. On average, relative to the cardinal planes at the sterno-costoclavicular joint, humeral elevation in scapular plane is accompanied by 16 degrees of retraction, 6 degrees of elevation and 31 degrees of posterior axial rotation of the clavicle(Ludewig et al., 2009). The retraction and elevation of the clavicle are greater during abduction in the coronal plane than any other plane. In a clinically oriented study, the clavicle retracted 35 degrees, and dorsal axial rotation was 50 degrees by the time the humerus reached an abduction angle of 180 degrees(Abbott & Lucas, 1954). The axial rotation of the clavicle can occur up to 55 degrees, assisting clockface rotation and dorsal tilt of the scapula during the final stages of the arm elevation(Inman & Saunders, 1946).

Throughout arm elevation, the elevation of the clavicle that begins in the initial stages of motion at the glenohumeral joint is nearly complete by the time the humerus reaches 90 degrees of abduction(Inman et al., 1944). For every 10 degrees of elevation of the arm, there are 4 degrees of elevation of the clavicle at the Sternoclavicular articulation. Beyond 90 degrees, the elevation of the clavicle is negligible(Inman et al., 1944). This additional yet negligible elevation of the clavicle is due to the camming effect produced by the posterior-inferior projection of the sternal end lifting the acromial end passively by 5 to 10 degrees or even more depending on the size of the projection.

Although several reports suggest that in the establishment of the pectoral girdle, the absence of a clavicle, whether partial or total excision, the clavicle is functionally a redundant link as essential functions of the girdle are maintained(Abbott & Lucas, 1954; Van Tongel et al., 2015; Wessel & Schaap, 2007). Nonetheless, claviculectomy may adversely affect the strength, overall range of motion and scapulothoracic rhythm(Rubright et al., 2014). Initially, even if patients compensate for the loss of the clavicle with minimal functional deficit, in the long-term follow-up, with loss of compensation, there is a reduction in strength and appearance of scapular dyskinesis(Rubright et al., 2014). The clavicle may be a 'passive' linkage but not at all a redundant player when it comes to the strength and normal movements of the scapula and humerus.

The normal kinematics of the clavicle support regular movements at the scapulothoracic synsarcosis. The native orientation of the clavicle in an elevated and retracted position brings biomechanical advantage to the scapula and glenohumeral kinematics in all the planes. The equilibrating force at the sternal end is Cleidobrachialis pectoralis and Cleidomastoid head of the Sternocleidomastoid. At the acromial end, the couple formed by the Cleidobrachialis deltoideus and the Occipitocleidal trapezius stabilizes the clavicle during the "setting phase". The solo stabilizer of the clavicle is the Subclavius muscle, which maintains its native position relative to the first rib, preserving the infraclavicular neurovascular space, assisted by the clavipectoral fasciae.

11.0 Acromiohumeral synsarcosis:

In literature, the subacromial space has also been called the subdeltoid 'joint'(Kapandji, 2005). It represents the functional space of the acromiohumeral synsarcosis. When the cowling of substantial Deltoid muscle is raised from its origin at the lateral one-third to half of the acromial end of the clavicle, acromioclavicular joint, acromion and the inferior lip of the spine of the scapula, flipping the muscle backwards, hinged on its insertion, the anatomy of the diarthrodial space of acromiohumeral synsarcosis comes into full view (**Fig. 8**).

Figure 8. The author's dissection – The cowling of the deltoid muscle was flipped backwards, exposing the subdeltoid bursa— a hypodermic needle in the bursa.

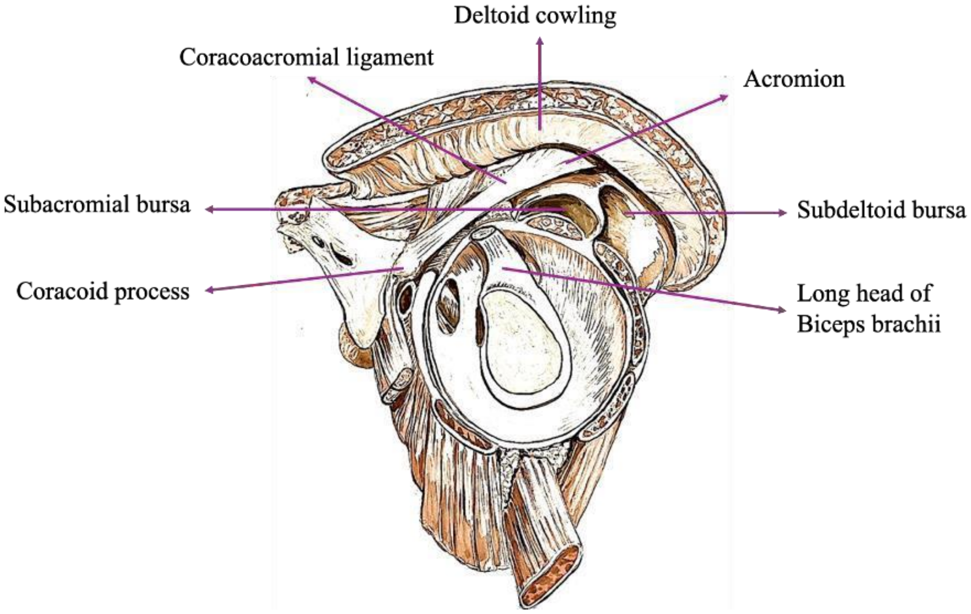


Figure 9. Artwork: An illustration of acromiohumeral synsarcosis in the supraglenoid space. Modified from Standring, S. (2016). Gray's Anatomy: The anatomical basis of clinical practice. In Standring S et al (Ed.), Edinburgh. Elsevier Churchill Livingstone (Forty-First); page 809.

11.1 Structure of acromiohumeral synsarcosis:

The acromiohumeral synsarcosis, a 'soft tissue articulation,' is without an articular cartilage, a capsule or ligaments. It is a 'false' articulation. The space between the osteoligamentous arch above and the humeral head below encloses several soft tissue structures arranged strategically to provide kinematic stability, concentricity and dynamic congruency to its diarthrodial relationship.

Like the scapulothoracic synsarcosis, the absence of articular cartilage confers the advantage of freedom from arthrosis. However, unlike the scapulothoracic synsarcosis, it is confined to much smaller surface area with higher probability of developing high compressive and shear contact points due to lifestyle related overuse activities. Consequently, the epithelial surfaces and subsequent structures of the synsarcosis are disadvantaged by impingement and friction, leading to inflammation, attenuation and atrophy of the soft tissues. The space is bound superiorly by the concave undersurface of the coracoid process, coracoacromial ligament, inferior acromioclavicular ligament, and the acromial arch **(Fig. 9)**. The ceiling of the space is smooth, flat, or curved, with varying curvature radii depending on the variational anatomy of the acromion(Biglani et al., 1986; MacGillivary et al., 1998). There is a gradual transition from a flat acromion in the second decade of life to increased curvature in its mid-sagittal and lateral-sagittal planes, as well as greater forward angulation over the humeral head, with increasing age(MacGillivary et al., 1998).

Inferiorly, the space is bound by the convex humeral head and its tuberosities, with its articular surface covered by the capsule of the glenohumeral joint, the superior glenohumeral ligament, and the coracohumeral ligament arising from the base of the coracoid process blending with the rotator cuff tendons, inserting into the humeral tuberosities. Deep to the glenohumeral capsule is the extra-synovial long head of the Biceps brachii tendon lying in the rotator interval between the Subscapularis and Supraspinatus muscles. The rotator cuff muscles, superficial to the glenohumeral capsule arise from the costal and dorsal surface of the scapula, and their tendons insert on the tuberosities of the humeral head. From anterior to posterior, the Subscapularis inserts on the lesser tuberosity; the Supraspinatus, Infraspinatus, and Teres minor insert on the superior surface of greater tuberosity, blending with the capsule, and merging at the anatomical neck of the humerus(Clark & Harryman, 1992).

As a result of the age-related variations in the curvature of the acromion, there can be altered geometry and volume of acromiohumeral space. The space can be further compromised following a malunited fracture of the clavicle, depending on the morphology of the acromion, the underlying humeral head and the stability of the glenohumeral articulation due to soft tissue degeneration.

11.2 Potential motion spaces:

Like any other large diarthrodial synovial articulation, the acromiohumeral synsarcosis has a watertight potential space extending from under the coracoid process to the middle of the acromion, lined by two serous membranes, often referred to as a bursa. There are several potential bursal spaces between the concave coracoacromial arch and the convexity of the humeral head in the supraglenoid region(Klatte-Schulz et al., 2022; Lie & Mast, 1982; Standring, 2016).

The superficial space between the coracoacromial arch and the superior surface of the rotator cuff tendons, more precisely, the Supraspinatus tendon, with variable extensions, either as multiple loculated spaces or a single space known as the subdeltoid bursa, which is commonly referred to as subacromial bursa. The deeper submuscular space contains bursae that separate the rotator cuff tendons from the joint capsule, except for the Supraspinatus and Teres minor. There is a constant bursa between the tendon of the Subscapularis and the capsule, as it changes its direction to insert on the lesser tuberosity. A bursa between the infraspinatus and the capsule occasionally communicates with the joint; another one lies between the Teres major and the long head of the Triceps brachii. As a separate entity within the complex of acromiohumeral synsarcosis, the Subscapularis bursa communicates directly with the synovial cavity of the glenohumeral joint.

Figure 10. The author's dissection – A single subdeltoid bursa laid open over the humeral head.

The large superficial subdeltoid bursa, spreading out under the acromion, coracoacromial ligament and the coracoid process does not communicate with the joint (**Fig. 10**). This bursa made of two layers of serous membrane, is often met as three sacs: subdeltoid, subcoracoid, and subacromial, with partial or complete partitions (Codman, 1934; Lie & Mast, 1982; Strizak et al., 1982). They had been demonstrated using the bursography technique in the past(Lie & Mast, 1982; Strizak et al., 1982). The reflections of subdeltoid bursal membrane form lateral, anterior, medial and posterior boundaries that extend anteriorly to the insertion of the conjoint tendon of the Coracobrachialis and short head of the Biceps Brachii, medially to the coracoclavicular ligament complex and laterally and posteriorly under the Deltoid(Matthews & Fadale, 1989). The reflections of the bursa limit the gliding plane of the acromiohumeral synsarcosis. In a healthy articulation, the potential spaces of the subdeltoid bursa are filled with a lubricating film of viscous fluid secreted by the lining endothelium. The endothelium has a layer of synoviocytes and immune cells with the organized architecture of fibrous tissue as the sublayer, which consists of fibrocytes, a few vessels but no nerve fibres(Minkwitz et al., 2021).

Recurrent physical injury and chronic inflammation fill these potential spaces with inflammatory fluid, forming recognizable fluid-filled sacs, resulting in bursitis. The inflammatory fluid, with altered rheological properties, exhibits poor lubrication, leading to loss of cohesion between the bursal membranes and altering the biomechanics of composite structure of the acromiohumeral synsarcosis. With increased vascularity and appearance of the nerve fibres, it becomes the epicentre of experienced pain(Minkwitz et al., 2021).

11.3 Physiology of acromiohumeral synsarcosis:

The concave undersurface of the coracoacromial arch articulates congruently with the convexity of the humeral head(Matsen III et al., 2009). The centre of rotation of the acromiohumeral synsarcosis coincides with the centre of the glenohumeral articulation in a normal shoulder, except that the length of their radii varies because of the thickness of intervening capsuloligamentous and rotator cuff structures. There is a definitive concentric relationship between the space of the acromiohumeral synsarcosis and glenohumeral articulation, centring the glenoid fossa under the humeral head(Matsen III et al., 2009). The glenohumeral joint is extrinsically stabilized by a spherical nimbus of atmospheric pressure surrounding the surface of the shoulder complex and intracapsular subatmospheric pressure, in addition to the synovial fluid surface tension.

The lubricating film of the viscid fluid separating the two membranous layers creates a cohesive force due to fluid surface tension and its shear strength, generating a low shear resistance favouring gliding motion. In a normal acromiohumeral synsarcosis, the negative pressure (*sub-atmospheric*) and cohesion of membranes maintain a constant distance between the concave coracoacromial arch and the convex head of the humerus to stabilize the congruent tracking of acromiohumeral motion(Matsen III et al., 2009). It prevents the displacement and falling away of the humeral head from the coracoacromial arch during forward thrusting of the arm, carrying heavy pendular weights, and high-velocity delivery of projectiles. Recurrent forceful high-velocity movements at the glenohumeral articulations cause joint distraction, leading to a further drop in the negative pressure in the acromiohumeral synsarcosis space, sucking the lax glenohumeral capsule into the joint space(Habermeyer et al., 1992). This disrupts the fluid mechanics within the potential bursal spaces of the acromiohumeral synsarcosis, ultimately disturbing its' concentricity and congruency.

The musculotendinous structures and the intervening epithelized serous spaces filled with fluid film potentially bind the articulating surfaces of the glenohumeral joint. The biomechanics and the contours of these structures stabilize the moving bone elements throughout arm elevation. Thereby generating a uniform "scapulohumeral rhythm" with individual-specific constancy under normal physiological conditions. Changes in volume and pressure within the acromiohumeral synsarcosis would alter the ascent and descent of the humeral head, producing injury-related pathology.

Any periarticular breach, whether through an arthroscopic portal or even a needle puncture, would bring the extracapsular interstitial tissues and intracapsular space to equalize with atmospheric pressure. It would distort and displace the pre-existing arrangement of tissues. As a result, the natural anatomy of the joint might not be apparent. In this regard, all cadaveric studies are static and can be misleading. While cadaveric biomechanical experiments are excellent study tools, they cannot be directly translated to living individuals for clinical applications, due to varied population morphologies, morphometric parameters and experimental conditions.

12.0 Relationship of long head of the Biceps brachii tendon, rotator interval and the coracoid process:

The rotator interval is a triangular lax area on the anterior-superior aspect of the glenohumeral capsule, bounded by the anterior margin of the Supraspinatus, the superior margin of the Subscapularis tendon, and medially by the mobile tip of the coracoid process giving rise to the conjoint tendon of the Coracobrachialis and short head of the Biceps brachii muscles(Matsen III et al., 2009; Standring, 2016). Its floor contains the intracapsular, extra-synovial long-head tendon of the Biceps brachii. The coracohumeral ligament, arising from the lateral aspect at the base of the coracoid process, merges with the joint capsule in the rotator interval, expands laterally to integrate with the tendons of the Subscapularis, Supraspinatus, and bridges across the long tendon of the Biceps brachii inserting into lesser and greater tuberosities of the humerus(Di Giacomom & Pouliart, 2008).

The superior glenohumeral ligament is a local capsule thickening in the rotator interval. It attaches between the supraglenoid tubercle and a slight depression on the lesser tuberosity of the humerus, sending reflection to the transverse ligament over the Biceps pulley. At rest, the intracapsular, oblique course of the long tendon of the Biceps brachii in the floor of the rotator interval is at an angle between 30 and 45 degrees to the vertical plane, passes through the bicipital groove and over the humeral head(Petchprapa et al., 2010).

The merger of the coracohumeral and superior glenohumeral ligaments with the capsule at the rotator interval provides stability and protection from impingement against the curved edge of the acromion at external rotation of the humerus during abduction, before the Biceps tendon wipes against the undersurface of the Supraspinatus in high-velocity throwing activities. The impingement initiates the extrinsic striking of the Supraspinatus tendon against the undersurface and the anterior edge of the acromion, as well as the intrinsic striking of the intracapsular long-head tendon of the Biceps brachii against the capsule, leading to the extrinsic and intrinsic wear, respectively. If the injury persists, the extrinsic and intrinsic friction wear of the Supraspinatus tendon, the adherent capsule, and the long tendon of the Biceps brachii gradually progresses. In the process, both the

Supraspinatus tendon and the long head of the Biceps brachii develop varying degrees of pathology because of their different structure and distances from the prestressed coracoacromial ligament and undersurface of the acromion.

As the Supraspinatus undergoes attrition leading to a tear, the coracohumeral and superior glenohumeral ligaments within the interval, along with the long head of the Biceps brachii show degenerative changes. Chronic wear at the anterior margin of the Supraspinatus tendon, combined with the stabilizing role of these ligaments, fails to prevent subluxation of the long head of the Biceps brachii, resulting in cyclic movement over the lesser tuberosity.

During coronal and scapular plane abduction of the humerus, the tip of the coracoid process, under the Cleidobrachialis deltoideus and anterior fibres of the middle portion of the Deltoid muscle, concurrently courses from its resting position in the infraclavicular fossa to the rotator interval. Relative laxity of capsuloligamentous structures in the floor of the rotator interval normally adapts well to the coracoid process, depending on the degree of its external rotation, before the rotating head of the humerus translates inferiorly and posteriorly. The coracoid then returns nearly along the same path to its original resting position, depending on the hysteresis experienced by the attached ligaments and the concentric-eccentric contraction of the muscles attached to the coracoid process.

The ligamentous thickenings serve as static restraints to anterior and inferior translation during abduction, external rotation, and posterior translation during forward flexion. After an anterior-inferior dislocation of the humerus, increased laxity of the rotator interval leads to subluxation of the humeral head. The traditional [1] Putti-Platt technique— double-breasting of the subscapularis tendon, underlying joint capsule, and adjacent rotator interval —to stabilize the glenohumeral joint is a reasonable procedure, provided that an isometric joint arc is maintained during abduction and associated external rotation of the humerus. Excessive soft tissue tightness during plication would restrict the range of abduction in both coronal and sagittal planes, limiting the external rotation of the humeral head. Similarly, bony and soft tissue injury involving the clavipectoral fascia extending into the infraclavicular fossa, floor of the axilla and structures of the rotator interval will significantly affect the range of abduction in both coronal and scapular planes.

12.1 A dynamic biomechanical theory - mutual injury to the Supraspinatus tendon and long head of the Biceps brachii tendon:

The recurrent high-velocity overhead movements cause high shear stresses between the intrinsic surface of the Supraspinatus tendon merged with the joint capsule, and the long head tendon of the Biceps brachii, which are simultaneously compressed against the acromial arch. During frequent high velocity loaded abduction exceeding 90 degrees with external rotation of the humerus, the *'wiper'* movements of the obliquely running intracapsular,

Figure 11. Belt-and-buckle analogy demonstrating extrinsic and intrinsic wear out of the Supraspinatus (*leather strap*), the buckle frame as the acromion, and the wiper effect with impingement of the long head of the Biceps brachii tendon (*tine*).

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[1] The Putti-Platt technique for anteroinferior laxity of the shoulder capsule is a straightforward reconstructive procedure. After arthrotomy, the lateral flap of the capsule and the overlying merging tendon of the subscapularis are tucked under the medial flap at an isometric point, sutured with a few interrupted sutures. Stitch the lateral edge of the medial flap over the lateral flap with a continuous suture of a suitable material to reinforce the rotator interval, strengthening the construct. Avoid excessive shortening of the capsule and the tendon. In the young, instead of the double-breasting, it is a matter of cutting the capsule and tendon complex and suturing them, taking in 3-5 mm of the flap edges on either side, allowing isometric range of shoulder movements. In the older, where the healed post-traumatic capsule and tissues overlying the rotator interval are lax, perform the traditional double-breasting.

extra-synovial long head tendon of the Biceps brachii with accompanying impingement against the intrinsic surface of the capsule experience high shear forces between them. The deepening extrinsic and intrinsic wear of the capsule and the Supraspinatus tendon against the acromial arch and wiping of the long tendon of the Biceps, ultimately culminates in a full-thickness rupture. This mechanism, which causes simultaneous pathology of the Supraspinatus tendon and the long tendon of the Biceps brachii, is akin to 'belt-and-buckle' wear (**Fig. 11**). If the tine of a buckle is analogous to the long tendon of the Biceps brachii and the buckle frame as acromion, then the outer and inner wearing of the strap resembles the dynamic injury to the Supraspinatus tendon with the joint capsule juxtaposed to the acromion and the long head tendon of the Biceps brachii tendon. These kissing tendons suffer pathology to varying degrees: tenosynovitis to tendinosis or even a rupture by the Biceps brachii and from simple to massive tears of the Supraspinatus tendon and adjacent infraspinatus.

13.0 Scapulohumeral rhythm:

The process of scapulohumeral rhythm is dependent on the simultaneous synchronous motion of five articulations: sternoclavicular, acromioclavicular, and glenohumeral joints; scapulothoracic and acromiohumeral synsarcoses, involving four linkages: clavicle, scapula, rib cage and humerus. The clavicle and the scapula, in the presence of normal thoracic anatomy, are the key players in the execution of a normal range of glenohumeral movements. The specific pattern of the scapulohumeral rhythm in an individual is crucial for effective and efficient overhead and underhand delivery. All studies of scapulohumeral rhythm pertain to the overhead movements, and there are no studies on underhand scapulohumeral rhythm, in sports like curling for precise delivery of the stone, where the focus is on lower range of forward flexion combined with few degrees of abduction.

The chief reasons for the varying scapulohumeral angular ratios reported in the literature are the variable anatomy and the biomechanical architecture of the clavicle and scapula, the plane and speed of arm elevation, and the changing methodology over the past fifty years. In addition, there must be no deformity of the thoracic cage and cervical and thoracic spine for a normal scapulothoracic rhythm. Thoracic kyphosis will cause protraction and anterior tilt of the scapula and increase the angle between the clavicle and the scapula in the transverse plane at rest.

The movement of the humerus is voluntary, but the clavicle and the scapula have obligatory conjunctive movement during arm elevation. Once the elevation of the humerus begins, depending on the plane and speed of movement, there is a time-dependent proportional translational speed of the scapula in conjunction with the clavicle coordinated by various groups of muscles. The mechanism underlying the scapulohumeral rhythm is a synchronized activity of the pectoral girdle muscles under the control of the peripheral and central nervous systems, directing the glenoid under the moving head of the humerus.

An alteration in the muscle length-tension relationship in any couple-forming muscle will disturb the synchronous motion of the entire complex, with or without clinically noticeable adverse effects, such as reduced strength and early fatigability. During a concentric contraction, the skeletal muscles experience 'stiffness' in the form of resistance to change in length when loaded(Huxel et al., 2008). This muscle stiffness varies with muscle tension per unit length, initially assisting to stabilize one or more joints before generating power to move one or more linkages connected to it. Following a clavicle fracture with shortening and other malunion disturbances, the muscle lengthtension response causes variable concentric contraction of one or more muscles due to disturbed Actin-myosin coupling, which fails to generate the required movement and force. A delayed or absent matching eccentric lengthening also contributes to scapulothoracic motion disturbances and deep ache, through sensory proprioception and mechanoreceptors.

Translatory rotation of the scapula at the scapulothoracic synsarcosis in clockwise or counterclockwise directions, tilts the glenoid fossa cranially or caudally, and with swivelling face in anterior or posterior direction. These movements occur in conjunction with that of the clavicle at both the acromioclavicular and sternoclavicular joints. In a [2]sex-based analysis of scapular kinematics, during the coronal, scapular, and sagittal plane elevation of the arm between 30 and 120 degrees, there is less upward rotation *(lateral translation and rotation of the inferior angle)* and dorsal (*posterior*) tilting angle of the scapula in women, with a progressive increase in humeral elevation(Nakayama et al., 2018). Similarly, the internal rotation and external rotation (*protraction and retraction*) of the scapula also varies among men and women, with the degree of elevation of the humerus in all planes, suggesting that the scapular movements play a key role in elevation of the humerus(Nakayama et al., 2018).

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[2] The term sex refers to the biological differences in anatomy, physiology, chromosomes, and genes at birth between males and females. In contrast, gender pertains to the socially constructed roles, characteristics, and sexual behaviours of men and women. (Heidari S, et al Sex and gender equity in research: rationale for the SAGER guidelines and recommended use. Res Integr Peer Rev. 2016; 1:2.)

13.1 Degrees of freedom at the glenoid surface and scapulohumeral rhythm ratios:

The glenohumeral joint has six degrees of freedom in the coronal and scapular planes: abduction-adduction, sagittal flexion-extension and external-internal (*lateral-medial*) rotation both beside the body and at 90 degrees in coronal and sagittal planes with the elbow flexed at 90 degrees. The external and internal rotation is essential to avoid the impact of the greater tuberosity against the acromial arch beyond 90 degrees of elevation in the coronal and scapular planes and to allow the arm to return beside the body. At the acromiohumeral synsarcosis, the acromion and the prestressed coracoacromial ligament form the supraglenoid arch, facilitating smooth gliding of the humeral head. In the sagittal plane, abduction (*forward elevation/flexion*) of the arm, the internal rotation of the humerus is accompanied by internal rotation (*protraction*) of the scapula. This conjunct internal rotation occurs because of tightening of the coracohumeral ligament(Gagey et al., 1987).

Differences in the path of the scapula are due to the carried load, focus of the target and the varying motion velocities during arm elevation(Sugamoto et al., 2002). Other factors include individual structural variations and the methodology, which explains the differences in the scapulohumeral rhythm ratios among the earlier and most recent studies (**Table 1**) (Doody et al., 1970; Freedman & Munro, 1966; Inman et al., 1944; Ludewig et al., 2009; Poppen & Walker, 1976; Saha, 1971; Sugamoto et al., 2002).

Table 1: Scapulohumeral ratios in various studies in the last 50 years.

Inman et al. (1944)	2:1
Freedman and Munro (1966)	1.35:1
Doody et al. (1970)	1.74:1
Poppen and Walker (1976)	4.3:1 (<24° elevation) 1.25:1 (>24° elevation)
Saha (1971)	2.3:1 (30–135° elevation)
Sugamoto (2002)	2.4 (Low speed) 2.9 (High speed, 60°elevation) 1.7 (High speed, 150° elevation
Ludewig et al (2009)	2.1:1 (Coronal plane) 110° elevation) 2.2:1 (Scapular plane) 2.4:1 (Sagittal plane)

13.2 Phases of scapulohumeral rhythm:

The scapulohumeral rhythm is defined by four phases of abduction at the glenohumeral joint. In a clinical examination of the shoulder, the initial phase of abduction in the coronal and scapular plane begins from the resting position of the arm beside the trunk. Historically, each phase of the angular rotation of the humerus is considered in increments of 30 degrees, up to a maximum of 120 degrees of abduction. There are simultaneous, synchronous involuntary (*obligatory*) multiplanar and multiaxial movements of the clavicle and the scapula throughout voluntary (*intentional*) abduction of the humerus, occurring at a specific ratio and pace that defines individual specific scapulohumeral rhythm.

When abduction exceeds 90 degrees and external rotation occurs, the reciprocal motion of the humeral head relative to the distal end, along with the tautness of the posterior capsule and ligaments, pushes the head forward, onto the anterior-facing glenoid fossa. The Scapulothoracic and Scapulohumeral muscles effectively reposition the scapular body and the glenoid fossa in readiness under the humerus. As the humerus moves, its head find a new instantaneous centre of rotation on the articular surface of the glenoid fossa, remaining concentric with the undersurface of the acromion, which ensures congruency within the acromiohumeral synsarcosis.

13.2.1 Phase 0 to 30 degrees (the "setting phase"):

At the initiation of the first 30 degrees, the optimal positioning and stabilization of the clavicle and scapula to reposition the glenoid fossa is called the "setting phase"(Inman et al., 1944). The Cleidobrachialis deltoideus and Occipitocleidal trapezius act together to rotate the clavicle ventrally by 8-10 degrees and stabilize the acromioclavicular joint, while the Cleidobrachialis pectoralis and Cleidomastoid act on the clavicle's sternal end to stabilize the sternoclavicular joint, with assistance of the Subclavius. There is biphasic swivelling of the scapula around a vertical axis, turning the face of the glenoid fossa posteriorly by 10 degrees during zero to ninety degrees of abduction, and beyond 90 degrees, the glenoid face turns anteriorly by 6 degrees(Kapandji, 2005).

13.2.2 Phase 31 to 60 degrees (turning of the scapula):

The clavicle begins to elevate at 30 degrees of humeral abduction. Simultaneously, tension in the ligaments of the acromioclavicular joint and coracoclavicular ligamentous complex initiates the lateral rotation of the scapula's inferior angle. The middle and inferior heads of the Trapezius, coupled with powerful middle and lower digitations of the Serratus anterior, turn the inferior angle of the scapula clockwise on the left and counterclockwise on the right when seen from behind(Bagg & Forrest, 1988). The horizontal sagittal plane axis of rotation is located furthest from the glenohumeral articular surface, near the vertebral end of the scapular spine, allowing for maximum mechanical advantage in turning the scapula(Bagg & Forrest, 1988). The rotation of the scapula follows the elevating clavicle at a rate of 4 degrees for every 10 degrees of humeral elevation with simultaneous dorsocranial axial rotation in the clavicular fossa of the manubrium sterni(Inman et al., 1944). The Serratus anterior rotates the inferior angle of the scapula higher as soon as the inferior head of the Trapezius elongates.

13.2.3 Phase 61 to 90 degrees (cranking phase):

The active elevation and the dorsocranial rotation of the clavicle peaks with the rolling motion between 60 and 90 degrees of abduction. There is limited movement of the acromion on the sagittal axis due to the tightening of acromioclavicular joint ligaments and the conoid ligament, halting elevation of the acromial end of the clavicle towards the end of this phase(Abbott & Lucas, 1954). The clavicle reaches maximum conjunctive axial rotation, and the coracoid process turns away from the clavicle, stretching the conoid ligament to rotate the clavicle further. Fixed by the conoid ligament, the axially rotating clavicle continues to roll, retracting dorsally. The cranking effect of the lateral curvature torques the clavicle further to increase the stored elastic strain energy. The preexisting screw twist due to the varying angle of torsion and the version amplifies the cranking effect and the differential screw pitch between the medial and the lateral curvatures effectively speeds up the driving force of the clavicle directed laterally, tightening the trapezoid ligament and stabilizing the acromioclavicular joint. The superior angle of the scapular blade begins to tilt dorsally with the axial rotation and retraction of the clavicle, lifting the acromion, maintaining the height of the subacromial space, and ensuring the acromiohumeral synsarcosis remains concentric and congruent. Moreover, at the end of the phase (*90-degree abduction*), the arriving greater tuberosity of the humeral head escapes impingement against the acromion, by translating posteriorly to a new location on the glenoid face with external rotation of the humerus.

13.2.4 Phase 91 to 120 degrees (cam-effect):

Beyond 90 degrees of the arm elevation, the continued axial rotation of the elevating clavicle causes the cam like conical posterior-inferior projection of the articular sternal end, to engage with the costoclavicular articulation, passively elevating the acromial end of the clavicle further by 5-10 degrees, which is made possible by the laxity of the anterior and inferior capsule. The inferior angle of the scapula rotates approximately 40 degrees away from its original dorsolateral resting position. By the time the humeral shaft is ready to move higher, the humeral head has already rotated posteriorly— assisted by ontogenetically determined humeral shaft torsion —to clear the smooth acromial arch, centring on the now cranially facing glenoid fossa, achieving 120 degrees or more of abduction. The superior angle of the scapular blade, approaching 20 degrees of dorsal pitch, reciprocally engages the inferior angle against the thoracic cage, acting as a brake to further tilt, assisted by the clavicle reaching its zenith, with unfolding of the scapular blade storing strain energy for reversal to its resting position.

The final reach of the abduction beyond 120 degrees varies with individual geometries of the linkages, joints and the performance of the force couple in action at the scapulothoracic synsarcosis and scapulohumeral muscles at the glenohumeral joint and the acromiohumeral synsarcosis. To deliver a projectile, at the final position of the hand, the scapula is stabilized by its maximum dorsal tilt, with its inferior angle pressing against the ribcage, having a dampening effect on the elevating arm, frequently with contralateral flexion of the trunk. Upon reaching 180 degrees, there is an obligatory extension, contralateral flexion, and rotation of the thoracolumbar spine to generate additional power for the projectile.

13.3 Scapulothoracic rhythm variations:

After 30 degrees of elevation to reach 180 degrees, the ratio between scapular clockface rotation and humeral elevation remains relatively constant at 2:1. For every 15 degrees of humeral elevation, there is a 5 degrees of outward and upward turning of the inferior angle of the scapula to a total of 60 degrees, and 10 degrees of external rotation of the humerus(Inman et al., 1944). In a study where Kirschner wires were inserted in the lateral third of the clavicle, the acromial base on the scapular spine, and in the humerus at the insertion point of the Deltoid muscle, the motion of the clavicle and the scapula were measured relative to the sternum. For elevation of the arm to 110 degrees in all three planes, the scapulohumeral rhythm ratio was 2.1:1 in coronal plane abduction, 2.2:1 in the scapular plane, and 2.4:1 in the sagittal plane(Ludewig et al., 2009). At the sternoclavicular joint, the clavicle retracted by 16 degrees from its resting to 23 degrees retracted position, elevated by 6 degrees, and rotated dorsally by 31 degrees on its longitudinal axis(Ludewig et al., 2004).

The clavicle retracts more in the coronal plane than in the scapular and sagittal planes, during arm elevation. Conjointly, the clavicle and scapula align the glenoid fossa, centring beneath the humeral head, maintaining glenohumeral and acromiohumeral congruency and stability. Of the two bones, the restoration of clavicle's normal anatomy and patient-specific biomechanical architecture are paramount, given its high fracture rate, for the return of patient-specific scapulohumeral rhythm.

The experimentally reported ranges of motion of linkages at their respective joints are based on non-clinical conditions. Therefore, they only produce near-normal population-based averages. They are not reliable for predicting surgical outcomes for either surgeon-based or patient-based satisfaction. There can be substantial patient-specific ontogenetic variations in biomechanical architecture and neuromuscular responses following clavicle fractures.

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