DOI: https://doi.org/10.24297/ijct.v26i.9858

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

Part 2 Functional Anatomy of the Clavicle and Scapula

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

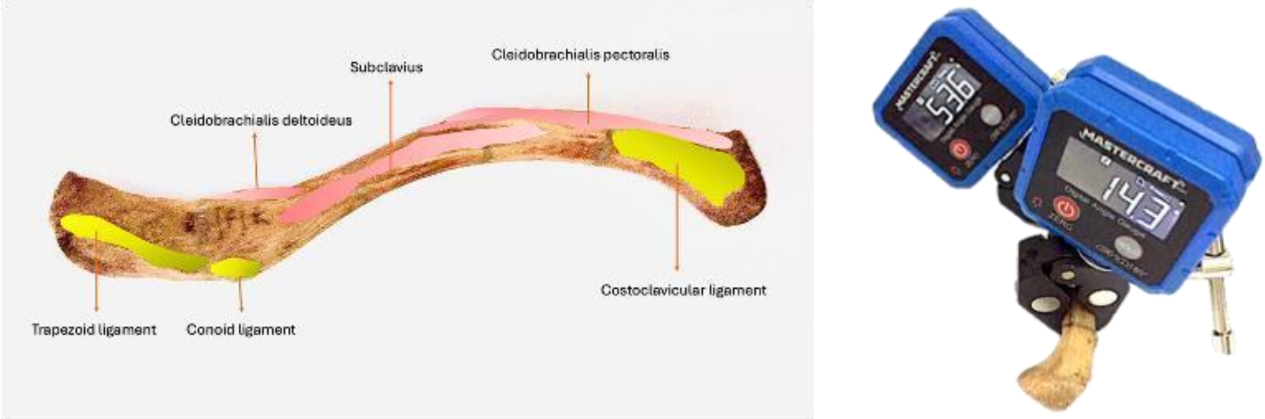
Orthopaedic surgeon, Honorary Staff, Hamilton Health Sciences, Hamilton, ON, Canada

Email: harjeetg52@yahoo.co.uk

Highlights: The characteristic serpentine shape of the clavicle makes it a precision machine for power transmission. The cross-sections of the expanded sternal end and the medial three-fifths of the medial curvature and lateral two fifths are highly variable. Phylogenetically (*origin and evolutionary development*) and ontogenetically (*individual development*), the curvatures, torsion and version of the clavicle are related to the dorsolateral positioning of the scapula and force amplification.

On average, the variable torsion angle along the diaphysis of the clavicle is - 35 degrees. It is distinct from the version angle, which can be greater or less than it. Generally, the left clavicle tends to be longer than the right, and the right clavicle has a larger mid-shaft diameter. The male clavicle shows asymmetry across all parameters, including muscle and ligament footprints.

Graphic abstract:



Keywords: Clavicle anatomy, Clavicle torsion and version angles, Clavicle morphometry, Clavicle fracture, Scapular anatomy, Clavicle directional asymmetry, Pectoral girdle, Human anatomy

1.0 The clavicle:

The serpentine-shaped clavicle is a precision machine within the organization of the pectoral girdle system. It is set horizontally and positioned obliquely in coronal and transverse planes to reposition the scapula, for parasagittal positioning of the arm, enabling overhead hand movements, widening the panoramic view when facing forward, and broadening and balancing the upper body on the pelvis during forward propulsion. Its embryonic and foetal development should not be considered in parallel with its antecedent design of the primates, because the human clavicle differs(McConnell, 2001). Since the beginning of its postcranial descent, the skeletal and muscular anatomy of the pectoral girdle, has evolved remarkably in response to the mechanical demands of the vertebrates by reorganizing the scapula and redesigning the clavicle to repurpose the function of the shoulder joint for overhead projectile delivery. It has a much longer gestation period than its ancestors, from fish to primates, and serves a unique mechanical function within the forelimb anatomy to propel against resistance in fluid media.

At a cursory glance, it may resemble a strangely curved hockey stick during its early embryonic phase; other times, it is like an S-shaped or *f*-shaped musical key. All these simplistic descriptions are valid when one inspects and palpates its three-dimensional anatomy. However, it shows significant anatomical variation in the size and shape of its curves and of its biomechanical architecture to meet mechanical demands of the individual.

2.0 Morphology of the clavicle:

The clavicle is a forelimb bone and the first link between the axial and appendicular skeleton of the upper extremity. It is classified as a long bone because it has an epiphysis at each end, which is often less remarkable at the acromial end, defining its diaphysis *(between physes)* as in any other long bone. The clavicle is subdermal throughout its length. Its inclined orientation relative to the transverse and coronal planes is almost perpendicular to the body's median plane, unlike the parallel orientation of the other long bones in a resting anatomical posture. The clavicle does not have a true medullary canal. Instead, the cortical shell in the medial two-thirds of its diaphysis encloses a trabecular network, and there may be a rudimentary medullary canal in the central zone, when present. The thickness of the cortex varies, being thickest at the transition between the medial and the lateral curvatures.

The unique architecture of the clavicle bone possessing a longitudinally elongated ς-shape (sigma, the eighteenth letter in the Greek alphabet) has instantaneously noticeable two opposing curvatures of unequal lengths. Owing to its evolutionary and developmental history, during the post-cranial descent of the scapula, the clavicle has strategically maintained the most proximal position, allowing the pectoral girdle and the thoracic cage to mutually adapt to the upright posture and bipedalism for unobstructed swinging of arms for progressive gait. Additionally, the hand at the end of the upper extremity can trace a circumduction path and perform other complex helical movements, creating an irregular cone with its apex at the sternoclavicular joint and a broad oblique elliptical base at the acromial end.

From an engineering perspective, the topology of the optimized clavicle with its elegant yet convoluted design in terms of size and weight, material distribution and strength are well-organized within limited space at the root of the neck between the superior angle of manubrium sterni and the highly mobile scapula. It enables extremely dynamic mobility of the upper extremity in terms of power, velocity, and acceleration, from grasping an object in hand to delivering it, to reach at the desired target. Of course, this ability varies considerably between individuals.

The clavicle with the scapula forms a clasp around the upper lateral aspect of the tapering elliptical thoracic cylinder. With its articulation at the manubrium sterni, the shaft of the clavicle is generally oriented at 10-20 degrees cranial to the transverse plane, 15-20 degrees dorsal to the fore-coronal plane, with the angle opening laterally and approximately angled at 60 degrees to a plane passing through the spine of the scapula opening medially(Kapandji, 2005). The plane of the scapula is at an angle of 30-35 degrees to the rear-coronal plane (**Fig. 1**). The 60-degree clasp angle between the clavicle and spine of the scapula varies with their relationship to the elliptical convexity of the thorax during arm elevation due to movements at the acromioclavicular joint. The clavicle's medial expanded club-shaped end (sternal end) articulates at clavicular fossa of the manubrium sterni and first costal cartilage; the lateral flat end (acromial end) articulates with the matching flat acromion of the scapula.

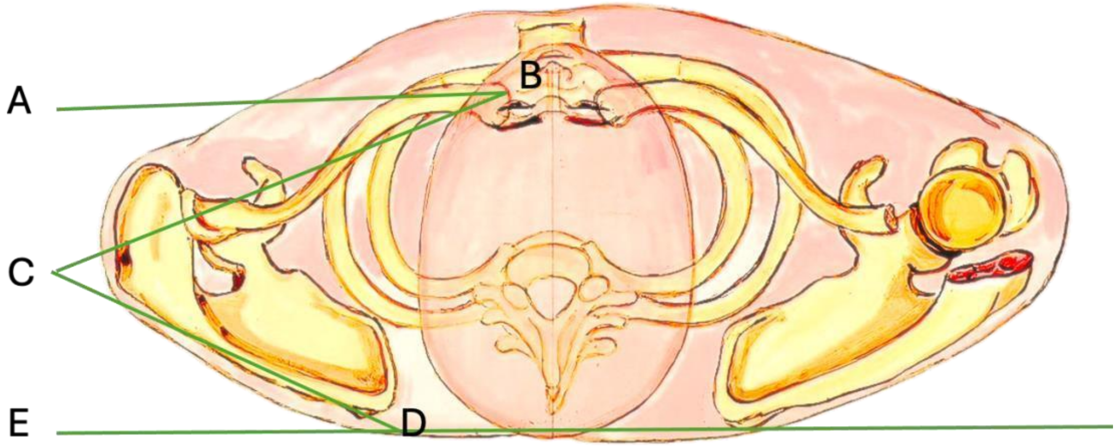
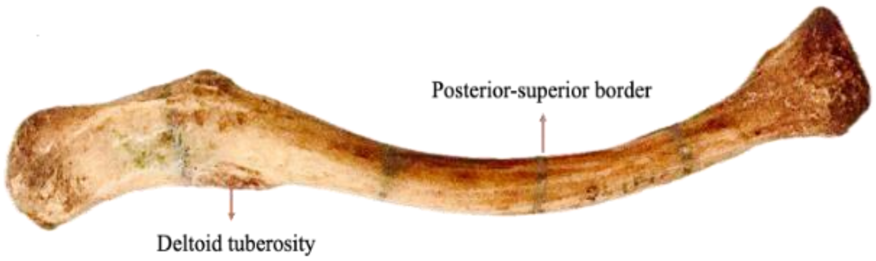


Figure 1. Artwork: Angular formation of the clavicle and the scapula, clasping the thoracic wall. ∠ABC 15-20°, clasp angle ∠BCD 60° and ∠CDE 30-35°.

2.1 Borders and surfaces of the clavicle:

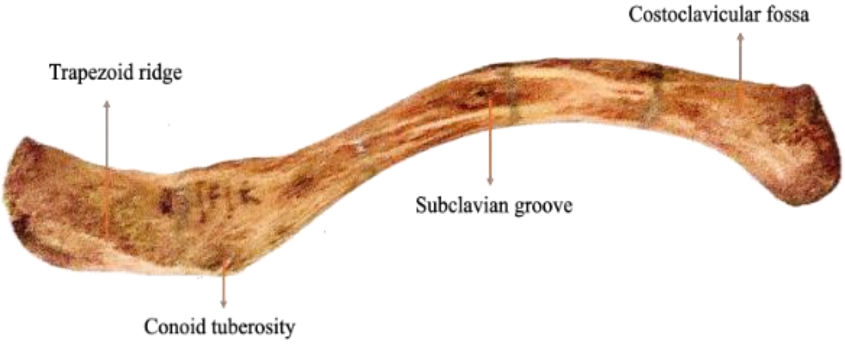
The gross three-dimensional anatomy of the clavicle is best described when articulated. From a cranial-caudal view (*seen from above*) for its medial and lateral curvatures and surfaces (**Figs. 2 A, B**). From a dorsoventral (*from behind or front*) view to describe anterior and posterior surfaces and inferior and superior curves (**Figs. 2 C, D**). Human anatomy textbooks do not describe the axial twist (*segmental variation in torsion angle and version*) in the clavicle shaft. It has been reported rarely and barely described in the recent implantology and anthropology literature(Lambert et al., 2016; Melillo et al., 2019) (**Fig. 2. G**). DePalma (1957) mentions it as a localized anterior torsion of the acromial end while reporting on variations of the acromioclavicular joint(J. L. Vanderbeck et al., 2009). There is no mention of a version angle between the sternal and the acromial ends.

A.



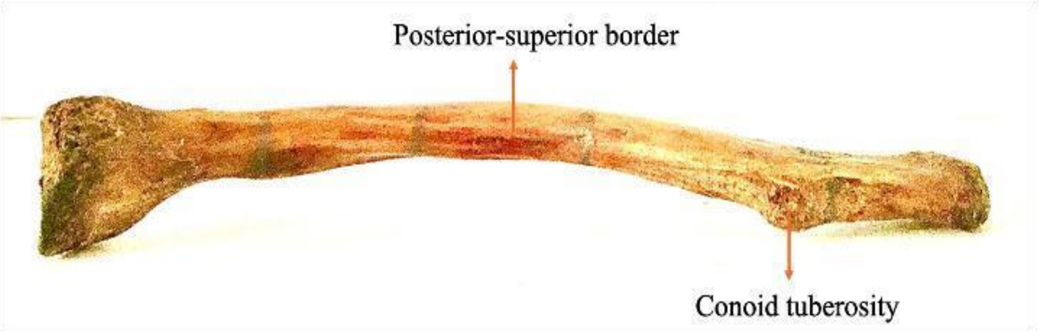
Superior surface

B.



Inferior surface

C.



Posterior surface

D

Anterior surface

Figure 2. Morphology of the clavicle: **A, B, C, D, E, F —** superior, inferior, posterior and anterior surfaces showing various borders, and medial, lateral and inferior curvatures; ridges and tubercles; and **G.** Axial twist, showing version angle.

The clavicle is best divided into fifths to describe surface features precisely for clinical purposes. There are significant morphometric gender and individual variations. The medial curvature is convex anteriorly (ventrally). It is a long, less pronounced, shallow curve. It occupies little more than medial three-fifths of the clavicle length. The lateral curvature is convex posteriorly (dorsally). It is relatively short, sharp and deep. The cross-sections of the expanded sternal end and curvatures of the medial three-fifths and lateral two-fifths are highly variable (**Fig. 3**).

Figure 3. Highly variable shapes and sizes of the cross-sections of the same Sawbone©, viewed from both sides of the same section of the diaphysis, on the left is the sternal end. The holes are remnant of an intramedullary implant inserted from the acromial to the sternal end.

Starting from the prismoid shape at the sternal end, the diaphysis becomes more circular, transforming from an oval to flat form. The anatomical orientation of the clavicle within a virtual three-planar space defined by axii, X, Y and Z, has various borders and surfaces, better demarcated at the flat lateral two-fifths. By convention, it has anterior, posterior, superior and inferior surfaces. Much of the reflected variability in cross-sectional anatomy is mainly caused by the narrowing of the inferior surface at certain places, which gives the oval sections the appearance of a triangle due to truncation and a rounded superior surface. Therefore, the clavicle has three or four poorly palpable partial borders.

2.2 Borders of clavicle:

The borders are highly variable and often poorly defined in the central three-fifths of the bone. The rounded anterior-inferior border, beginning at the costoclavicular fossa, separates the anterior surface from the inferior surface, continues with the anterior border of the lateral two-fifths of the flat acromial end. The part of the border between the footprints of the Cleidobrachialis pectoralis and the Cleidobrachialis deltoideus is smooth **Fig. 2D**). The pectoralis ridge separating the footprints of the Cleidobrachialis pectoralis and Cleidomastoid on the anterior surface of the medial one-fifth continues as the anterior-superior border ending into the deltoid tubercle on the anterior surface of the lateral concavity of the acromial end (**Figs. 2A and 2D**). This border separates the anterior and superior surfaces. The posterior-superior border, extending from the conoid tuberosity to the superior corner of the quadrangular sternal end, separate the posterior surface from the superior surface of the clavicle. The posterior-inferior border runs from the posterior border of the costoclavicular fossa to the posterior border of the subclavius groove on the inferior surface.

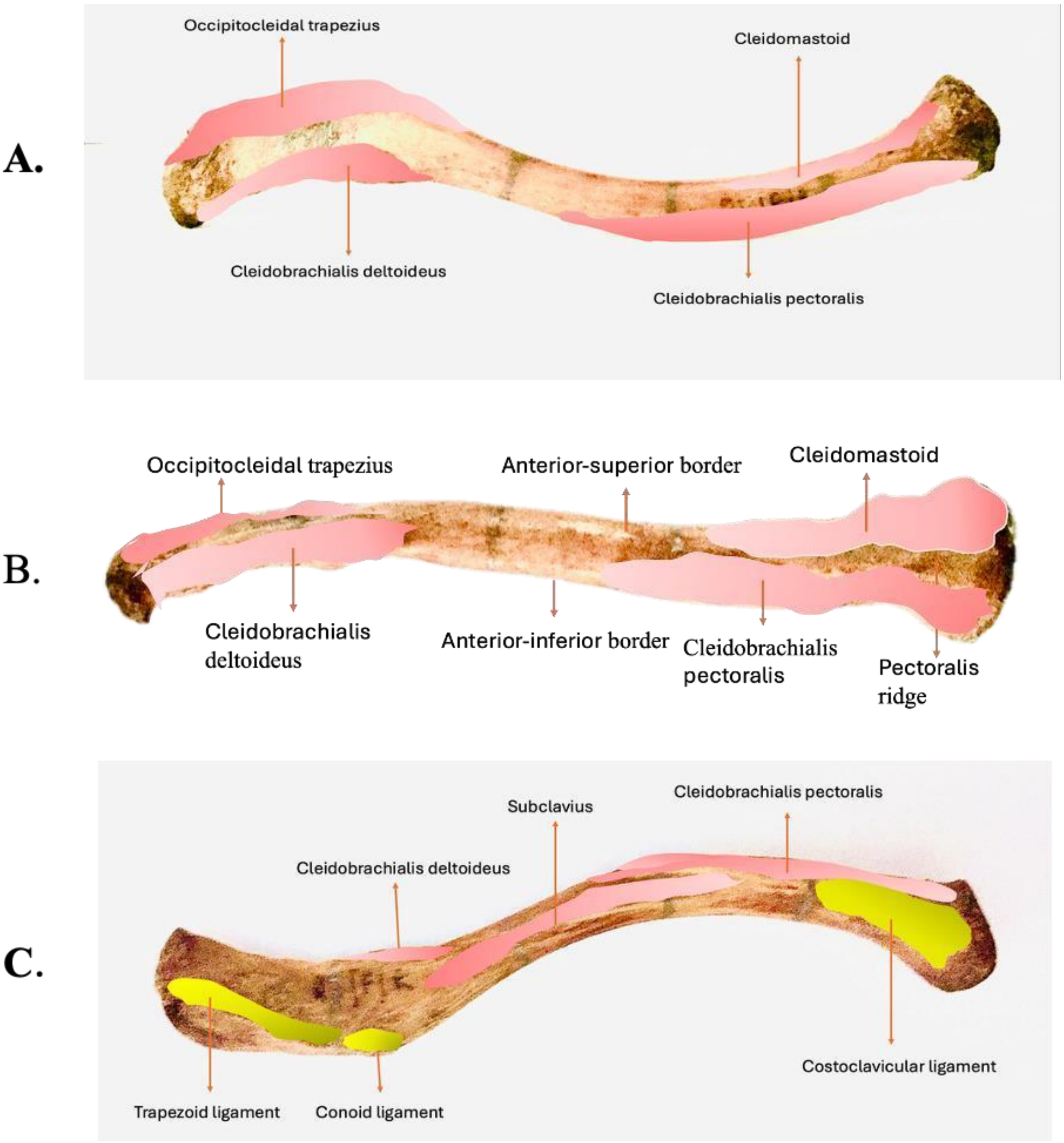


Figure 4. A. Anterosuperior surface, **B.** Anterior surface, **C.** Inferior surface illustrating, the footprints of various muscle attachments (created in the PowerPoint).

2.3 Surfaces of clavicle:

The smooth subcutaneous anterior surface continues with the superior surface, as the rounded anterior-superior border is smooth along most of its length, covered by the platysma when present and subcutaneous adipose. The superior surface is convex in one-fifth between the medial and lateral curvatures. The medial two-thirds of the anterior surface is covered by the footprint of the Cleidobrachialis pectoralis edging with the footprint of the

Cleidomastoid occupying most of the medial half of the superior surface and part of the posterior surface (**Fig. 4**). Between the two footprints is the pectoralis ridge, for the attachment of the Cleidobrachialis pectoralis fibre(Lee et al., 2014). This palpable ridge is a useful surgical landmark for antegrade entry of an intramedullary implant.

Figure 5. Note the nutrient foramen on the posterior surface.

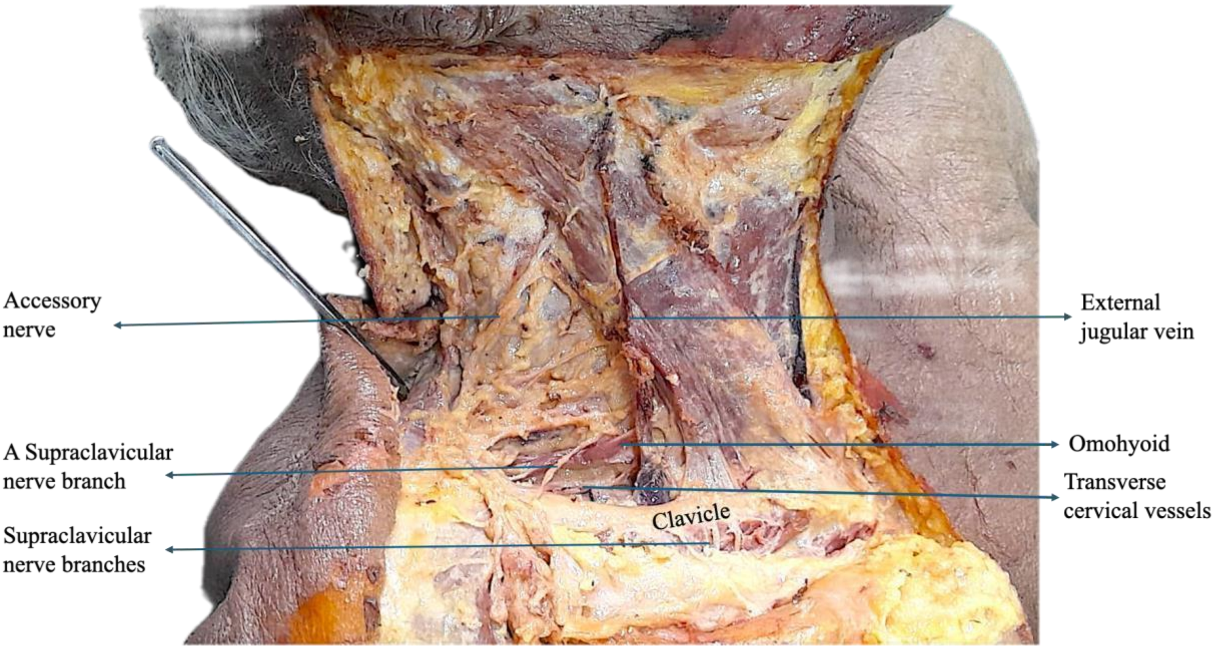


Figure 6. The author's dissection - Immediate relationship of the transverse cervical vessels to the posteriorsuperior border of the clavicle, just below the Omohyoid.

The posterior surface forming the concavity of the medial curvature facing the thoracic aperture is smooth between the conoid tuberosity and the articular margin of the sternal end. The most salient feature near the middle of the medial curvature is the presence of a constant nutrient foramen, directed obliquely towards the acromial end in most dry bone specimens (**Fig. 5**). The posterior surface of the clavicle is related to the Thyrocervical trunk and its branches, as well as the Suprascapular and Transverse cervical vessels **(Fig. 6)**. The Suprascapular vessels transit hidden behind medial curvature of the clavicle. The Subclavian vessels and Brachial plexus are associated with the first- and second-fifths of the medial curvature as they leave the thorax before entering the infraclavicular fossa over the superior surface of the first rib. At its sternal extremity is the attachment of the Sternohyoid muscle.

At the sternal end, the medial part of the inferior surface is broad, having a rough area, either as a shallow fossa or an eminence for the attachment of the costoclavicular ligament (**Fig. 4B**). The eminence often articulates with the upper surface of the first costal cartilage and adjacent rib to form a synovial pseudarthrosis (**Fig. 7**). Further laterally, the remainder of the inferior surface is grooved, narrow medially, and widens towards the acromial end for the attachment of the Subclavius muscle (**Figs. 2E, 2F, and 4C**). The posterior edge of the groove continues laterally to meet the conoid tubercle. The nutrient foramen found located at the lateral end of the groove is directed towards the acromial end. The ascending Clavipectoral fascia splits, enclosing the Subclavius muscle, attaches to the anterior and posterior edges of the groove. The posterior layer of the fascia ascends posteriorly, merging with the periosteum of the clavicle. It continues proximally with the deep cervical fascia enclosing the inferior belly of the Omohyoid muscle (**Fig. 6**).

Figure 7. Showing costoclavicular fossa for the costoclavicular ligament and a prominent shelf for the costoclavicular synostosis.

The lateral two-fifths of the clavicle have posterior convexity and anterior concavity. Its flat rectangular crosssection has four surfaces, anterior (ventral) and posterior (dorsal), with borders separating superior (cranial) and inferior (caudal) surfaces. The concave anterior surface has a raised rough area, the deltoid tubercle, for the tendinous origin of the Cleidobrachialis deltoideus. The thick and rough convex posterior surface is for the origin of the Occipitocleidal head of the trapezius. On the inferior surface close to the posterior surface, one-fourth of the length of the clavicle from the acromial end is the prominent conoid tubercle/tuberosity for attachment of the conoid ligament. From the lateral side of the tubercle, on the inferior surface, an oblique ridge runs anteriorly and laterally to the edge of the acromial end for the attachment of the trapezoid ligament (**Figs. 2E, 2F, and 4C**). The tendinous fibres of the Occipitocleidal trapezius and Cleidobrachialis deltoideus are attached to the respective halves of the superior surface, including the anterior and posterior surfaces, as well as the borders. The Subclavius groove often extends over the inferior surface of the lateral curve beyond the transition zone anterior to the trapezoid line and conoid tubercle.

2.4 Articular ends of the clavicle:

The expanded form and variable cross-section of the sternal extremity of the clavicle can be prismoid, triangular or even quadrangular - the prominent posterior-inferior corner projects towards the root of the neck (**Fig. 8A**). The articular facet facing in the anteromedial and inferior directions articulates with the superior angle of the manubrium sterni, forming the sternoclavicular joint at the clavicular fossa. The articular facet is usually irregular and pitted.

Figure 8. **A.** Sternal articular surface and **B.** articular and non-articular surface of the acromial end.

The inferior crescent-shaped part of the articular surface continues with the inferior surface to articulate with the first costal cartilage. The articular margin of the sternal end is rough due to the attachment of the capsuloligamentous structures. The posterosuperior part provides attachment to the intra-articular disc. The expanded sternal end of the clavicle rises above the articular facet of the manubrium sterni, forming the lateral boundary of the jugular notch. Posterior to the notch is the cricoid cartilage, the cricoid membrane, the lower part of the thyroid cartilage, the tributaries of the jugular vein and the brachiocephalic vein.

At the flattened acromial end is an oval articular facet that articulates with the medially facing articular surface of the acromion (**Fig. 8B**). The clavicular side of the facet faces laterally and inferiorly. The superior, anterior and posterior margins of the facet are rough due to the attachment of the capsule and ligaments.

3.0 Curvatures, torsion and version:

The architecture of the clavicle in primates and Homo sapiens evolved through gradual dorsolateral repositioning of the scapula and changes in the functions of the upper extremity at the glenohumeral articulation to enable the newly acquired motion of brachiation and projectile delivery. The medial and lateral curvatures seen on the craniocaudal view are related to arm elevation in the coronal, scapular and sagittal planes to provide speed and power (Voisin, 2006). The superior and inferior curves in the coronal plane, mainly the laterally concentrated inferior curve seen in the anterior to posterior view, relate to the positioning of the scapula (**Fig. 2**). These curves help determine the strategic insertion of the muscles and the ligaments, their line of action and lever arm length, which give momentum to a particular movement during arm elevation.

3.1 Curvatures – Topographic relationships and biomechanical significance:

Of the two curvatures on cranial view, the lateral curvature is generally more pronounced than the medial curvature, the latter being longer. The less pronounced medial curvature helps safeguard against compressive loads and is less likely to fracture. The medial curvature skirting the thoracic aperture allows abduction of the humerus in the scapular, coronal and sagittal planes. The medial and inferior curvatures apart from allowing the positioning of the scapula dorsally, prevent Thoracic outlet obstruction(Jenkins et al., 1978).

The lateral curvature of the clavicle enables it to act as a crankshaft, facilitating the final half of scapular rotation(Inman & Saunders, 1946). Loss of this curvature restricts the full range of scapular rotation, hindering complete elevation of the humerus, causing increased shearing forces and, consequently, degenerative changes at the acromioclavicular joint (Inman & Saunders, 1946; Ljunggren AE, 1979). An excessive exaggeration of the lateral curvature, as in a malunited fracture, interferes with the axis of clavicular rotation, resulting in displacement of its sternal extremity and causing pain at the sternoclavicular Joint(Inman & Saunders, 1946). The greater the lateral curvature, the more effective the crank effect of clavicle's axial rotation. A relationship exists between the end-to end length of the clavicle and its medial and lateral curvatures, known as the clavicle index, described by DePalma, which is the sum of their radii of curvature divided by the specimen's length(J. L. Vanderbeck et al., 2009). The correlation between the clavicle index and its clinical relevance has not been further investigated in the surgical reconstruction of clavicle fractures.

There are four variations of dorsal-view coronal plane curves in various combinations(Qiu et al., 2016). Type 1. Horizontal, a straight clavicle; Type 2. A laterally concentrated inferior curve; Type 3. A superior concavity mostly concentrated at the sternal half; and Type 4. An inferior curve towards acromial half and a superior curve at the sternal half. The cranial view transverse plane curvatures have a mechanical correlation with the most encountered laterally concentrated inferior coronal plane curve on the dorsal view.

The superior coronal curve in primates allows a high dorsal scapula on the thorax. It makes pendular movements possible but is less frequently seen in humans(Voisin, 2006). In humans, clavicles with a superior curvature and a straight shaft have scapulae located higher on the thorax. It is probable that due to the laterally concentrated inferior curve, lowering the scapula on the dorsum of the thorax allows a greater range of glenohumeral motion(Voisin, 2006). This feature is not associated with a rigid acromioclavicular joint, thereby reducing the incidence of degenerative changes. A relatively pronounced lateral curvature at the acromial side of the clavicle is associated with anterior tilt of the scapula. Conversely, where the medial curvature in the transverse plane is more pronounced, the less marked inferior curvature in the coronal plane is associated with a more superiorly positioned scapula(Melillo et al., 2019).

In the newborns, the clavicle is more elevated and protracted due to the roundness of the thorax, which positions the glenoid more anteriorly and facing forward, suitable for a progressive quadrupedal crawl. The transverse plane curvatures of the clavicle are more pronounced at birth. During postnatal development, whether genetic or biomechanical forces, the clavicle's curvatures gradually become flatter with maturity. The lateral curvature consistently gets deeper than the medial curvature, and the medial curvature significantly correlates with the cross-sectional area and length of the clavicle, indicating independent development of the curvature morphologies(Barros Anna, 2013; Corrigan, 1960)

It is unknown whether human clavicle morphology and its morphometric proportions are preserved as in hominoids. However, since the medial curvature covaries with the length of the clavicle, it can be inferred that the medial curvature is more likely to be preserved than the lateral curvature, suggesting that biomechanical forces have a much greater effect on the latter. Meanwhile, their proportions remain constant. The morphologies and topographic relationships of clavicle orientation and dorsal positioning of the scapula on the thorax are partly preserved genetically to optimize the alignment of the glenoid fossa in primates and partly modified during development to allow a greater range of scapulothoracic and glenohumeral movements(Voisin, 2006).

The difficulty in explaining the significance of ventral and dorsal convexities of the sigmoidal curvatures of the clavicle in the transverse plane means a poor understanding of the collaborative anatomical and biomechanical function of the medial and lateral curvatures. Intuitiveness dictates that the concavity of the medial curvature circumvents the neurovascular structures at the base of neck and apex of the lung, reaching the neck of the first rib. The clavicle lies superior and anterior to the neurovascular structures that run in the grooves on the superior surface of the first rib. Besides this, the medial curvature, acting as a cranking mechanism, is also related to the biplanar retracted and elevated orientation of the clavicle, which repositions the scapula dorsally and redirects the glenoid face laterally during development of the rib cage.

The inferior curve in resting orientation increases the volume of infraclavicular space for the passage of the neurovascular structures and elevation of the first rib by the Scalenus anterior during deep respiration. With further elevation and retraction of the clavicle, during abduction in both coronal and sagittal planes, the concavity of the medial curvature conforms to the tapering apex of the lung. When the conjunct elevation of the first rib closes onto the clavicle, the dorsal axial rotation of the clavicle maintains the infraclavicular space volume. These architectural features of the clavicle in motion help accommodate the structures at the root of the neck to escape compression and confer biomechanical advantage, assuming the anatomy of the clavicle is normal.

Furthermore, the compression of the structures during clavicle retraction is prevented by the isometric arc and built-in mechanism of motion at the acromioclavicular joint. The clasp angle between the clavicle and spine of the scapula increases during scapulothoracic translation over the broader section of the elliptical thorax(Ljunggren AE, 1979). The medial border of the scapula retracts towards the vertebral spinous processes by an equivalent distance at the end of the abduction movement, with rising of the medial curvature concavity of the clavicle, which correlates with the apical volume of the lung. Typically, the anterior (ventral) concavity of the acromial end curvature, the laterally concentrated inferior curvature, and dorsal (posterior) rotation of the elevating clavicle also increase the volume of the subacromial space for the elevating humeral head, as it translates superiorly and rotates externally. During baseball pitching, this prevents collision and impingement of the subacromial structures as rapid pitching movement culminates, with the completion of the cocking phase and acceleration, or similar projection movements of the arm.

The skeleton is not a defense against external trauma, nor is it designed to protect the underlying structures and organs in the body cavities, as taught, except for the calvarium. It is a mechanical system optimized in size, form, shape and weight, creating a stable tensegrity network of linkages and joints, with musculotendinous and ligamentous structures for unobstructed locomotion. Biologically, it serves for mineral turnover and haemopoiesis. Normally, the latter function of the skeleton regresses and recedes to bone ends with maturity. The clavicle is not intended to protect the Subclavian vessels and Brachial plexus against trauma. On the contrary, the presence of the medial curvature to circumvent the structures at the root of the neck, rather poses a danger to the vessels, despite the interposing subclavius. The neurovascular structures and the lung apex may be pierced by the jagged ends of the fractured fragments during a direct high-velocity impact and with sudden telescoping of the fragments driven in posteriorly and superiorly, along with fracture of the first rib.

However, the biomechanical architecture of the clavicle is such that on an end-on impact— the typical mode of injury— the fracture forces dissipate at the transition zone just lateral to neurovascular structures, with the fragments angulating superiorly and posteriorly, thereby avoiding the vessels and the lung. Unlike side impacts, when the assault on the clavicle is head-on, the endangered vessels and nerves posterior and inferior to it are cushioned against the spongy, air-filled, and incompressible lung apex, which is inflated instinctively to resist injury, may be injured in return.

The curvatures of the clavicle are phylogenetically related to the anatomy of the scapular spine and acromion(Barros Anna, 2013). Similarly, the medial curvature is phylogenetically associated with the morphology of the lateral curvature to assist the kinematics of the glenohumeral articulation(Barros Anna, 2013). A prominent inferior curve is associated with decreased medial and lateral transverse-plane curvatures, and vice versa(Barros Anna, 2013). In individuals with less pronounced lateral curvature of the clavicle, the acromion may develop a more pronounced downward curve. Therefore, the anatomy of the acromial end of the clavicle is variable, modifying depending on individual activities, which influences humeral shaft torsion and head version, the inclination angle of the acromion and the version of the glenoid fossa.

3.2 Torsion and version:

Torsion (from Latin *torsio - onis* meaning twist) occurs where one end of something is twisted while the other is either held stationary or twisted in the opposite direction. The torque applied to a bar or a cylinder causes shear stress, resulting in a spiral path for its constituent elements. Torsion is inherent in the diaphysis of all long bones. It is uncertain whether it is genetically determined to be present from the embryonic period, pre-torqued during foetal development, or acquired during postnatal development. Moreover, whether long bones typically experience torque during postnatal development due to biomechanical forces acting on the end-physes in the opposite directions, remains poorly understood. The literature lacks a consensus on the definition of torsion in relation to bone anatomy. In practice, the term "torsion" is often applied to describe twist along the entire length of the bone, from the proximal to the distal articular surfaces. Sometimes, the term carries a pathological implication, while at other times it is used interchangeably with "version".

A version (from Latin *versio, -onis*, act of turning < *vertere* means to turn; turning one in contrast to the other) is progressive evolution within the substance of a matter when sequentially turned such that a particular point contrasts with the others, attaining a final degree of twist, taking a new form following a new function. In biology, such evolutionary repurposing of a bone or an organ typically replaces preexisting iterations, indicating development and that its function is refined in the new species for adaptation. Technically, the term version, when used in conjunction with torsion, means the inclusion of a few sequential twists when torque is applied between two points at the end of a bar or segmentally along the entire length of a bar. Depending on the material distribution and the shape of the cross-sections of a cylinder, with one end held stationary and the other end given a twist, the angle of rotation at the moving end relative to the stationary end is the angle of version, such as between the two articular surfaces of a long bone.

The version angle may not be the average of the segmental variable twist or torsion angles between the two physes. The measured angle between far ends is the version angle, while the in-between angles are the torsion angles at various sections or a specified region of interest. In body coordinates, when viewed end-on, conventionally, the proximal end– such as in the case of the femur, where the moving end turning anteriorly is termed anteversion and posteriorly is called retroversion. The right-handed version and torsion by screw thread convention will be clockwise, whereas the left-handed version and torsion will be counterclockwise.

3.2.1 Torsion

The only consistent surface features described in long bone diaphysis are borders and surfaces. Often, there is a twist— an important biomechanical structural parameter caused by the spiral pathway of the collagen bundles, which have a large pitch extending from one end of the bone to the other. The elastic spiralling collagen bundles, due to the axial twist within the substance of a bone, possess energy-storing capacity, which has been completely ignored in the clavicle. The clavicle has poorly demarcated borders and surfaces due to segmentally varying screw twists, rapidly changing cross-sectional anatomy, and varying material distribution. In both the articulated and disarticulated clavicle, the inherent torsion and version are difficult to map. To accurately identify its anatomical and biomechanical features, hold a dry clavicle bone as a free body in its articulated orientation relative to three body planes and the axii.

To define torsion as a distinct morphometric feature in a long bone, measure it in between the two physes when present and, after maturity between the metaphyseal zones. Identify the anterior and posterior borders of the shaft and draw lines connecting proximal and distal metaphyses or any other pair of easily identifiable borders. Understanding how biomechanical forces influence the torsion angle in a long bone across a population at specific developmental stages will help achieve consistent, reproducible results with fewer intra- and interobserver errors. The angle measured between the projected lines at the far ends of the bone in the end-on view will tentatively provide the version angle in each specimen (**Fig. 2G**). No long bone exhibits a complete 360-degree torsion like a screw thread along its entire length around the longitudinal screw axis. When twisted, the twist in a beam flow in opposite directions at each end. This principle applies to the axial twist of a long bone as well. Therefore, the torsion angles of a dry bone can be measured between its physes or metaphyses in either clockwise or counterclockwise direction along its longitudinal screw axis using an analogue or a digital goniometer (**Fig. 9**).

One can also measure the torsion angle by standardising the position of the limb or a region of interest in a fixed position within a customized frame, or angular measurement on a computer screen between two computed tomography image slices from each end. Computed tomography is a reliable radiographic method for measuring the torsion and version angles in a long bone. This method can be applied to a resynthesized fractured clavicle against the intact contralateral clavicle. Nevertheless, excessive radiation is prohibitive in cases with frequent injuries. Instead, a medial-to-lateral shoot-through of a single-beam X-ray radiography is clinically more acceptable, as described in part 4 of this series, and may have future clinical applications.

In this regard, the clavicle is no different from being a long bone. Hold the dry bone in its articulated orientation in space, or preferably fixed in a customized frame, and mark its anterior-inferior and posterior-superior borders from

Figure 9. Digital goniometer devices are applied at the proximal and distal parts of the diaphysis of a cadaveric clavicle, which has a torsion angle of 39.3 degrees.

proximal to its distal end. The angle between any two segments from the costoclavicular fossa to the conoid or deltoid tubercle represents torsion angles of the middle three-fifths of the clavicle's diaphysis (**Fig. 9**). None of the normal long bones has more than a quarter twist of a screw thread, most commonly ranging between 10 to 50 degrees. The reported mean twist measured on computed tomography imaging of the clavicles at the transition segment between the medial and lateral curves, the experimenter's region of interest for designing a pre-contoured plate, was 35 degrees(Lambert et al., 2016). However, the torsion angle measured between two points on the clavicle's length can vary in everyone. To date, there is no known study that has reported the sequential measurement of the torsion angles at multiple diaphyseal stations of the clavicle.

The torsion of the clavicle is related to the position of the scapula on the dorsal aspect of the thorax and its anterior tilt in the coronal plane are reflected in the torsional and inclination angles of the acromion. The reported torsional angle of the acromion defined as the anterior-posterior angulation relative to the lateral clavicle against the sagittal plane is 80 degrees, which is approximately 10-15 degrees to the transverse axial plane(Zenker et al., 2022). The defined inclination angle, the angulation between the most lateral intersection line on the inferior surface of the acromion and the superior surface of the clavicle, is 16 degrees(Zenker et al., 2022). Although there is no correlation between these two angles, suggesting significant variability in the shape of the acromion, but following a malunited clavicle fracture, the angular variability in an individual will cause an altered volume of the subacromial space.

The subacromial space is clearly affected by the fracture anatomy of the clavicle, and so will the long axis of the resting glenoid, which normally faces anterolaterally with head of the humerus lying directly under the acromion. During abduction, the axial posterior rotation torquing the elevating clavicle with retraction also reorients the glenoid fossa facing more cranially and laterally. The torque experienced by the clavicle is stored as elastic energy, which is released to help the clavicle, scapula and humerus to return to their resting position. The cumulative effect of these stepwise mechanisms will be adversely affected following altered torsion and version angles in a malunited fracture of the clavicle.

The entire longitudinal torsion or screw twist of the clavicular shaft is a measure of the orientation of the distal stations around the screw axis relative to that of the proximal stations, which are twisted in the opposite direction. The changing direction of torsion in the clavicle shaft also alters the orientation of the borders, other surface features, and soft tissue attachments, from the sternal end to the acromial end. This gradual structural transformation, due to the spiralling of bone elements between the two ends of a bone, introduces the concept of version or the angle of version.

3.2.2. Version:

Generally, version is often applied to the most proximal subsection in the case of the femur and the humerus relative to their distalmost ends, as if the end were stationary. It refers to the angular alignment of the proximal and distal ends of an articulated and disarticulated bone when placed in its anatomical orientation. The version or version angle is the angular difference between these two ends (**Fig. 10**). It is measured between lines drawn touching or parallel to and through the centroids of the articular surfaces, which are the affected functional parts of the bone. The anterior angular tilt or turn, called anteversion, is considered the positive version, while the posterior angular turn or tilt, called retroversion, is regarded as negative version.

In the clavicle, the virtually stationary end is at the pivoting sternal end, while the turning end is at the acromial end. The difference in angular measurement between the two ends is the version angle. When seen end-on from the acromial end, like the femur both right and left clavicles turned anteriorly or ventrally and inferiorly, indicate anteversion or has a positive version. No known morphometric studies report on the version angle of the clavicle.

Figure 10. Digital goniometer measurements taken at the furthest sternal and acromial ends of a right cadaveric clavicle, showing a version angle of 37.8 degrees.

Both the shifting segmental torsion and version angles provides the same biomechanical energy-storage advantage for right and left-handed people when throwing a projectile or pitching a cricket ball.

3.3 Power transmission and torsional deflection:

In a mechanical system, power transmission via shafts involves moving mechanical energy from one place to another through rotational motion. The rotating and rolling clavicle transfers power of the attached muscles to the scapula and humerus at the glenohumeral joint. When a shaft is already twisted or pre-torqued, creating torsion in its substance, it bends slightly, just like the changing anatomy of the clavicle with an offset between the medial and the lateral curvatures. This twisting with bending of the shaft is called static torsional deflection. In engineering, understanding how a shaft twist underload is crucial for safe and efficient power transmission system. Phylogeny and ontogeny have achieved this for the evolving claviculate in the Animal kingdom and Homo sapiens, with modifications for individual adaptation, which occurs during the postnatal development under biomechanical forces.

The applied torque and the resulting torsional deflection are governed by material properties *(shear modulus of elasticity),* its distribution and geometric cross-sectional area *(Polar moment of inertia)* and length. These factors are the key reasons for gender variations and directional asymmetry of the clavicle. The cortical thickness along the shaft of the clavicle varies because the torsional stress distribution in a circular shaft is non-uniform, with maximum stress occurring at the outer surface of the shaft and decreasing linearly towards the centre. Therefore, depending on the centripetal forces acting on an individual clavicle, the medullary anatomy may also vary. Similarly, the segmental angle of torsion in a clavicle varies depending on the segmental torsional loading, which is directly proportional to the applied torque and the shaft's length and inversely proportional to the torsional stiffness *(modulus of rigidity)* of the shaft.

Aside from the fixed offset between the medial and lateral curvatures, with pre-existing torsion, as static torsional deflection of the clavicle, additional oscillatory dynamic torque *(changing twisting force)* or time-varying deflection during movement— known as dynamic torsional deflection or angular displacement in motion of a shaft —occurs when the shaft is subjected simultaneously to torsional loading and bending. A dramatic increase in dynamic torsional deflection in a case of a fall on an outstretched arm can potentially cause an oblique or spiral fracture of the clavicle's diaphysis. Since power, torque, and rotational speed are fundamental to the performance and efficiency of a throwing athlete, excessive torsional deflection can result in shaft failure. Repetitive arm elevation over time may cause microcracks that develop into stress fractures. Although rare in the clavicle, such fractures have been reported in javelin throwers, gymnasts, weightlifters and even coffee tamping(Constantinou & Kastanos, 2008; Yusuf et al., 2020). Conjunct axial rotation and rolling during arm elevation continuously shift the stresses along various segments and the surfaces of the clavicle, likely preventing excessive dynamic torsional deflection and avoiding frequent stress fractures.

3.4 Clinical significance and relationship of torsion and version within biomechanical architecture of the clavicle:

In clinical practice, the purpose of measuring the angular features of torsion and version angles in a long bone is to support individual inherent and developmental biomechanical functions, to stabilize the adjacent joints, to allow smooth, balanced, and energy-conserving locomotion and prevent injury. These angular features also offer the same advantages to the horizontally oriented clavicles, which transmit forces from the hand to the ground and vice versa, through the kinetic chain. The clinical studies of epiphysiodesis and epiphysiolysis suggest that the torsion of the diaphysis arises from the physis during growth, establishing the spiral arrangement of the cells and collagen in the substance of the bone because of biological chirality. Biological chirality is the formation of opposing spirals at the submicron and gross anatomical levels, such that the right-side structures cannot superimpose on those structures of the left(Inaki et al., 2016). For instance, the left hand cannot be superimposed on top of the right hand; therefore, the right-side forearm pronation and supination are opposite to the left.

Torsion and rotational deformities in bones can follow physeal injuries or iatrogenic epiphysiolysis and epiphysiodesis. In bones and soft tissues, the opposite bilateral spiral arrangement (*chirality*) of elastic collagen fibres gathers and stores energy, releasing it passively during the reversal of a motion, transferring ground-reaction forces through links and joints of the skeletal system. Mechanically, the passive reversal of motion in bones, joint ligaments and capsules conserves energy. Many muscles also act synergistically and antagonistically, in a conjunct and adjunct role to coordinate movement and its reversal to a resting state through concentric and eccentric muscle contractions. Therefore, to prevent injury and rapid atrophy after injury, retraining and warm-up are recommended to avoid eccentric injury against sudden increases in load during acceleration. There is an increase in the weight of the mass with increasing velocity (*a Newtonian concept, weight = m× g, mass is constant because the matter does not change, the weight change is due to g, the gravitational acceleration*) during the initiation of a movement, acceleration and its release. Thus, the cumulative effect of the repeatedly accelerated combined mass of the object and the arm is much higher, causing chronic shoulder injuries than realized.

The simple biomechanical design, concentrated in the clavicle's architecture, is a significant evolutionary development for delivering high-velocity projectiles. The angles of torsion and version resulting from pre-torquing of the spiralling collagen bundles in the clavicle have received no attention so far; therefore, they have been overlooked in treatment strategies for managing clavicle fractures.

The "anterior torsion" described in the older literature (DePalma, AF) refers to the anterior tilt of the acromial end of the articulated clavicle, which varies with plane of the acromioclavicular joint facets directed inferiorly and medially to the sagittal plane(J. Vanderbeck et al., 2009). The tilt angle also covaries with the inferiorly and laterally directed plane of sternoclavicular articulation. The anteriorly directed tilt of the acromial end has an inverse relationship to the angular planes of both the acromioclavicular and sternoclavicular joints. The greater the acromioclavicular joint angle, the lesser the degree of tilt and rounding of the articular surfaces(J. Vanderbeck et al., 2009). With the increasing acromioclavicular joint angle, the lateral curvature of the clavicle becomes more prominent *(the radius of curvature gets shorter with deepening of the curve)*, with thickening of the acromial end. There is a significant correlation between the lateral curvature and the angulation of the acromion, producing various types of inferiorly directed anatomy of the acromion, which lead to variable subacromial space volume.

The differing segmental torsional angles between the right and left clavicles in an individual, under different biomechanical forces, can be expected to show sectional variation along the clavicle's length, leading to different version angles. In many respects, the design of the clavicle is analogous to an aeroplane propeller, featuring a changing twist from the shank to its tip, resulting in varying angular speeds, with the greatest at its tip. Thus, maintains an equal amount of thrust along its entire length. The aeroplane propeller blade has a variable cross-section, changing from a round shank to an ellipse, and then flattening, with a decreasing blade angle towards the tip (**Fig. 11**). A scimitar-type of propeller has a curve towards its apex.

The prismoid sternal end, oval to-round diaphysis, becoming elliptical to a flat acromial end, longitudinal torsion, version, and various curvatures built into the clavicle are technically comparable in design to the aeroplane propeller blade. The clavicle's highly developed technical features generate [1]power at the glenohumeral articulation for thrusting a projectile into the air and lifting heavy weight overhead.

For experimental studies, finite element modelling and morphometry of the dry clavicles for measuring torsion and version angles, and curvatures can be performed on a computer's visual display unit from three-dimensional computed tomography or three-dimensional photography images using a combination of software platforms, such as Amira, tpsDigs, and Geomagic Suite.

---

[1] Power = Force x Distance/Time

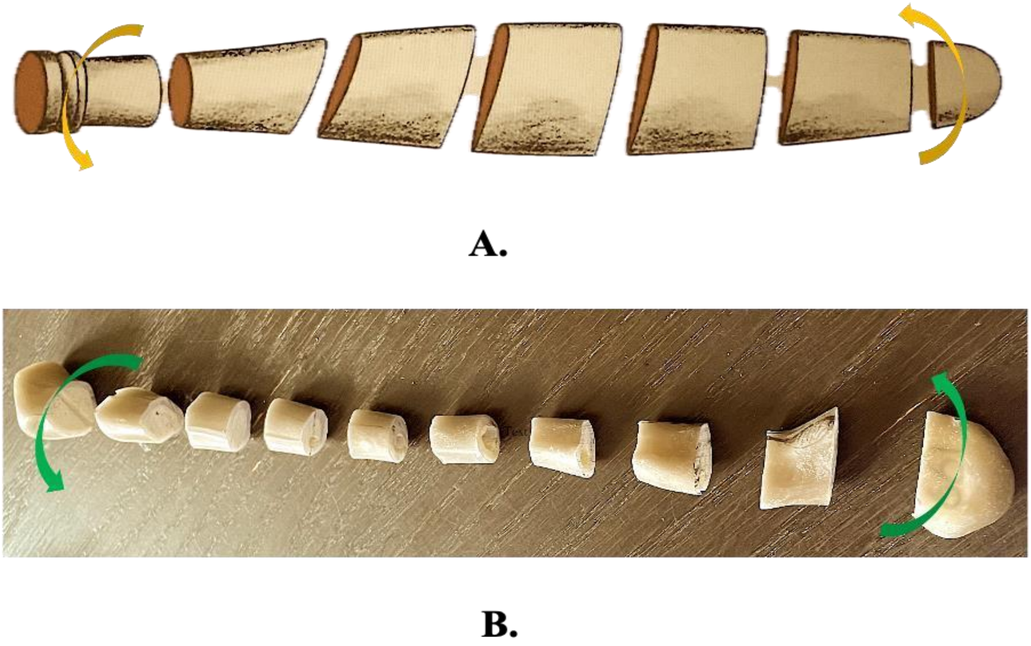


Figure 11. A. Variable cross-sections of an aeroplane propeller blade without curvature, with a right-handed twist at the flat tip and a left-handed at the shank and B. The variable cross-sections of the right Sawbone© clavicle resemble those in appearance and have a clockwise twist at the flat acromial end in contrast to the broader sternal end.

4.0 Other angular parameters of the clavicle:

4.1 Pitch angle and pitch axis:

The pitch or pitch angle is a rotational or turning angle between the centreline of the clavicle and pitch axis, around which it rolls from the ventral to the dorsal direction at the sternoclavicular joint during movement of the arm at the glenohumeral joint. The conjunct axial rotation of the clavicle, depending on the strain, the segmental torsion angles at each station of the clavicle's diaphysis, an equivalent amount of elastic energy is stored, which varies with the amount of the applied torque. The pitch angle affects the sectional moment arm *(the variable distance between the pitch axis and the anatomical axis or the centreline),* changing the experienced torque at each section of the diaphysis between the pitch axis and the anatomical axis passing through the centre of each section along the length of the clavicle. This varies significantly due to the offset between medial and lateral curvatures (**Figs. 12 and 13**).

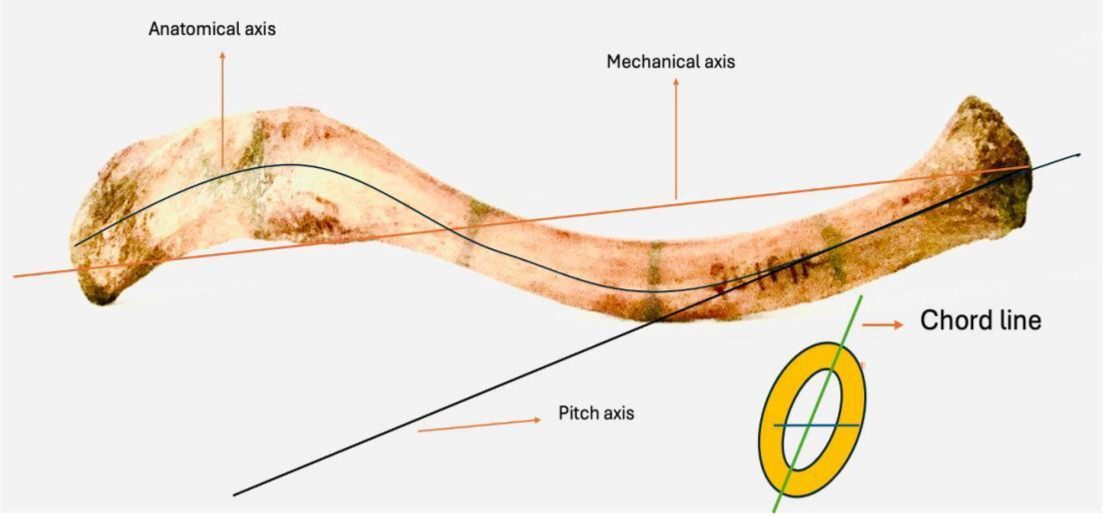


Figure 12. Anatomical axis, mechanical axis and pitch axis of the clavicle. The chord line of a cross-section.

Figure 13. An offset between the medial and the lateral curvatures

The pitch angle of the clavicle depends on rotation at the sternoclavicular joint, whereby the acromial end of the clavicle traces a part of an irregular elliptical base of a cone as it rolls around the pitch axis with its apex at the clavicular fossa of the manubrium sterni. This provides additional torque and acceleration, thereby imparting forward thrust to a projectile. Whether the change in pitch angle is passive with the elevating arm or active due to the assistive action of one or more muscle force couples acting synergistically and supportively is difficult to say, as no single muscle actively causes turning of the clavicle, like the pronator and supinator muscles acting on the radius in the forearm. And there is no muscle responsible for axial rotation of the clavicle on its mechanical axis.

The pitch axis is the axis around which the clavicle rolls upwards and backwards, which is different from its longitudinal mechanical axis around which it rotates or oscillates **(Fig.12)**. It is a characteristic of the clavicle's biomechanical architecture due to the combined influence of the curvatures, torsion and version. Therefore, the population has as many pitch angles and pitch axii as many clavicles due to subtle differences in the sectional twist angles, curvatures and the degree of offset between medial and lateral curves. The pitch axis is a straight line relative to the three planes, projected through the centroid of the sternal end of the clavicle and directed laterally towards the acromial end. It becomes the 'mechanical axis', which is different from the mechanical axis of axial rotation of the clavicle, when the articulated clavicle rolls, ventral to dorsal direction, with vertical elevation and dorsal retraction during arm elevation.

The anatomical axis and the mechanical axis do not pass perpendicular to the mid-point of the chord lines in each variably shaped cross-section through the intersection of nearly horizontal transverse and vertical coronal planes of the clavicle in situ, like in the case of an almost straight tibia. Furthermore, the articulated clavicle is not perpendicular to the median plane, nor to the vertical axis defined by gravity. The clavicle exhibits a significant offset between its medial and lateral curvatures (**Fig. 13**). Unlike the cone traced by the acromial end of the rolling clavicle around the pitch axis, when the articulated clavicle rotates on its mechanical axis at the centroid of the sternoclavicular articular surface, the acromial end draws a smaller cone angle open laterally, with an oblique elliptical base.

The articulated clavicle in its biplanar pose is inclined cranially in the transverse plane and retracted dorsally in the coronal plane, the pitch axis of the rolling clavicle from ventral to dorsum and vice-versa is at variable distances from the anatomical axis because of the offset and the centroids of the changing cross-sectional chord lines of the medial, lateral and other curvatures are not in a straight line **(Fig. 12)**. Therefore, the pitch angles vary at each station, as do the diaphyseal angles of torsion. Nor is the cone angle close to zero or the same at any two points on the anatomical axis. Consequently, each clavicle is optimized at every station *(segment)* to provide optimal kinematic and kinetic values at the glenohumeral joint.

4.2 Twist in the clavicle:

After a bone fracture, the failure to restore the anatomy and biomechanical architecture of the bone can only worsen its mechanical function as a linkage within a mechanism. It also applies to the pectoral girdle mechanism and that of the upper extremity with a malunited clavicle fracture, even after the early adolescent years. The uncorrected mechanical and pitch axii means there will be an altered state of retraction and elevation angles. The angles of torsion are a result of how the material is distributed around the axis of each station or a section passing perpendicular to the midpoint of the cross-sectional centroids at the chord lines. This reflects the average angle of torsion along the entire length of the diaphysis, and the version between the proximal and distal articular planes. Applying the right-handed screw convention to the clavicle, viewing from the acromial end, from observing and palpating the surface features, the torsion path is clockwise on the left and counterclockwise on the right.

Theoretically, the screw twist encircles the screw axis, closely following the anatomical axis, runs along the diaphysis of the clavicle from medial to lateral direction. The large screw pitch, beginning at the proximal

Figure 14. A left Sawbone© - black line marking the posterior-superior (posterosuperior) border showing clockwise torsion when viewed from the acromial end.

metaphysis, changes direction along the anteroinferior (anterior-inferior) and posterosuperior borders, shifting from the anterior to posterior at the transition zone between the medial and lateral curves (**Fig. 14**). Then, suddenly, at the vertex (*peak of the convexity*) of the lateral curve, it runs from posterosuperior surface to inferior surface to exit through the articular facet at the acromial end with a much shorter pitch. If a bar is twisted like the clavicle, the two ends will twist in opposite directions, resulting in a screw thread with both a long and a short screw pitch, forming a differential screw mechanism that will turn at variable speeds. The spiral formed by the collagen bundles is naturally pre-torqued, twisted about its own axis, and behaves like an industrial torsional spring, absorbing the applied force. Similarly, the bone absorbs energy due to its inherent material properties and helical collagen structure, reverting to its original state once the stress applied during motion is removed. The collagen fibres within osteons and lamellae in long bones exhibit alternating chirality(Standring, 2016). As there are no studies available, it is likely that the collagen bundles in the clavicle also exhibit alternating chirality, forming a meshwork of double helices, with a predominance of clockwise spirals in the cortex of the left clavicle and counterclockwise in the right clavicle.

The varying torsion angles and a large screw pitch of the clavicle's medial curvature help store elastic strain energy and accelerate axial rotation at the shorter pitch of the lateral curvature, not only during baseball pitching but also when throwing a ball, underhand curling, and in many other less popular sports, as well as in daily activities. The force required to drive a right-handed screw forward overtightens the twist of the clavicle, increasing its elastic strain potential energy. This energy is then released as the twist unwinds, returning the clavicle to the resting state and preparing for the next turn. Remember, the twist runs opposite at the two ends, and strain takes effect when the sternoclavicular joint attains the closed-packed position. Although no visible twist appears in the diaphysis during motion, there is an intrinsic structural change at the micro level in the torsion angles at infinitesimal sections, with a smooth return because of the viscoelastic nature of the bone material. The variable cross-sections and thickness of the cortical shell, together with the arrangement of the trabeculae in the medulla of the clavicle effectively bear the compression and torsional loads.

The gradually changing cross-sectional anatomy from the sternal to the acromial end offers uniform transmission of the thrust and the offset between the medial and lateral curvatures, analogous to a scimitar propeller, which reduces vibration, saves energy, and increases thrust and performance, depending on individually optimized shape and form of the clavicle. In the articulated state, the clavicle, with its quadrangular cross-section at the sternal end, has a high polar moment of inertia. The flat acromial lateral two-fifths, oriented anterior to posterior, has a high second moment of area when loaded in the transverse plane. There are no known studies showing how the bone viscoelasticity will contribute to the unique architecture of the clavicle in its articulated or disarticulated state under experimental conditions, other than its load dependent material distribution, especially under torsional loads in an intact clavicle and fracture callus.

5.0 Vascular and neural anatomy of the clavicle:

Among all surface features, the number and distribution of nutrient foramina of the clavicle have recently attracted significant interest. Nutrient foramina serve as entry points for the nutrient artery and/or vein, as well nerve supplying the endosteum (**Fig. 5**). The secondary blood supply occurs through the periosteal sleeve, which is thicker and more vascular in children than adults.

In a study of paired dry clavicle bones, of the total number of nutrient foramina 70% were in the middle third, 20% in the medial third, and 10% in the lateral third sections. In the paired bones, all right clavicles had patent foramina, whereas only 30% of the left clavicles did, allowing a 24G hypodermic needle(Fatima et al., 2024). The site of the nutrient foramen on the posterior or inferior surfaces or both in the middle third of the diaphysis indicates the initial invasion of the nutrient artery roughly at the site of embryonic endochondral ossification centres.

One of the earliest cadaveric studies using a low-viscosity injectable polymer did not observe any nutrient artery in their adult specimens(Knudsen et al., 1989). The lateral four-fifths of the clavicle received a network of periosteal branches of the Supraclavicular and Thoracoacromial arteries. The one-fifth sternal end of the clavicle received blood supply from periosteal branches of the Internal thoracic artery. The group tested the Sternocleidomastoid arterial branch to examine the supply through the muscle attachments, but it did not produce a periosteal network.

In a limited anatomical study, a thoracic branch of the Thoraco-acromial artery passing deep to the Cleidobrachialis pectoralis divided to form a periosteal network over the medial third of the clavicle, and its acromial branch penetrated deep to the Cleidobrachialis deltoideus dividing to create a separate periosteal network to vascularize acromial one-third(Havet et al., 2008). The Supraclavicular artery sends posterior periosteal branches to the medial and lateral thirds on the posterior surface of the clavicle and sent a branch into the posterior nutrient foramen about 45mm from the acromial end to serve the middle third. Thus, supplying both the endosteal and periosteal surfaces of the cortex.

A recent systematic review of thirty-three studies found 3358 nutrient foramina in 3760 clavicles. Ninety-seven per cent of the clavicles had one or more foramina; 75% were in the middle third of the diaphysis, and just over half were on the posterior surface and the remainder on the inferior surface(Ejlersen, 2023). Over 99% of the foramina were directed obliquely towards the acromial end. The study called for an update to the textbook's description, which stated that 98% of clavicles have nutrient foramina on the posterior and inferior surfaces.

The traumatic loss of periosteal blood supply is considered a likely cause of clinically observed rates of non-union of 11-16.5% of the middle three-fifths, 28-44% in the lateral one-fifth, and only 5% in the sternal one-fifth(Asadollahi S & Bucknill A, 2019; Serpico & Tomberg, 2021).

Almost all observational studies mapping the distribution of nutrient foramina are conducted on dry clavicle bones. Therefore, it is difficult to determine whether the nutrient foramina during postnatal development are functional, or if the ‘ghost’ openings are from the foetal days and childhood years. There is a lack of in-vivo angiographic studies and inconsistencies in the reported studies on dry clavicles. It is likely that the clavicle has a predominantly periosteal blood supply to most of the diaphysis and through muscular insertion of the Subclavius, the Cleidobrachialis pectoralis, and the Cleidomastoid rather than through tendinous insertion of the Sternocleidomastoids, Trapezius and Cleidobrachialis deltoideus.

The sternal, diaphyseal and acromial branches of the Supraclavicular nerves innervate the periosteum of the clavicle on its superior and anterior surfaces along its entire shaft. The subclavian nerve (nerve to the Subclavius) supplies the posterior and inferior surfaces of the middle and medial thirds. The lateral pectoral nerve innervates the inferior surface of the middle and lateral thirds of the bone(Leurcharusmee et al., 2021).

6.0 Morphometry of the clavicle:

Numerous morphometric studies measure the clavicle's lengths, biplanar external and internal diameters, medial and lateral transverse-plane curvatures, and angles along the centreline or surface radii of curvature. Few studies have measured tangential angles of the curves in the coronal plane. The laterally concentrated inferior curve, the superior surface curve of the diaphysis at the inflection region flowing towards the acromial end of the clavicle have received the least attention. The version and segmental torsional angles have never been measured, except for the torsional angle at the junction of the transverse plane medial and lateral curvatures(Lambert et al., 2016). The available morphometric data in the literature are derived from dry clavicles for anatomical, forensic, and anthropological studies. Over the last hundred years, information has been available from almost all continents at the regional level, including cadaveric collections in anatomy departments, forensic medicine, and museums.
Recently, the trend has been to study the clavicle morphology and morphometry from computed tomography.

6.1 Morphometry of dry cadaveric clavicles:

Initially, the bidirectional asymmetry in length and mid-shaft diameter, as well as gender differences, of the clavicles attracted attention in the second decade of the 20th century, with greater interest continuing into the 21st century(Jit & Singh, 1956; Kaur H & Sahni H, 2002; Parsons, 1916). The bilateral asymmetry is not unique to the anatomy and biomechanical architecture of the clavicle, as it is influenced by genetics and environmental factors. There is a directional asymmetry in diaphyseal width and length of long bones of the upper and lower extremities, with right sided bias, which is less pronounced in length(Auerbach & Ruff, 2006).

The upper extremity morphometry shows a much more remarkable right-sided bias. The right humerus has a greater mid-diaphyseal circumference and length compared to the left, except that the angle of torsion is biased to the left and inversely proportional to the other parameters(Dare et al., 2019). Variability in the circumference and angle of torsion within a population is due to individual manual activities and handedness. One of the mechanical functions of the clavicle is to increase the parasagittal distance of the arm from the median plumb line, the vertical gravitational axis of the body for right and left equilibrium and stability during bipedalism. It is the total functional length of the upper extremity that matters most, reaching into three-dimensional space and swinging to add power to progressive gait.

Statistically, on average, the left clavicle is longer than the right clavicle, while the right clavicle has a greater midshaft diameter. The dry bones are measured using analogue or digital linear and angle-measuring instruments. In computed tomographic studies, the clavicle is either left set-in situ or virtually segmented in a disarticulated static state. Since it is at the root of the neck, the collected radiology samples include non-trauma clavicle images from the computed tomography of the thorax and neck. Clavicle anatomy is measured and reported using the PACS tools on a computer visual display unit. Some studies have even developed computer-based models and multiple atlases to define various parameters for surgical applications and customize fracture fixation implants.

A study from the Northwest region of the Indian subcontinent reported that in males, the length of the clavicle increases by 7.11 mm on the right and 6.49 mm on the left between the ages of 18 and 30 years(Kaur H & Sahni H, 2002). In the same study, both male and female adults showed significant correlations between clavicle length, supine body length, body weight, body surface area, and age. The right and left asymmetry does not apply to foetuses and newborns. The greater centre line angle of the lateral curvature on the left side than on the right side adds length to the left clavicle.

In an English cohort of 100 pairs of half-and-half male and female clavicles, 54% of left clavicles were longer than the right, 34% of right clavicles were longer than the left, and in the remaining 12%, the clavicles on both sides were equal in length(Parsons, 1916). In a cohort of paired 100 male clavicles in Punjab, 66.3% of left clavicles were longer than right by 0.5 to 13.0 mm, while 24.4% of the right were longer than the left by 0.5 to 8.0 mm. The remaining 9.3%, had clavicles of equal length on both sides(Jit & Singh, 1966). As individual variations in various parameters can be significant, the reported statistics are good for reporting general trends but have limited value for patient specific surgical planning.

Most recent morphometric studies are focused on the design of on lay or intramedullary implants. A detailed survey of freshly plastinated cadaveric clavicles, with examples of embedded intramedullary implants, studied several parameters(Andermahr et al., 2007). Female clavicles with smaller diameters have shallower curves (*having a longer radius of curvature and longer chords*) compared to male clavicles. The mean cortical thickness was 0.23 +/- 0.05 mm at the sternal end, 2.05 +/- 0.20 mm at the midpoint, and 0.95 +/- 0.35 mm at the acromial end. The convex medial ventral cortex and the dorsal aspect of the acromial end had the thinnest cortex. The highest average cortical thickness was in the dorsal quadrant of the middle third (*concave posterior cortex*). The narrowest segment of the medulla of the clavicle measured was 6.7 +/- 2.6 mm in the segment between the two curves. Bone density decreased from medial to lateral.

In practice, it is essential to identify the various segmental morphometric measurements and cortical thickness as an indicator of bone density on plain radiography. Three-dimensional volumetric CT images provide greater accuracy. Not only the length but also the cortical thickness, inner and outer diameters, and depth of the curves of the clavicle in each patient are key parameters to consider during surgical planning.

6.2 Three-dimensional computed tomographic measurements:

A computed tomographic study of three-dimensional models of segmented clavicles (*a virtual state of disarticulation*) quantified intramedullary canal shape and size, and other morphological features(Aira et al., 2017). It included centreline deviations, radii of medial, lateral and inferior curvatures from the centreline and diameters. The narrowest average external cortical and intracanalicular diameters measured were 13.29 +/- 2.05 mm and 3.82 +/- 1.02 mm. Between 40 and 60% of the length from the sternal end, the parameters were larger in males than in females. Males had a longer radius of curvature at the medial curve, ranging between 56.88 and 139.85 mm, compared to females. On average, the radius of the medial curvature on the left-sided clavicle was 4.70 mm longer than the right due to the flatter curve. The radii of the lateral curvature ranged from 10.44 to 75.93 mm, on average, which was 1.66 mm longer in the females compared to the males. The range of the inferior curve in the coronal plane ranged between 96.02 and 802.23 mm. The absolute length (*end-to-end*) varied between 125.24 and 176.46 mm, whereas female clavicles measured 10% shorter than those of males. Overall, the right clavicles were significantly shorter by 2.39 mm than the left. In males, the absolute length was shorter by 3 mm on the right side, while in females, it was 2.52 mm shorter. The actual length (*centreline*) of the clavicles ranged from 137.09 to 197.70 mm., with high correlation between the two measurements. The side difference was 4.32 mm in males and 1.57 mm in females. Eccentricity exists between the centre of the outer surface and the medullary canal due to variable cortical thickness and varying cross-sectional anatomy along the length of the clavicle(Aira et al., 2017).

There is morphometric bidirectional asymmetry, as demonstrated by various dry bone and computed tomography studies. Currently, for surgical outcomes, the length of a clavicle is the main variable. Apart from the end-to-end length, coronal and transverse diameter geometry, internal and external diameters, cortical thickness, and bone density are other important parameters to consider in the surgical management of acute clavicular fractures. The external and internal diameters and the depth of the medial and lateral curvatures are crucial for choosing the size of an intramedullary implant to prevent microcracks due to hoop stresses and to achieve an interference fit for stability. Apply these parameters carefully in cases of non-union and malunion of the clavicle with significantly deformed geometry and notable bidirectional variations.

Becoming cognizant of the acromial end concentration of inferior and superior curvatures is vital in cases of acromial third fractures. The inferior coronal plane curve is more pronounced on the left than on the right in both male and female clavicles(Bernat et al., 2014). Smaller patients have shorter, more curved (*shorter radius of curvature*) clavicles, whereas taller patients have longer, less curved (*longer radius of curvature*) clavicles. A 170 cm tall person has an average clavicle length of 145 mm(Fontana et al., 2020). There can be a difference of up to 58 mm between the smallest and largest clavicles in an experimental cohort(Aira et al., 2017).

None of these studies measured torsion or version angles. The axial rotation of the clavicle plays a vital role in attaining full coronal, scapular and sagittal plane abduction, as well as glenohumeral joint kinetics in overhead and underhand throwing mechanisms.

Directional asymmetry refers to significant unimodal population-level deviations from bilateral symmetry that most likely arise from lateralized behaviours(Auerbach & Ruff, 2006). The directional asymmetry favours stout features on the right side with a greater diaphyseal diameter but a shorter length. The reasons left and right clavicles deviate slightly in anatomy and biomechanical architecture are believed to be due to genetic, hormonal, and biomechanical stresses as the primary explanation leading to asymmetrical development of entheses, size and shape, body size and individual activities(Auerbach & Ruff, 2006; Schlecht, 2012). The diaphyseal robustness is more sensitive to the loading conditions than the length of the clavicle. However, the length asymmetry is significantly greater in males than in females(Abdel Fatah et al., 2012). The male clavicle shows asymmetry in all parameters, including muscle and ligament footprints. In contrast, female asymmetry is more significant, showing curvature variations between right and left clavicles(Abdel Fatah et al., 2012).

The highly variable parameters demand early surgical planning to procure the required implant sizes, especially for the outliers, reasons of gender differences, and geographical variations. The most obvious size difference in a set of clavicles is between sternal and acromial ends, transformation of the shape from prismoid to flat and diameters in ventral to dorsal and cranium to caudal directions. The middle two-fifths are elliptical, oval and circular, but what varies most are the curvatures. First, the clavicle morphometry is undertaken as a whole bone, followed by a structurally specific region of interest to select patient-specific implants for expected outcomes in each patient. The less recognized torsion and version angles and variations in the screw pitch need further research for better understanding and greater attention in the future.

7.0 Surgical application of morphometric variations and bidirectional asymmetry of the clavicle:

The term “shape” refers to the solid geometrical form of the clavicle. It describes surfaces and borders, various curvatures, depressions and eminences, as well as prismatic, circular, oval, elliptical, and flat cross-sections. These shape characteristics apply to both the outer cortical and inner endosteal surfaces of the clavicle. In addition, the changing torsion angles *(twist in the diaphysis)*, version *(the angular difference between the flat acromial end of the clavicle relative to the expanded sternal end)*, and three primary curvatures.

Besides knowing the significant bidirectional asymmetry and differences within and between biological male and female genders, the key morphometric parameters relevant at the time of planning for the clavicle fracture reconstruction for satisfactory surgeon and patient-based outcomes are the restoration of clavicle length, radii of medial and lateral curvatures, coronal plane laterally concentrated inferior curvature and convexity of the superior surface at the third-fifth (3/5) and fourth-fifth (4/5) segments of the diaphysis, awareness of the sectional angle of torsion and version, medial and lateral curvature offset, and changes in the screw pitch at the transition section, by matching the external and internal diameters of the major fragments in coronal and transverse planes. Consider these anatomical features when selecting either extramedullary on-lay surface or intramedullary implants and reorientating the clavicle for patient-specific dorsolateral repositioning of the scapula on the thorax to prevent winging and scapular dyskinesis, which are assessed clinically and radiologically at the end of surgery.

The recovery of the cross-sectional area at the fracture site is critical for resisting axial compression and torsional forces. The centroid is the geometrical centre of an area or a volume. The moment of inertia (*second moment of area or polar moment of inertia*) relates to the geometry of infinitesimal sections or stations. It describes resistance to bending and torque. In case of the clavicle, the anatomical axis passes through the centre line of the diaphysis. The mechanical axis is a straight virtual line passing not through the centre of the joint surfaces but through the centroid of the expanded prismoid sternal end and the variably oriented flat rectangular acromial end.

Note these parameters when analyzing an intact clavicle for simulation during surgical preplanning to restore the anatomy and biomechanics of the fractured clavicle. The nearest simulation model for comparison is the intact contralateral clavicle of the patient rather than atlases of clavicle morphology and morphometry from a few thousand specimens in the literature. The external and internal diameters at various stations are central to plating and intramedullary implants when choosing fixation points for greater triplane stability and restoration of the influential length *(an effective length of each station and total length of the clavicle in the context of stress distribution, transfer of forces between the proximal and distal linkages, anti-buckling and refracture resistance as a result of the length to diameter slender ratio and altered material properties, kinematic and kinetic values of a mechanical linkage to load)* of a reconstructed clavicle.

The length of the clavicle changes with a change in the chord and the radii of curvature of the lateral and medial curvatures. The intact contralateral clavicle provides the best database for the restoration of a clavicle to its prefracture length by a simulation technique despite directional asymmetry in 65-75% of the population. It will help correct deformation not only in length, but also the transverse and coronal plane curvatures at its minimum. Advanced radiological study including three-dimensional computed tomography for the correction of the angle of torsion, version, offset and screw pitch. These parameters are essential for attaining preinjury strength and range of motion at the sternoclavicular and acromioclavicular articulations, scapulothoracic and acromiohumeral synsarcosis, and glenohumeral articulation. For maximum original length attainment and correction of all the curvatures, measure the centreline length (*reference length generated by connecting several dots in the centre of the medulla of the clavicle, from the articular surface of the sternal end to that of the acromial end*) of the intact clavicle and of fracture fragments and the gap left by loss of tiny bone particles (**Fig. 15**). Fill any gap exceeding 2mm with autogenous iliac bone cancellous particles, or cancellous dowels(Missiuna & Gandhi, 2011). In a comminuted fracture pattern with unrecoverable multiple fragments, consider fixation with a suitable plating system instead of the intramedullary implant.

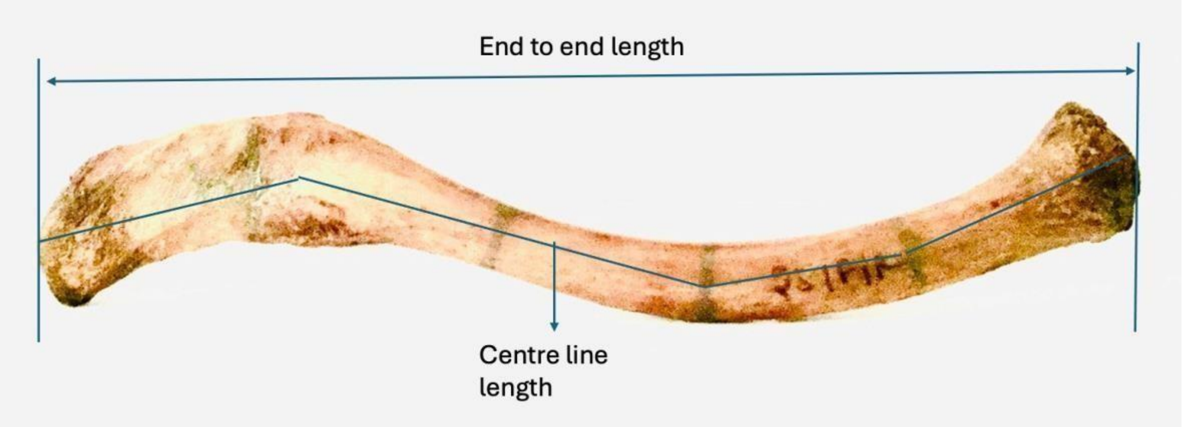


Figure 15. Measuring end-to-end and centreline lengths

Depending on the radii of curvature, the difference between the centreline length and end-to-end length can be significant(Aira et al., 2017; Kaur H & Sahni H, 2002). Use the contralateral clavicle database to check the structural offsets in curvatures and angular deformations of the restored clavicle. Comparing the geometrical parameters with the characteristics of the patient's intact clavicle in-plane *(compression and shear)* and out-of-plane *(bending and twisting)* database baseline *(working loads)* is essential before the fracture callus matures. It will help to plan the resting and rehabilitation periods before returning to vigorous activities. Remember, there is no single rehabilitation plan for all patients for same injury. The residual deformity may improve with rigorous physical rehabilitation and daily activities, based on the principles of functional load modification in bone remodelling *(Wolff's, Volkman's and piezoelectric effect)*. Otherwise, early corrective surgery is imperative for a patient-specific biomechanical outcome.

8.0 A preliminary morphometric study for measuring of version angle, sectional torsion angle in dry clavicle bones:

A pilot study was conducted at the Anatomy Department of the Government Medical College, Amritsar, Punjab—permission was granted upon request. Ten unmarked, dry clavicles were randomly selected by the bone keeper of the department. No information on age, gender or cause of death was available.

The study focused on demonstrating sectional torsional and version angles with varying cross-sections and twist between sternal and acromial ends, as explained above.

Methodology: Ten cadaveric dry clavicles and one large Sawbone© clavicle were included to measure torsion and version angles. The pre-existing domed heads of the set screws on photography stand clamps were machined flat, allowing levelled placement of the magnetic bases of the digital inclinometers (Mastercraft©). Each specimen was identified as right and left by placing in its anatomical orientation based on the curvatures, surface features, and sternal and the acromial ends. On each clavicle specimen, posterior-superior and anterior-inferior borders were defined from the sternal to the acromial end. A centring angle on the inner surface of the clamp jaws, bearing the rubber cushions to prevent damage to the clavicle specimen, was applied, aligning along the two borders at selected sites.

Figure 16. Measurement of the version angle and the sectional torsion angles at one-fifths' intervals from acromial to sternal end of a large left Sawbone©.

Measurements: The end-to-end lengths of the clavicles were measured using a pair of vernier callipers and a steel ruler. The anteroposterior and craniocaudal diameters measured at mid-shaft are not recorded here. For measuring the version, the clamps were applied at the sternal and acromial ends as close as possible to the articular surfaces and held in place firmly with finger tightness to prevent slipping off the sloping surface of the bone (**Fig. 16**). The torsion angles measured from acromial to sternal end between first-fifth (1/5) and fourth-fifth (4/5); second-fifth (2/5) and fourth-fifth (4/5); and third-fifth (3/5) and fourth-fifth (4/5) segments along the diaphysis of the clavicles. Each time, the inclinometer was calibrated within 0.2 mm tolerance of the instrument before applying it to the clamps. The measurements were recorded after allowing the clavicle specimen and the inclinometers to reach a steady state, I recorded the readings from both the instruments. The difference in the readings between two inclinometers at any two diaphyseal segments was recorded as the torsion, and the measurements between the furthest ends of the clavicle as the version angles.

Results: All specimens showed variability in length, anteroposterior, craniocaudal diameters, border markings, and footprints of ligament and muscle attachments. The variability in medial, lateral and inferior curvatures, torsion and version angles was evident when the clavicle specimen laid on its cranial and caudal surfaces. The offset between medial and lateral curvatures was evident when standing perpendicular on its sternal end articular surface.

The recorded length, version angle and torsion angles between various stations are given in Table 1. The missing details are either because of experimental error due to difficulty in getting a stable fixation of the inclinometers or the slenderness of the diaphysis at the second-fifth and third-fifth stations to get a sufficient grip of the clamp jaws **(Table 1).**

Table 1

Specimen number and side	Length in mm	Version angle	Torsion angle between 1/5 and 4/5	Torsion angle between 2/5 and 4/5	Torsion angle between 3/5 and 4/5
1 Right	155	6.9	22.2	22.1	29.5
*2 Right	137.12	18	32.8	37.9	30
3 Right	133.53	Error	36.3	28.3	41.3
4 Left	160	32.2	25.8	30.6	Slender
5 Right	149.55	19	8.5	Slender	Slender
6 Left	144.56	14.2	14.0	Slender	Slender
7 Right	144.54	34	36.6	38.9	Slender
*8 Left	149.50	48	40.7	39.3	37.7
9 Right	146.34	37.8	25.5	Error	39.3
10 Right	142.9	20.2	Slender	Slender	Slender
11 Left Sawbone©	170	42.24	45.3	45.1	10.4

The mean length of the dry cadaveric bones – 146.90mm Mean

Version angle – 25.5 degrees

Mean torsion angle between 1/5 and 4/5 – 26.93 degrees

Mean torsion angle between 2/5 and 4.5 – 32.85 degrees

Mean torsion angle between 3/5 and 4/5 – 35.56 degrees

For the large left sided replica Sawbone© clavicle: Length 170mm

Comments: Technically, only cadaveric specimens 2 and 8 marked with a * sign produced reliable measurements among the ten dry clavicles. The torsion angle varies across different sections of the diaphysis, and the version angle can be lower or higher than the sectional torsion angles. The diaphyseal segmental torsion angles may be measured from the sternal to the acromial end or vice versa, or between any two adjacent of segments to demonstrate the segmental variability. In future experiments, for consistency, the clavicle should be segmented from the sternal to the acromial end, aligning with the screw twist following the likely course of the collagen bundles in the bone. The main limitation of the study was that the clamping device was too large for small-sized clavicles, and the inclinometer did not maintain the desired position. The clamp must be able to grip all sizes of the clavicles from the sternal to the acromial end without skidding off the inclined and irregular surface of a clavicle.

For greater accuracy, a frame is needed to hold the clavicle in an articulated orientation, with 15-20 degrees of cranial elevation to the transverse plane and 20-30 degrees of dorsal retraction to the coronal plane, thereby accommodating the offset between the medial and lateral curves. The torsion angles between 1/5 and 2/5, 3/5 and 4/5 stations, and the version angle are technically crucial for the restoring the cranking and energy storage functions of the clavicle, by paying greater attention to reconstructing the medial and lateral curvatures. It is imperative to correct the offset between the two major curvatures and the version angle to achieve patient-specific repositioning of the scapula to prevent scapular dyskinesis, which must be assessed while the patient is still under anaesthesia. At the same time, with the arm in the anatomically neutral position, radiographically verify that the coracoid process has returned to its resting position compared to the contralateral side, on the AP X-ray (**for details see Part 4**).

Further studies are needed to better understand the roles of the torsion and version angles, screw twist and the correction of offset between medial and lateral curvatures. If the clavicle length and version angle are corrected at the surgery with an intramedullary implant and immobilized in a broad shoulder immobilizer until the appearance of the provisional callus to stabilize the fragments, then between 8 and 12 weeks, the implant may be removed to enable remodelling of the fracture site with gradually increasing activities, based on patient-specific biomechanical forces acting at the fracture site to regain the biomechanical architecture over time.

9.0 Scapula:

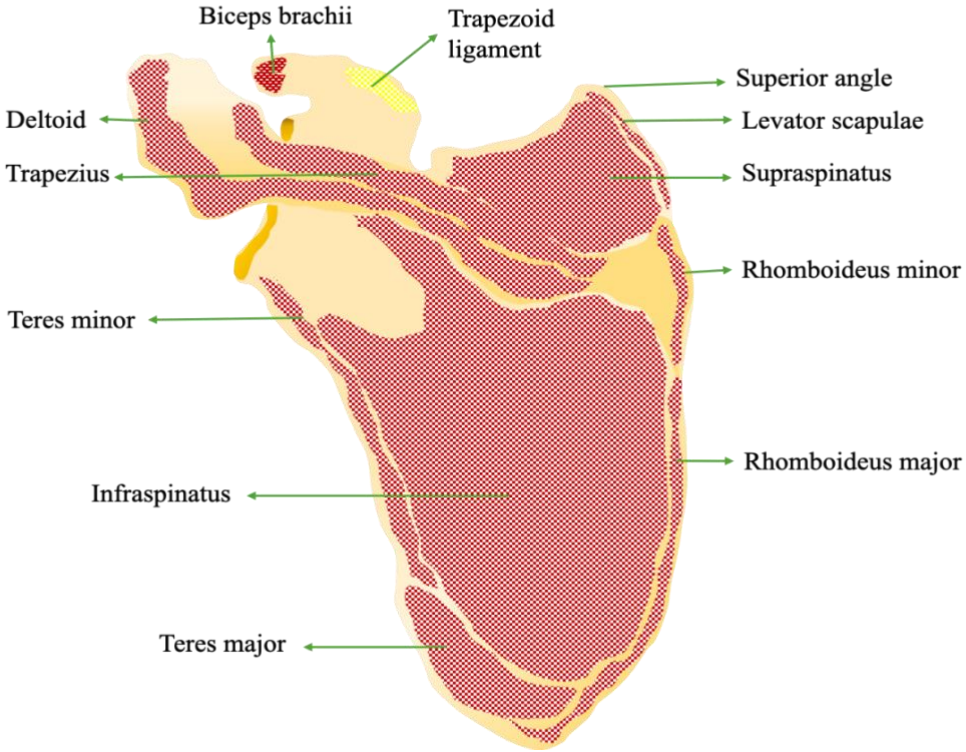
The scapula is a sister bone to the clavicle, forming a pair yoked at the acromioclavicular joint. The two bones are mechanically interdependent units of the pectoral girdle mechanism that assists in elevating the arm in multiplanar directions. It functions as the sliding linkage of the girdle, translating along the thoracic wall, separated by muscle layers, creating a soft tissue articulation called scapulothoracic synsarcosis (syn- together, union + sarx > sarkose > flesh), a fleshy union.

9.1 Body:

The scapula is an irregular, arc-shaped, extremely well-optimized bone designed for strength through optimal distribution of bone density around its margins and the spine. Like a mono-leaf spring, the scapula has energy storing function due to the concavo-convex curvature of its thin blades, above and below the thick base of the spine, which acts as a fulcrum. It is positioned dorsolateral, with its superior angle at the level of the second rib and its inferior angle reaching at the level of the seventh rib, aligned along a vertical craniocaudal axis(Standring, 2016). During arm elevation, the changing orientation of the scapula coordinates the biomechanical architecture of its rhizomatic (rhiza- root + matos > mate - one of the pair) companion, the clavicle.

The triangular blade-shaped scapula has a concave costal surface and a convex, subcutaneous dorsal surface. It has three borders and three angles **(Fig. 17)**.

Its two processes, the acromion and the coracoid, along with its borders possess a cortico-cancellous structure analogous to the clavicle, for load suspension and muscle attachments. Its concavo-convex body tilts anteriorly in the coronal plane, as if overlooking the shoulder at the clavicle. The articular costal surface is primarily congruent with the thoracic wall, the intervening muscles, and a thin film of tissue fluid between the superficial and deep layers



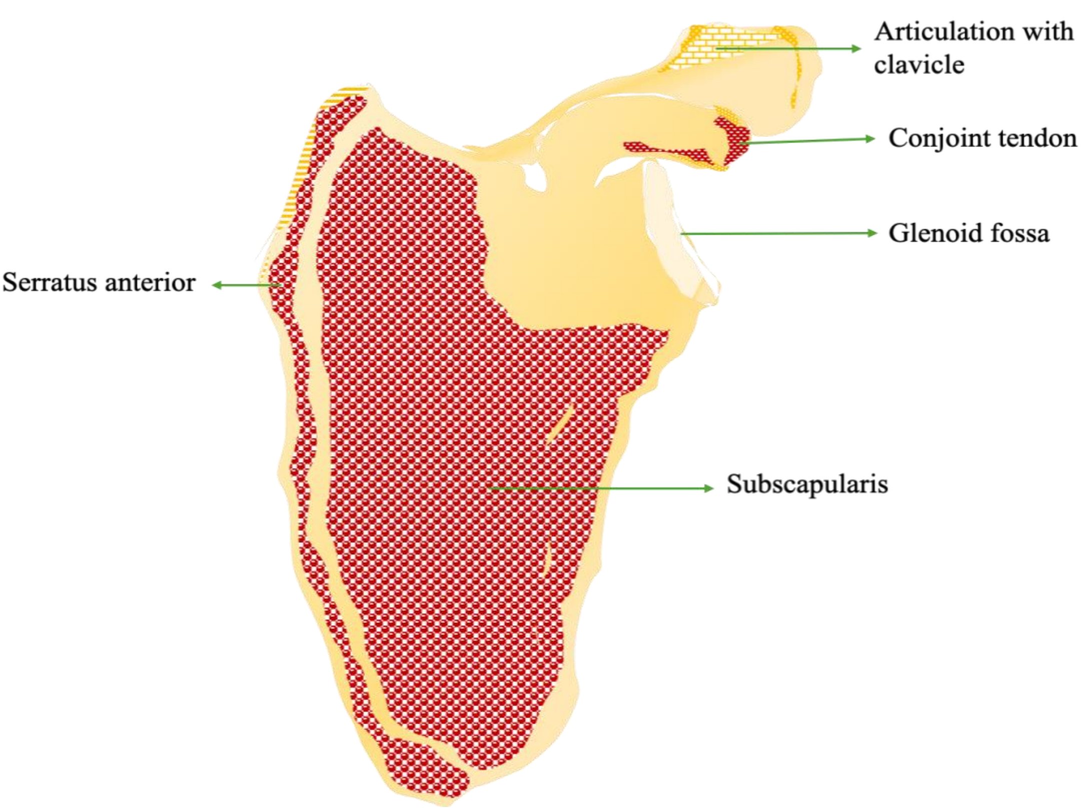


Figure 17. Dorsal (top) and costal (bottom) aspects of the scapula (created in PowerPoint).

of the muscle. In its medial two-thirds, the costal surface has oblique ridges running superiorly and laterally for tendinous origins of the Subscapularis muscle. More medially, the smoother areas provide insertions for digitations of the Serratus anterior muscle. The anteriorly curved section above the scapular spine forms a significant angle to the larger inferior segment of the blade. The line of angulation at the base of the scapular spine passes through the glenoid fossa at its lateral angle.

The relatively thicker lateral border, compared to the medial and superior borders, extends inferiorly from the oviform glenoid fossa. From its upper two-thirds arises the Teres minor, while the lower one-third, extending over the inferior angle gives origin to the Teres major. The superior extension of the ridge virtually intersects the glenoid fossa vertically, creating a continuum that acts as a weight-bearing pillar when a load is carried overhead with the humerus abducted. Levator scapulae originate from a narrow band on the dorsal surface of the medial border above the root of the spine. Below it, at the medial angle, arises Rhomboid minor and distal to it, reaching the inferior angle, is the origin of the Rhomboid major.

9.2 Spine:

The spine of the scapula divides the dorsal surface into approximately the upper one-third and lower two-thirds areas, called supraspinatus and infraspinatus fossae, respectively, for the origin of the similarly named muscles.

The insertion of the descending middle fibres and ascending inferior fibres of the Trapezius muscle, with the origin of the posterior fibres of the Deltoid muscle, shares the crest of the spine. The acromion, extending anteriorly at a right angle from the lateral end of the scapular spine, overhangs the glenoid fossa and the humeral head.

The spine, which strengthens the body of the scapula, acts as a fulcrum for the bending of its blade. During a forceful, extreme range of overhead arm elevation with posterior tilting, the unfolding of the curvature of the thin scapular blade plays a vital energy-storing function in returning the scapula to its resting state.

9.3 Acromion:

The trapezoidal flat acromion has variable thickness, a smooth concave inferior surface and a rough, convex superior surface. The longer, lateralized thick and irregular border is a continuation of the inferior lip of the crest, forming the acromial angle, is a reliable palpable surface marker. The shortest apical anteromedial border and shorter, radiused medial border continue with the superior lip of the spinal crest. The fourth virtual border is the junction between the spine and the acromion. The middle fibres of the Trapezius, inserted on the medial border, and the middle fibres of the Deltoid, originating from the lateral border, share the respective sides of the acromion's superior surface. The apical anteromedial border and the adjacent superior surface give origin to the anterior fibres of the Cleidobrachialis deltoideus, and deep to it, attaches the coracoacromial ligament. The anterior most part of the acromion's medial border bears the articular surface to form the acromioclavicular articulation.

There are three types of acromia based on the curve of its inferior surface. Type I has a flat undersurface; Type II has a curved undersurface, and in Type III, the apex of the acromion shows a sharp downward curve forming a hook(Biglani et al., 1986; Bigliani et al., 1991; McLean & Taylor, 2019). Type III is more common in men and Type I in women. There are no significant gender differences in the width of the acromion and the distance between the undersurface of the acromion and the glenoid fossa(Paraskevas et al., 2008).

On average, the acromion measures 27 mm in width, and the inferior surface is highly variable, with a torsional angle of 80 degrees to the sagittal plane and an inclination angle of 16 degrees relative to the transverse plane(Zenker et al., 2022). There are geographical and gender variations in the prevalence of various types of acromia. How these various acromial morphologies adversely affect the clavicle motion and volume of the subacromial space, between the undersurface of the acromion and the peak of the greater tuberosity of the humerus, in malunited fractured clavicles, is not well studied.

9.4 Coracoid process:

The thick beak-shaped coracoid process has a broad base and a rounded, smaller apex. It has variably shaped and sized round-to-oval cross-sections, from the base to its apex. Arising from the anterior and superior part of the scapular neck, the coracoid process ascends horizontally, initially directed superiorly and medially. It then sharply turns at nearly a right angle to run anteriorly, laterally and inferiorly towards the glenohumeral joint line. With the arm resting beside the chest in internal rotation, the tip *(true apex)* of the coracoid is directed anteriorly and laterally, depending on the scapulothoracic relationship. The false apex (*elbow of the process*) of the coracoid process is palpable an inch (*two-finger breadth of the patient*) below the clavicle in the infraclavicular fossa.

Beyond the circular base, the ascending horizontal and medially directed oblique portion of the coracoid has a saddle-shaped smooth undersurface that acts as a pulley for the passage of the Subscapularis muscle during arm elevation(Standring, 2016). The superior surface of the ascending portion is convex and rough. From the point where it changes direction towards the tip, the rough area is the footprint of the coracoclavicular ligament complex, consisting of conoid and trapezoid ligaments. The conoid ligament attaches to the medial side of the angle (*false apex*). The trapezoid ligament arising from the upper surface of the horizontal portion runs obliquely in the anterior and lateral direction. The Pectoralis minor tendon attached to the rough inferomedial border extends to its convex irregular superolateral surface lateral to the trapezoid ligament. The coracoacromial ligament extending to the base of the coracoid process arises from the lateral border opposite to the insertion of the pectoralis minor. The origin of the conjoint tendons of the Coracobrachialis, the short head of the Biceps brachii muscles, and the coracoclavicular portion of the Clavipectoral fascia covers the true apex (*tip*) of the coracoid process.

Like the door handle lever, the L-shaped coracoid process plays a significant biomechanical role through the attachments of the coracoclavicular ligament complex to the clavicle and the conjoint muscle and coracohumeral ligament to the humerus. The "prestressed" coracoacromial ligament completes the acromial arch over the glenohumeral articulation. The coracoid process on its medial and inferior surface is related to the Axillary vein, Axillary artery, Brachial plexus, and sensory articular branch of the Lateral pectoral nerve to the anterior capsule of the shoulder joint. The acromial branch of the Thoracoacromial artery passes superior to it. The intimate path of neurovascular structures inferior to the coracoid process has earned it the title of "Lighthouse" of the shoulder(Matsen III et al., 2009; Mohammed et al., 2016).

The morphometric variations and gender-specific differences of the coracoid process skewed in vertical and horizontal projections with sharp angulation, make it difficult to identify its orientation and various radiographic features(Bhatia et al., 2007). Nonetheless, the orientation of the coracoid process is a usable patient-specific radiological marker relative to the clavicle's anatomical triplane orientation in anterior-to-posterior shoulder imaging, which has gone unrecognized. It is of radiological importance in cases of clavicle fractures for comparing bilateral post-reduction images. Normally, with intact clavicles, the anterior aspect of the anterior, laterally and inferiorly directed portion past the point of angulation *(false apex)* to the tip *(true apex)* of the process at the shoulder joint line appears as a smooth, uniformly elongated oval to rectangular in outline. The radiographic changes related to the clavicle fracture and its recovery following the restoration of its anatomy is discussed later in the series. For a consistent AP radiographic view of the shoulder joint and coracoid process, the muscles attached to the coracoid process should be at rest.

Conflict of interest: The author declares no conflict of interest.

Acknowledgement: The author would like to thank Dr. Rajiv Devgan, Director Principal; Dr. Jagdev Singh Kullar, Professor & Head, Department of Anatomy, Government Medical College, Amritsar, Punjab, India, for granting permission to perform anatomy dissection and for providing dry clavicle bone specimens; and S. Jasminder Singh, Anatomy artist, Government Medical College, Amritsar, Punjab, India, for preparing the artwork to compliment the text,

Funding: The author received no financial support for the research, travel, authorship and publication of this 9 Part series.

References:

Abdel Fatah, E. E., Shirley, N. R., Mahfouz, M. R., & Auerbach, B. M. (2012). A three-dimensional analysis of bilateral directional asymmetry in the human clavicle. *American Journal of Physical Anthropology*, *149*(4). https://doi.org/10.1002/ajpa.22156

Aira, J. R., Simon, P., Gutiérrez, S., Santoni, B. G., & Frankle, M. A. (2017). Morphometry of the human clavicle and intramedullary canal: A 3D, geometry-based quantification. *Journal of Orthopaedic Research*, *35*(10). https://doi.org/10.1002/jor.23533

Andermahr, J., Jubel, A., Elsner, A., Johann, J., Prokop, A., Rehm, K. E., & Koebke, J. (2007). Anatomy of the clavicle and the intramedullary nailing of midclavicular fractures. *Clinical Anatomy*, *20*(1). https://doi.org/10.1002/ca.20269

Asadollahi S, & Bucknill A. (2019). Acute medial clavicle fracture in adults: a systematic review of demographics, clinical features and treatment outcomes in 220 patients. *J Orthop Traumatol*, *20*(1), 1–7.

Auerbach, B. M., & Ruff, C. B. (2006). Limb bone bilateral asymmetry: Variability and commonality among modern humans. *Journal of Human Evolution*, *50*(2). https://doi.org/10.1016/j.jhevol.2005.09.004

Barros Anna. (2013). *Ontogeny, phylogeny and functional morphology of the hominoid shoulder girdle ! !* [PhD Biological Anthropology]. University college, London, UK.

Bernat, A., Huysmans, T., Van Glabbeek, F., Sijbers, J., Gielen, J., & Van Tongel, A. (2014). The anatomy of the clavicle: A Three-dimensional Cadaveric Study. *Clinical Anatomy*, *27*(5). https://doi.org/10.1002/ca.22288

Bhatia, D. N., de Beer, J. F., & du Toit, D. F. (2007). Coracoid process anatomy: Implications in radiographic imaging and surgery. *Clinical Anatomy*, *20*(7), 774–784. https://doi.org/10.1002/ca.20525

Biglani, L., Morrison, D., & April EW. (1986). The morphology of the acromion and its relationship to rotator cuff tears. *Orthopaedic Transections*, *10*, 228.

Bigliani, L. U., Ticker, J. B., Flatow, E. L., Soslowsky, L. J., & Mow, V. C. (1991). The relationship of acromial architecture to rotator cuff disease. *Clinics in Sports Medicine*, *10*(4), 823–838.

Constantinou, D., & Kastanos, K. (2008). Sport related stress fracture of the clavicle with non-union: Case report and review. *International Journal of Shoulder Surgery*, *2*(1), 22. https://doi.org/10.4103/0973-6042.39583

Corrigan, G. E. (1960). The Neonatal Clavicle. *Neonatology*, *2*(2), 79–92. https://doi.org/10.1159/000239790

Dare, S. S., Masilili, G., Mugagga, K., & Ekanem, P. E. (2019). Evaluation of Bilateral Asymmetry in the Humerus of Human Skeletal Specimen. *BioMed Research International*, *2019*, 1–11. https://doi.org/10.1155/2019/3194912

Ejlersen, M. (2023). The human clavicle's nutrient foramen's prevalence, number, location, and direction: A systematic review and meta-analysis. *The Surgeon*, *21*(1), e48–e61. https://doi.org/10.1016/j.surge.2022.04.003

Fatima, K., Bhat, G. M., & Saify, I. (2024). Morphological and Topographical Anatomy of the Nutrient Foramen in the Clavicle: A Cross-sectional Study. *INTERNATIONAL JOURNAL OF ANATOMY RADIOLOGY AND SURGERY*. https://doi.org/10.7860/ijars/2024/66832.2964

Havet, E., Duparc, F., Tobenas-Dujardin, A. C., Muller, J. M., Delas, B., & Fréger, P. (2008). Vascular anatomical basis of clavicular non-union. *Surgical and Radiologic Anatomy*, 30(1). https://doi.org/10.1007/s00276-007-0278-1

Inaki, M., Liu, J., & Matsuno, K. (2016). Cell chirality: Its origin and roles in left-right asymmetric development. In *Philosophical Transactions of the Royal Society B: Biological Sciences* (Vol. 371, Issue 1710). https://doi.org/10.1098/rstb.2015.0403

Inman, V. T., & Saunders, J. B. (1946). OBSERVATIONS ON THE FUNCTION OF THE CLAVICLE. *California Medicine*, *65*(4), 158–166.

Jenkins, F. A., Dombrowski, P. J., & Gordon, E. P. (1978). Analysis of the shoulder in brachiating spider monkeys. *American Journal of Physical Anthropology*, *48*(1), 65–76. https://doi.org/10.1002/ajpa.1330480110

Jit, I., & Singh, S. (1956). Estimation of stature from clavicles. *The Indian Journal of Medical Research*, *44*.

Jit, I., & Singh, S. (1966). The sexing of the adult clavicles. *The Indian Journal of Medical Research*, *54*(6), 551–571.

Kapandji, I. A. (2005). The physiology of the joints. Volume 1, The Upper Limb. Edition Sixth. English Edition 2007. Churchill Livingstone (Elsevier Ltd.).

Kaur H, & Sahni H. (2002). Length And Curves Of The Clavicle In Northwest Indians'. *J Anat. Soc. India*, *51*(2), 199209.

Knudsen, F. W., Andersen, M., & Krag, C. (1989). The arterial supply of the clavicle. *Surgical and Radiologic Anatomy*, *11*(3). https://doi.org/10.1007/BF02337824

Lambert, S., Al-Hadithy, N., Sewell, M. D., Hertel, R., Südkamp, N., Noser, H., & Kamer, L. (2016). Computerized tomography-based 3D modeling of the clavicle. *Journal of Orthopaedic Research*, *34*(7). https://doi.org/10.1002/jor.23145

Lee, J. T., Campbell, K. J., Michalski, M. P., Wilson, K. J., Spiegl, U. J. A., Wijdicks, C. A., & Millett, P. J. (2014). Surgical Anatomy of the Sternoclavicular Joint. *Journal of Bone and Joint Surgery*, *96*(19), e166 https://doi.org/10.2106/JBJS.M.01451

Leurcharusmee, P., Maikong, N., Kantakam, P., Navic, P., Mahakkanukrauh, P., & Tran, D. Q. (2021). Innervation of the clavicle: a cadaveric investigation. *Regional Anesthesia & Pain Medicine*, *46*(12), 1076–1079. https://doi.org/10.1136/rapm-2021-103197

Ljunggren AE. (1979). Clavicular Function. *Acta Orthopaedica*, *50*(3), 261268.

Matsen III, F., Lippitt, S., Bertlesen, A., Rockwood, C., & Wirth, M. (2009). Glenohumeral Instability. In C. Rockwood, F. Matsen III, M. Wirth, & S. Lippitt (Eds.), *The shoulder* (4th ed., Vol. 1, pp. 617–770). Saunders Elsevier.

McConnell, I. M. (2001). The evolution of the pectoral girdle. *Journal of Anatomy*, *199*(1–2), 189–194. https://doi.org/10.1046/j.1469-7580.2001.19910189.x

McLean, A., & Taylor, F. (2019). Classifications in Brief: Bigliani Classification of Acromial Morphology. *Clinical Orthopaedics and Related Research*, *477*(8), 1958–1961. https://doi.org/10.1097/CORR.0000000000000770

Melillo, S., Gunz, P., Coqueugniot, H., Reske, S., & Hublin, J. J. (2019). Structural effects of variation in the human clavicle. *American Journal of Physical Anthropology*, *168*(4). https://doi.org/10.1002/ajpa.23787

Missiuna, P., & Gandhi, H. S. (2011). Anatomically safe and minimally invasive transcrestal technique for procurement of autogenous cancellous bone graft from the mid-iliac crest. *Canadian Journal of Surgery*, *54*(5), 327–332. https://doi.org/10.1503/cjs.028010

Mohammed, H., Skalski, M. R., Patel, D. B., Tomasian, A., Schein, A. J., White, E. A., Rick Hatch, G. F., & Matcuk, G. R. (2016). Coracoid process: The lighthouse of the shoulder. *Radiographics*, *36*(7). https://doi.org/10.1148/rg.2016160039

Paraskevas, G., Tzaveas, A., Papaziogas, B., Kitsoulis, P., Natsis, K., & Spanidou, S. (2008). Morphological parameters of the acromion. *Folia Morphologica*, *67*(4), 255–260.

Parsons, F. G. (1916). On the Proportions and Characteristics of the Modern English Clavicle. *Journal of Anatomy*, *51*(Pt 1), 71–93.

Qiu, X. S., Wang, X. B., Zhang, Y., Zhu, Y. C., Guo, X., & Chen, Y. X. (2016). Anatomical study of the clavicles in a Chinese population. *BioMed Research International*, *2016*. https://doi.org/10.1155/2016/6219761

Schlecht, S. H. (2012). Understanding Entheses: Bridging the Gap Between Clinical and Anthropological Perspectives. *Anatomical Record*, *295*(8). https://doi.org/10.1002/ar.22516

Serpico, M., & Tomberg, S. (2021). The emergency medicine management of clavicle fractures. In *American Journal of Emergency Medicine* (Vol. 49). https://doi.org/10.1016/j.ajem.2021.06.011

Standring, S. (2016). Gray's Anatomy: The anatomical basis of clinical practice. In Standring S et al (Ed.), *Edinburg. Elsevier Churchill Livingstone* (Forty-First). Elsevier. https://doi.org/10.1017/CBO9781107415324.004

Vanderbeck, J., Fenlin, J., Getz, C., & DePalma, A. F. (2009). Congenital Anomalies and Variational Anatomy of he Shoulder, in The Shoulder. In C. Rockwood, F. Matsen, Wirth MA, & S. Lippitt (Eds.), *The Shoulder* (4th ed., Vol. 1, pp. 101–143). Saunders Elsevier.

Vanderbeck, J. L., Fenlin, J. M., Getz, C. L., & DePalma, A. F. (2009). Congenital Anomalies and Variational Anatomy of the Shoulder. In *Rockwood and Matsen's The Shoulder*. https://doi.org/10.1016/b978-1-4160-3427-8.50009-x

Voisin, J. L. (2006). Clavicle, a neglected bone: Morphology and relation to arm movements and shoulder architecture in primates. *Anatomical Record - Part A Discoveries in Molecular, Cellular, and Evolutionary Biology*, *288*(9). https://doi.org/10.1002/ar.a.20354

Yusuf, B. S., Segaren, N., Segaren, N., & Di Mascio, L. (2020). Barista's fracture: a new occupational hazard. *JRSM Open*, *11*(5). https://doi.org/10.1177/2054270420918493

Zenker, M., Shamsollahi, J., Galm, A., Hoyen, H. A., Jiang, C., Lambert, S., Nijs, S., & Jaeger, M. (2022). Threedimensional morphometric analysis of the lateral clavicle and acromion: Implications for surgical treatment using subacromial support. *SAGE Open Medicine*, *10*. https://doi.org/10.1177/20503121221091395