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

Part 4 The Pathological Anatomy of Mid-diaphyseal Fractures, Controversy and new Paradigms in Radiography

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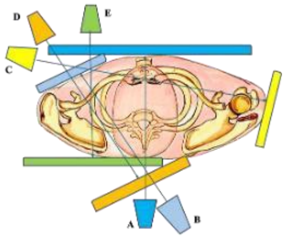
Highlights: The failure of the Subclavius muscle to depress the clavicle, the open state of the sterno-costoclavicular joint, and the deep cervical fascial traction encircling the neck elevate the medial fracture fragment. The persistent shortening of the clavicle with torsional deformity misaligns the scapula, causing subtle or even clinically significant posttraumatic mechanical “winging”.

For clavicle reconstruction, following its anatomical plane create clavicle-specific oblique slices, to generate 3D Computed Tomography images for greater accuracy. Longitudinal bidirectional asymmetry exceeding 10 mm occurs in 7% of cases. The repositioning of the coracoid process indicates three-planar reduction of a clavicle fracture. The study recommends a five-view trauma series for clavicle fracture assessment and management.

Graphic abstract:



Keywords: Clavicle fracture, Clavicle length, Clavicle shortening, Clavicle malunion, Clavicle radiography, Coracoid process, Pectoral girdle

1.0 Introduction:

The normal anatomy of the clavicle consists of long and short transverse-plane medial and lateral curvatures, a laterally concentrated inferior curvature in the coronal plane, an offset between the two principal curvatures, varying cross-sections with quadrangular, oval, circular and rectangular shapes, resulting in varying second moment of area and bone density distribution along its length. Biomechanically, it has different radii of curvatures and chord lengths, patient-specific changing diaphyseal torsion angle, version angle between the articular surfaces of the sternal and acromial ends, and the presence of differential screw twist between the primary curvatures. These functionally critical anatomical features contributing to the biomechanical architecture of the clavicle are disrupted upon its fracture. Ontogenesis modifies the anatomical features under biomechanical forces, making the management of a fractured clavicle a patient-specific problem, especially considering its normal development that continues into the late adolescent and early adulthood years.

1.1 Reflections of the structural hierarchy of bone, remodelling, and the disruption of soft tissues:

Ontogenetically, certain features of the clavicle’s shape and form are quite well preserved between the earlier claviculate primates and modern humans. The surface characteristics of a dry clavicle, including its cross-sectional anatomy parameters, are embedded within the structural hierarchy of cells, collagen orientation, and mineral distribution. Ultimately, it is biomechanical forces that influence bone microarchitecture, density, and strength at the nano- and microstructural levels(Gabel et al., 2017).

The curves and twists of the right and left clavicles are mirror images of each other; when overlaid, they cannot be exactly superimposed. This is due to the structural chirality— the way cellular-level structure and collagen bundles are functionally arranged in long spirals in the extracellular matrix from one end of a bone to the other —and their right and left orientation in adjacent skeletal segments.

Simply applying traction at the ends of a broken long bone to correct displacement and pull it to its 'original' length is a minimal-level restoration procedure. Following a clavicle fracture, correcting the co-relative anatomy of its curvatures, angles, and twists— whether through closed reduction or surgical resynthesis before immobilization is crucial. It is not a matter of correcting its plain radiological anatomy but also restoring the biomechanical architecture. The goal is to regain the clavicle's range of motion and strength, along with the function of the linkages and articulations of the pectoral girdle, within a justifiable timeframe. Once the fracture has initially united, bone remodelling can take 3-5 years, or even longer, depending on the patient's remaining years to full maturity. Complete remodelling may not occur in older patients. Functional recovery of the shoulder complex, including range of motion, strength and power at the glenohumeral joint, occurs gradually. Mobilization of the glenohumeral articulation should begin as tolerated, based on the type of fracture, the quality of reduction and the immobilization technique.

A plain radiographic study shows that there is very little predictable bone remodelling that correct itself after the age of 10 in girls and 12 in boys(McGraw et al., 2009). Even though the medial epiphysis of the growing end begins to ossify after the age of 18, it does not fuse until 25 or later in some. Restoring the length will correct the relationship between the muscle length and tension. However, if the anatomy of the curvatures, torsion and version angles, and axial screw twist and pitch are not corrected diligently, under correction and overcorrection, or reversal of torsion and version angles may persist, like malunion of any other long bone fracture. This can adversely affect the mechanical advantage of the clavicle's design.

The same principles apply to soft tissue attachments to the clavicle and to reflections of the deep layers of the deep cervical fascia that descend between the Omohyoid and the clavicle, adhering to its posterior periosteum. It merges with the ascending layer of the clavipectoral fascia, which encloses the Subclavius muscle(Standring, 2016). The enveloping fascial layers provide a larger attachment area for the Subclavius, making both the muscle and its fascia vulnerable to injury during clavicle fractures and surgical fixation The clavipectoral fascia extends laterally to attach to the coracoid process, enclosing the Cleidobrachialis pectoralis and Pectoralis minor deep to it. Finally, it acts as a suspensory ligament for the axillary fascia affecting its contour, and restraining arm elevation following clavicle malunion.

The naming of the regional fascial layers does not imply they terminate at regional boundaries. Instead, the entire regional fascia is part of a continuous deep fascial network of the trunk. The bilateral extensions of the variably thick deep fascial layer encase the upper extremities. Disruption of a regional deep fascia following an experimental controlled osteotomy in a cadaver— even with anatomical restoration —may leave the fascia warped, which can disturb the kinematics and function of adjacent joints and linkages. In a cadaveric study, following an osteotomy of the clavicle and restoring it anatomically, the experimenters could not determine the underlying mechanism why the glenohumeral joint kinematics failed to return to the original range of motion, despite satisfactorily resynthesizing the clavicle(Rosso et al., 2017).

A lack of meticulous surgical technique worsens this problem, and overly tensioned closure of the deep fascia at the time of the wound closure exacerbates it further. Uneven traction and gathering of the opposing cut edges create new tension lines during wound healing and contraction, developing widespread warping of the local tissues and of the surrounding regions. Wrenching the included micro-sized nerve fibres becomes an unrecognized cause of the chronic deep regional pain and neurogenic burning sensations. Looking at the surgical job and the postoperative X-rays, and announcing "good job, good job," as an encouraging note to self and learners must be carefully considered. A done job is good only once the patient has healed with a full range of motion, strength and power across all affected joints, linkages, and the end articulation.

2.0 One-fifth segmentation of the clavicle and election of fracture site:

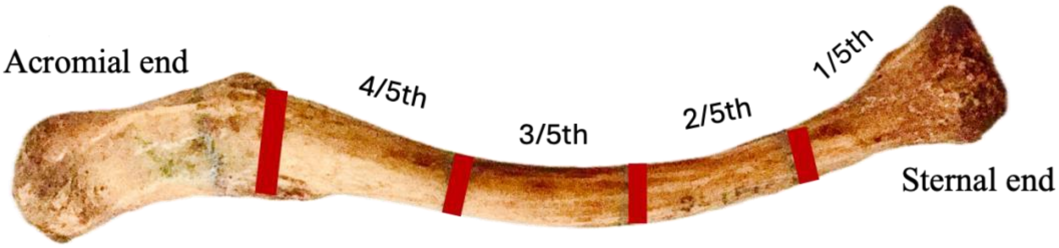


Figure 1. One-fifth segmentation of the clavicle

The anatomy of the clavicle lends itself well to one-fifth segmentation from the medial to the lateral end based on its surface features and curved diaphyseal geometry (**Fig. 1**). The medial one-fifth lies between the sternal articular surface and the lateral edge of the costoclavicular eminence or fossa. The diaphysis is divided into three sections: second, third, and fourth-fifth sections. The fifth section is from the conoid tubercle to the articular surface at the acromial end. The clavicle has been sectioned into fifths to later describe the indications for retrograde and antegrade operative techniques for implanting an intramedullary device (**for details see Part 8**).

The site-specific, varying cross-sectional area and material distribution define how the [1]second area moment of inertia resists bending and torsional forces in an intact clavicle, influence the site and type of fracture anatomy and the likely outcome(Harrington et al., 1993; Robinson et al., 2004).

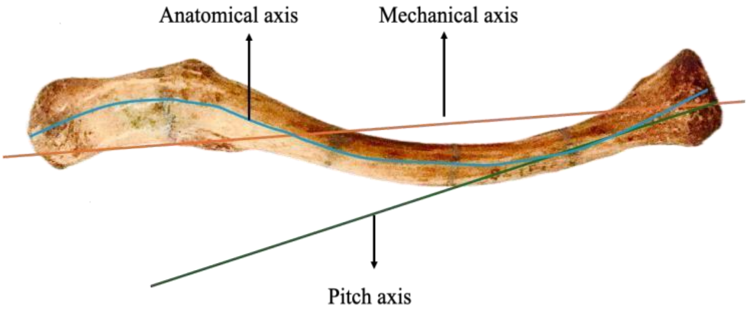


Figure 2. Various axii of the clavicle. Unlike the anatomical axis, the mechanical axis passes through the [2]centroids of the articular surfaces.

Primarily, varying compression and torsional forces are transmitted on impact to the changing cortical thickness and cross-sectional material distribution around the neutral axis of the clavicle(Harrington et al., 1993). In addition, the fracture site and development of fracture's pathological anatomy depend on the radii of curvatures, the vulnerable section between the transverse plane curvatures and laterally concentrated inferior curve, and the relative rotation of the clavicle's shaft, as well as the pose of the trunk, arm and hand at impact. The closer the position of the pitch axis passing through the diaphyseal mid-point on the centreline of the clavicle and from the mechanical axis (**Fig. 2**), the greater is the force needed at the shoulder on impact to produce yielding compression, bending and torsional forces to cause fracture. A direct, brutal impact on the clavicle's shaft is independent of its anatomy and the biomechanical architecture in an assault and road traffic accident. When the impact load exceeds strength and stiffness (*resistance to deformation)* of a structure, depending on the velocity and mass of the striking object, it leads to a proportionate level of explosion and destruction of the structure.

In the case of the clavicle, impact usually causes recognizable fracture patterns. These can include simple buckling (*plastic deformation with or without angulation*) of the cortex, stress fractures, transverse fractures with or without displacement, or short oblique or spiral fractures. More complex patterns may also occur, such as butterfly, segmental or multisegmented comminuted fractures, with bone shards scattered into the immediate surroundings. Several classification systems, such as Allman's, AO, Craig's, Robinson's, etc., describes these fracture patterns in various ways. However, the severity of fracture patterns has been changing with the evolution of society, and the modes of injury will continue to evolve.

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[1] The area moment of inertia is also called the second moment of area. It is the difficulty experienced to move the material within a given shape, which is proportional to the cross-sectional area, and the amount of material distributed around the neutral axis that determines the strength and stiffness to bend a shape. The distribution of the bone material around the axis is dependent on the geometrical shape and loading conditions. For a rectangular cross-section, the formula for the area moment of inertia is width multiplied by the cube of the height divided by 12. It is not a unique property of a cross-section as it varies depending on the bending axis around which bending force is applied. The crosssection of a geometrical shape that has the maximum amount of material further away from the bending axis has the highest second area moment of inertia, which provides greater resistance to bending. A cross-section of the I-beam has most of the material located far from the bending axis, which is well-optimised for carrying loads effectively and efficiently with a minimal amount of material.
The area moment of inertia around a perpendicular axis of a cross-section is called the polar moment of inertia. It represents the twisting of a geometrical shape to cause torsional deformation, accounting for how the area of the cross-section is distributed radially around the axis of rotation or twisting axis. Generally, as in the case of the tubular shaft, the greater the area of the cross-section further away from the axis of rotation, the greater its strength and stiffness to resist torsional moment.

[2] The centroid is the geometric centre of the cross-section at which an object can be balanced on the point of a needle.

3.0 Gravity and new muscle forces acting on the fracture fragments:

The occurrence of a fracture is an extremely forceful and dynamic process. The severity and fracture pattern depend on the load at the time of impact, ground reaction force and other multi-directional forces. It is impossible to know the exact fracture pattern on impact in each patient. On plain radiographic and computed tomographic views, what is seen are static images reminiscent of the post-impact state, reset by the muscles acting in response to the injury, and cannot be replayed. Later, the clavicle fracture may exhibit subtle changes, as seen on subsequent imaging, depending on the stability of the fragments and the supporting provisional and definitive splinting techniques. The delayed static appearance of the fracture pattern can help deduce the likely severity of bony injury.

The urgency indicated by vital signs and symptoms suggests damage to the regional soft tissues upon arrival at a healthcare centre. The injured limb is instinctively adducted and internally rotated, cupping the elbow with the contralateral hand. It helps lift the suddenly drooped shoulder against gravity, a function of several groups of shoulder muscles. At the same time, the natural response of the splinting muscles restrains the upper extremity, immobilizing the bleeding capillaries and small vessels. It stabilizes the induced intrinsic coagulation cascade, forming the fracture haematoma rich in fracture-healing elements.

Depending on the fractures site and orientation of the fragments. Various groups of muscles act on medial and lateral fracture fragments. The sustained contraction of the muscles (spasm) splints the displaced fragments, further checking unnecessary movements, aggravating the pain-causing nerve endings.

The muscles attached directly to the clavicle that may reorient the fracture fragments are the Cleidomastoid head of the Sternocleidomastoid, Cleidobrachialis pectoralis, Occipitocleidal trapezius, Cleidobrachialis deltoideus, and Subclavius (**Fig. 3**). The role of the cervical fascia and its extensions have been largely ignored in the literature. The Cleidomastoid arising from the superior and posterior surface of the sternal end of the clavicle and occasionally extending almost halfway on the diaphysis, inserts onto the mastoid process. Exactly opposite it, the Cleidobrachialis pectoralis originates from the convex anterior surface below the pectoralis ridge, reaching the middle of the medial curvature, is inserted on the lateral ridge of the bicipital groove of the humeral shaft. Typically, the origin of the Cleidobrachialis pectoralis extends much further laterally than that of the Cleidomastoid. The Occipitocleidal trapezius, arising from the medial half of the superior occipital ridge, inserts on the superior surface and posterior convex border of the lateral curvature. Opposite to it, the Cleidobrachialis deltoideus originates from the anterior half of the superior surface, the anterior concave border and the deltoid tubercle of the lateral curvature, inserting on the deltoid eminence of the humeral shaft.

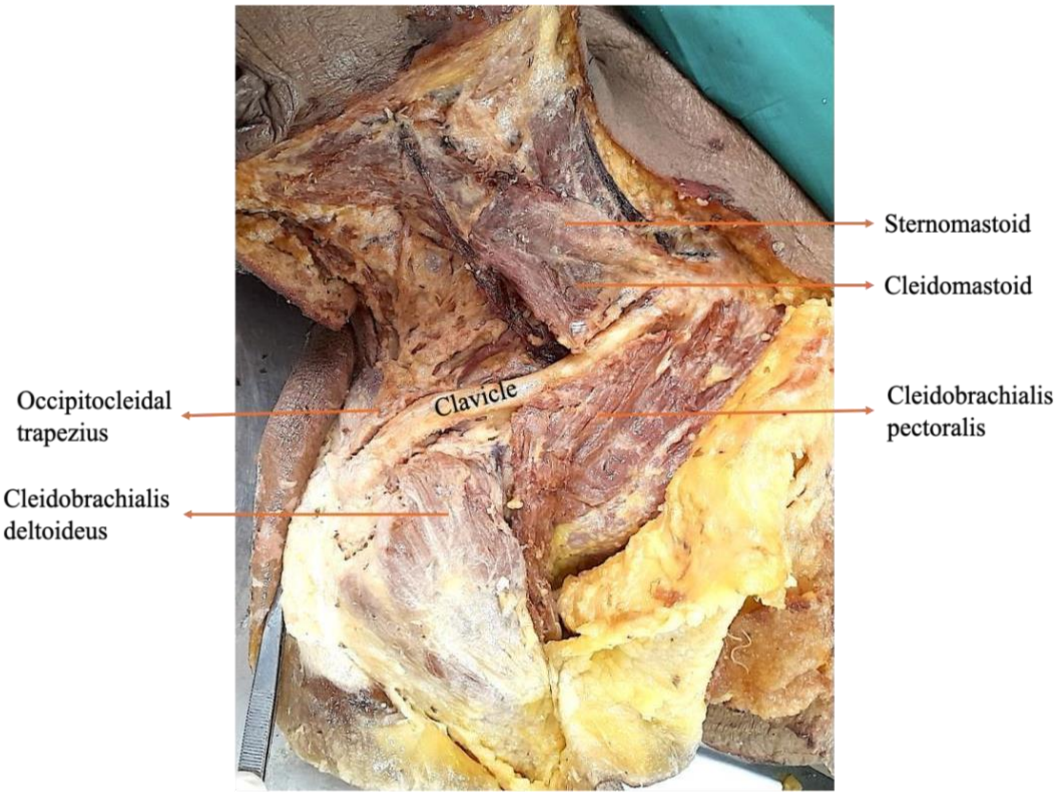

Figure 3. The author's dissection – The four muscles directly arising from the clavicle.

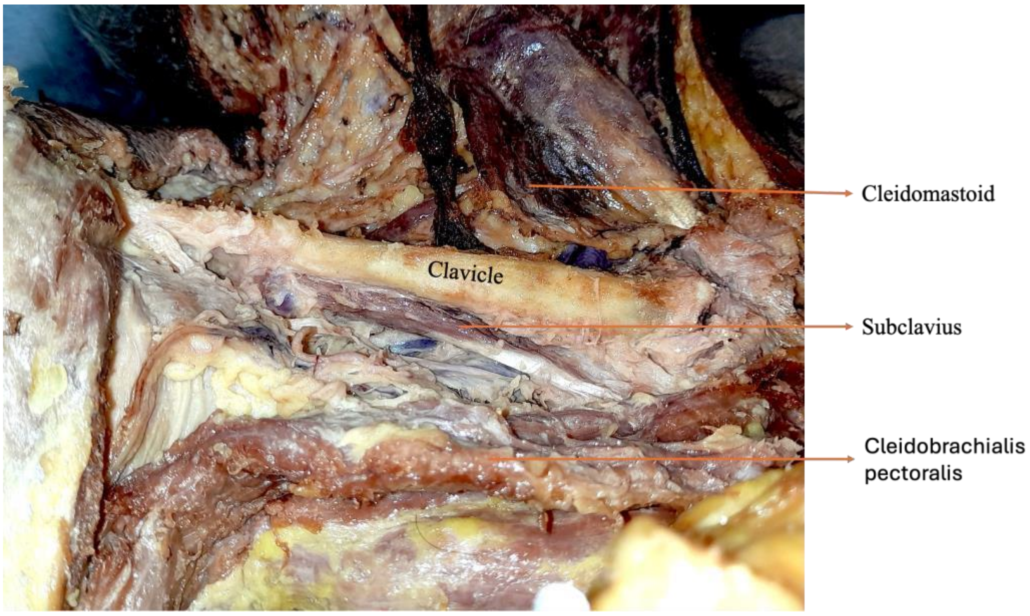

Figure 4. The author's dissection - Subclavius exposed with inferior reflection of the Cleidobrachialis pectoralis.

The fan-shaped Subclavius muscle has a tendinous origin from the first costal cartilage, the costochondral junction and the adjacent surface of the first rib (**Fig. 4**). It runs obliquely and laterally to insert into the groove on the inferior surface of the clavicle, extending from the middle of its medial curvature to the conoid tubercle and adjacent trapezoid ridge. This attachment spans the third and fourth sections, which are the most common sites for clavicle fractures. The nerve to the Subclavius runs close to the posterior surface of the clavicle diaphysis, making both the muscle and its nerve supply vulnerable to injury at the time of fracture. The Subclavius acts as a depressor of the clavicle and a stabilizer of the sterno-costoclavicular joint. In the event of a displaced fracture of the clavicle, it loses the ability to resist elevation of the clavicle and stabilize the sterno-costoclavicular joint, causing the medial fragment to elevate superiorly and posteriorly from its original position. With the injured arm resting against the torso, the relaxed Cleidobrachialis pectoralis has a little effect on the medial fragment.

The main action of the Cleidomastoid is to act at the mastoid from its origin on the clavicle, to bring about ipsilateral lateral flexion of the head and neck. Meanwhile, the Sternomastoid acts from its origin on the manubrium sterni on its insertion on the mastoid and the lateral half of the superior occipital line turning the face up and away. The vector of the Cleidomastoid action is too close to the Sterno-costoclavicular joint to effectively elevate medial fragment of the clavicle following a fracture.

There are no convincing electromyography studies establishing the function of the Subclavius muscle(Prado Reis et al., 1979). An acute explosive fracture force is sufficient to disrupt its integrity and prevent it from holding or depressing the medial fragment. Entrapment of the Subclavius muscle and the lateral fragment beneath it apparently maintain the elevated position of the medial fragment. Later, fibrosis of the Subclavius and formation of the contracture, limits elevation and retraction of the clavicle. The effect of the Cleidobrachialis pectoralis on the medial fragment is disregarded; nonetheless, the vector of the pull of muscles attached to the clavicle changes soon after its fracture. The Cleidobrachialis pectoralis no longer acts as an adductor of the arm because it lacks a stable, firm strut to act on the humeral shaft. Instead, gravity acts passively on the upper extremity and the lateral fragment. The medial fragment is rotated ventrally at the unstable sterno-costoclavicular joint by the Cleidobrachialis pectoralis unless the Cleidomastoid component of the Sternocleidomastoid has an extended insertion on the superior surface of the clavicle's middle third to counter it.

In an intact clavicle, the Cleidomastoid and Cleidobrachialis pectoralis are in equilibrium, and the Subclavius depresses and stabilizes the clavicle at the sterno-costoclavicular joint. Meanwhile, the Occipitocleidal trapezius and Cleidobrachialis deltoideus balance the intact clavicle at the acromial end. The paired muscles stabilize both the sterno-costoclavicular and the acromioclavicular joints, assisted by the Subclavius. The intercalated clavicle acts to keep the scapula in its dorsolateral resting position. The composite motion of the lateral flexion and rotation of the neck occurs at multiple intervertebral articulations of the cervical spine. Acting from the manubrium sterni, the Sternomastoid and from the clavicle the Cleidomastoid turn the head and neck towards the contralateral side, pointing the face upward and away at an angle, in combination with lateral flexion and axial rotation of the cervical spine(Baron & Tunstall, 2016; Gray, 1918). About 50% of cervical axial rotation occurs at the atlantoaxial joint(Baron & Tunstall, 2016).

The composite movement of lateral flexion and axial rotation of the head and the cervical spine occur at the atlantooccipital, atlantoaxial and the lower cervical spine joints. The muscles involved in lateral flexion at the atlantooccipital joints are Rectus capitis lateralis, Semispinalis capitis, Splenius capitis, Sternocleidomastoid and Occipitocleidal trapezius. The muscles producing axial rotation are the Obliquus capitis superior, Rectus capitis posterior minor, and the Sternocleidomastoid. At the atlantoaxial joints the movement is exclusively axial rotation around the pillar of the Axis vertebra, mediated by the same side Obliquus capitis inferior, Rectus capitis posterior major and Splenius capitis, and the contralateral Sternocleidomastoid(Baron & Tunstall, 2016; Gray, 1918). The Splenius capitis arises from the mastoid process and just below the lateral third of the superior nuchal line of the occipital bone, lying between the Sternocleidomastoid and Trapezius, forming part of the floor of the posterior cervical triangle above and behind the levator scapulae. It inserts into the tips of the spinous processes of the seventh cervical vertebra and upper three or four thoracic vertebrae, and the intervening supraspinous ligaments. It rotates the head ipsilaterally, acting synergistically with the contralateral Sternocleidomastoid. The Splenius cervicis arises from the transverse processes of the Atlas, the Axis and the posterior tubercle of the third cervical vertebra to insert into the third to sixth thoracic spinous processes. It produces lateral flexion and rotates the upper cervical spine and the head ipsilaterally.

Multiple groups of muscles, acting bilaterally, on the atlantooccipital, upper two and the lower five cervical vertebrae through conjoint motion, create a complex multiplanar pose of the head and neck. Lateral flexion occurs in conjunction with axial rotation. Multiple muscles act on the cervical spine segmentally rather than solely by the Sternocleidomastoid to pose the head and neck. It is less likely that the Cleidomastoid head alone being close to the Sterno-costoclavicular articulation elevates the medial fragment acting from above its merger with the Sternomastoid head unless the Sternomastoid acts as a strut due to spasm for the Cleidomastoid head to act from above. Otherwise, it has little or no effective role in elevating the medial fragment when clavicle's integrity is lost. Various cervical muscles act on the cervical spine proportionately, and the Sternomastoid head assists in posing head and neck. The other muscles directly attached to the clavicle, depending on the severity of the clavicle fracture, position and support the fracture fragments, while others relax to relieve traction on the uninjured structures, easing the pain.

There are no electromyographic studies of the Sternomastoid, Cleidomastoid, Cleidobrachialis pectoralis, Cleidobrachialis deltoideus, Occipitocleidal trapezius and the Subclavius during the early hours after the clavicle's fracture. No studies have evaluated the action of the two heads of the Sternocleidomastoid separately to show their differential activity during neck movements and their effect on the clavicle with fixation of the mastoid. It is unknown whether the eccentric contraction of the ipsilateral Cleidomastoid and the Cleidobrachialis pectoralis, with muscles at lateral curvature, rotates the intact clavicle ventrally or not. It is also unknown whether concentric contraction (*injury spasm*) of the Cleidomastoid head causes elevation and axial ventral rotation of the medial fragment following a clavicle fracture. In addition, the early radiological images cannot be relied upon for angular measurements relative to the median plane of the thorax and vertebral column, with injured side arm lifted in a shoulder immobilizer.

The sternal head of the Sternocleidomastoid is active in turning the head and neck away and upward, acting from its distal attachment, and is less likely to be acting in conjunction with the Cleidomastoid on the non-functional, unstable medial fragment of the clavicle. In an intact clavicle with fixed head posture, the Cleidomastoid head originating from the posterior and superior surface of the clavicle may play a role in rotating the clavicle ventrally in conjunction with Cleidobrachialis pectoralis and muscles attached to the lateral curvature, assisting during the "setting phase" at the initiation of ipsilateral arm elevation. The Subclavius muscle depresses and decelerates the elevating clavicle and stabilizes the sterno-costoclavicular joint as it shares the nerve supply with the joint(Lambert, 2016).

It is unlikely that the Cleidomastoid head of the Sternocleidomastoid favour's elevation of the medial fragment, pulling it superiorly and posteriorly (*cranially and dorsally*), and cause approximation of its origin and insertion on an unstable medial fragment. The position of the medial fragment is relative to the ptosis of the shoulder, which pulls the lateral fragment inferiorly and medially. It is more likely that the attained posture of the head and cervical spine is due to the contraction of the deeper group of the cervical spine musculature, causing ipsilateral flexion and contralateral axial rotation of the head and neck, relaxing the structures in the posterior triangle. At the same time, the Cleidobrachialis pectoralis rotates the medial fragment ventrally, acting from its attachment on the immobilized humerus.

It is the failure of the Subclavius muscle, the most contused of all the muscles and the likelihood of injury to its nerve that allow the craniodorsal elevation of the medial fragment at the destabilized Sterno-costoclavicular articulation. Secondly, in a displaced fracture, the interposition of the Subclavius passively maintains the relative superior position of the medial fragment, lifted against the lateral fragment, with ptosis of the shoulder acting as a lever under gravity, supporting it rather than the spasm or active contraction of the Cleidomastoid. The contralateral rotation and lateral head and neck flexion towards the fractured clavicle, with engagement of the Occipitocleidal trapezius and the Scalene anterior and medius muscles acting from below on the cervical spine, assist to reduce the traction on the brachial plexus trunks and layers of the deep cervical fascia.

In summary, it is unlikely that the Cleidomastoid head of the Sternocleidomastoid elevates the medial fragment, because only the sternal head is palpably stiff at its origin when the head and neck are turned up and away. The Cleidomastoid, inferior to its merger on the posterior surface of the sternal head, is relatively soft on lateral flexion and axial rotation of the cervical spine. Electromyography of each head within a reasonable time frame can help determine how the two heads act and how they affect the position of the medial fragment. Muscle function can be quantified by the non-invasive imaging technique of MRI elastography, which measures muscle stiffness by tracking shear waves through the muscle tissue, objectively providing passive and active muscle tension(Mariappan et al., 2010). The contraction of the Occipitocleidal trapezius, assisted by the middle portion of the Trapezius and Levator scapulae, and further assisted by Splenii and Obliquus capitis inferior, tilts the head backwards with ipsilateral lateral flexion to relax the neck, turning the face upwards and away from the fracture side. The failure of the Subclavius muscle to depress the clavicle, the open state of the sterno-costoclavicular joint, and the contralateral deep cervical fascial traction across the midline encircling the neck elevates the medial fragment.

4.0 Cervical fascia and tensegrity relationship of linkages and the joints:

The circumferential investing superficial layer of the deep cervical fascia encases the Sternocleidomastoid and Trapezius muscles bilaterally. The superior edge of the deep cervical fascia fuses with the periosteum along the superior nuchal line of the occipital bone, from the medial half of which the Occipitocleidal trapezius originates. The fascia extends anteriorly from the mastoid to the zygomatic arch and the mandible. Inferiorly, the superficial investing layer of the deep cervical fascia descends over the posterior triangle, enclosing the Sternocleidomastoid and Occipitocleidal trapezius, and fuses with the periosteum of the manubrium sterni, clavicle and the acromion(Watkinson & Gleeson, 2016).

The deep layer of deep cervical fascia, the prevertebral fascia, passes laterally and posteriorly as the scalene fascia, covering the Scalene muscles, Splenius capitis, and Levator scapulae(Watkinson & Gleeson, 2016). All the cervical ventral rami are behind the prevertebral fascia. The nerves to the Rhomboids and Serratus anterior stay deep to the prevertebral fascia, with the Accessory nerve superficial. Under the prevertebral fascia, the descending brachial plexus and Subclavian artery, emerging between Scalene anterior and medius, carry a sleeve of the prevertebral fascia behind the clavicle, deep to the ascending clavipectoral fascia and coracoid process, forming an axillary sheath with its neurovascular bundle entering the axilla. Posteriorly, the prevertebral fascia is attached to the spinous processes of the vertebrae and extends laterally to form the floor of the posterior triangle of the neck. These layers of the deep cervical fascia are continuous with one another, forming a distinctive part of the cervical musculoskeletal anatomy and an important biomechanical element.

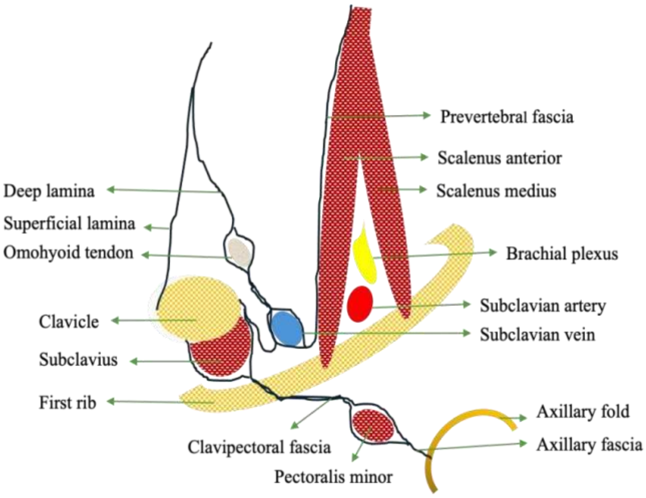

Figure 5. Illustration created in PowerPoint showing three layers of the deep cervical fascia – superficial lamina, deep lamina and prevertebral fascia, above and below the clavicle.

Variations in reflection of the deep fascial layers have led to a controversy over the limits and how the layers split to encase various muscles and neurovascular structures(Watkinson & Gleeson, 2016).

Superficially, the Platysma, when present, is embedded in the superficial adipose fascia arise from the fascia covering Cleidobrachialis pectoralis and Cleidobrachialis deltoideus ascends superiorly and medially across the clavicle. Its medial fibres interlace with the Platysma of the contralateral side in the median plane, attach to the symphysis menti, the inferior margin of the mandible and subcutaneous layer of the face(Standring, 2016).

The bilateral clavicles at the root of the neck form a common boundary between the neck, the thorax and the upper extremities. The deep lamina of the deep cervical fascia descends posterior to the clavicle (**Fig. 5**). Laterally, it continues above and lateral to the coracoid process, blending with the coracoacromial ligament. It encases the coracoid process and conjoint tendon of the Coracobrachialis and the short head of the Biceps brachii. From there, it reflects medially as the clavipectoral fascia to cover the Pectoralis minor and blends with the axillary sheath. It ascends to enclose the Subclavius muscle, attaching to anterior and posterior ridges of the Subclavius groove on the inferior surface of the clavicle, extending across three-fourths of the medial curvature from the sternal end, expanding the attachment of the muscle(Henry AK, 1957). The posterior layer continues with the deep cervical fascia, enclosing the intermediate tendon of the Omohyoid, indirectly connecting it to the clavicle. Further, medially deep to the Cleidobrachialis pectoralis, it blends with fascia covering the upper two intercostal spaces, attaching to the first rib and the Subclavius tendon. These fascial layers between the cranium and the pectoral region are intimately connected to the clavicle, forming tensegrity planes. Most of this structural [3]tensegrity (from "tension" and "integrity", from architecture, is biotensegrity, when applied to living system) of the soft tissues is lost instantaneously the moment the integrity of the clavicle is lost.

The axial rotation and lateral flexion of the head and neck over the fractured clavicle respond to the pulling effect of the drooped shoulder, relaxing the deep cervical fascial layers and muscles as soon as the clavicle collapses. This prevents the clavipectoral fascia from tugging around the neurovascular structures between the disrupted supraclavicular and infraclavicular fossae. Inferiorly, relaxation of the clavipectoral fascia prevents tension in axillary space, concurring with anterior and inferiorly protracted posture (*ptosis*) of the whole shoulder complex, assisted by the relaxed Coracobrachialis and short head of the Biceps brachii with adducted arm and flexed elbow. In addition, due to the protracted scapula, the Subscapularis and Latissimus dorsi muscles relax the deeper fascial layers, approximating the fractured fragments and unloading the neurovascular structures draped over the first rib at the thoracic aperture. The laterally placed Occipitocleidal trapezius and Cleidobrachialis deltoideus maintain their equilibrium to stabilize the ventrally rotated lateral fracture fragment, which has already been driven medially and inferior to the plane of the medial fragment. The lateral fragment, passively protracted, maintains its posture and holds the medial fragment at a higher level.

5.0 Axial rotation of the fracture fragments:

On an X-ray, the anterior rotation of the lateral fragment is, in part its normal anteversion due to the version angle and protraction at the scapulothoracic synsarcosis, with a ventral tilt of the acromion that shows the superior surface of the lateral curve more than usual. The lateral fragment may rotate ventrally only a little at the acromioclavicular joint, with eccentric contraction *(resisting stretch)* of the Occipitocleidal trapezius, in addition to concentric contraction (*spasm*) of the Cleidobrachialis deltoideus against gravity. However, as shown on electromyography, there is typically minimal activity of the Occipitocleidal trapezius in an unloaded arm and only a little contribution of it when carrying heavy weights(Lambert, 2016). The Cleidobrachialis pectoralis rotates the medial fragment ventrally depending on the remaining length of the medial curvature. When a clavicle fracture is treated in an arm sling, with the regression of acute pain, the normal action of the middle part of the Trapezius and Occipitocleidal trapezius on the acromion and the lateral fragment returns, effectively balancing the Cleidobrachialis deltoideus fibres raise the shoulder tip.

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[3] The term tensegrity was first coined by the architect R. Buckminster Fuller. It is the diminutive of tensional integrity of structural elements in compression and tension to maintain the equilibrium and stability of a structure. In the body, the bones are the 'rigid' bodies of the skeletal system under compression held in equilibrium and stabilized by the continuous tension of the widespread interconnected fascial layers dynamized by the muscles in its seemingly static resting state (*muscle tone*) and dynamic active state during locomotion by equalizing the "action and reaction" forces. The fascial layers and muscles are preloaded in tension, trying to collapse the structure, which is resisted by the bones in compression. The structure will collapse if either break. The simple formula for building a stable suspension bridge, the minimum number of strings = 3 multiplied by number of bars, was used to construct the Kurilpa bridge in Australia. In the case of the intercalated clavicle, there are strategically arranged layers of the cervical fasciae and four large muscles to hold the clavicle in equilibrium, with crucial role of the Subclavius to hold it down and decelerate, to allow recovery from a high velocity projectile delivery. In 1949, the concept of tensional integrity in iatrophysics (biomechanics) was rejected by the physicians, as many did not believe in it.

The Serratus anterior is at liberty to drive the scapula around the thorax, immobilizing it and fixing the scapulothoracic synsarcosis in conjunction with Pectoralis minor and other attachments to the coracoid process. Thus, turning the coracoid process downward and medially, away from the glenohumeral joint line, as seen on an anterior-posterior radiograph of the fractured clavicle. If, during the post-fracture period, the clavicle shortening with torsional deformity persists, the inferior angle of the mispositioned scapula in protraction is lifted off the thoracic wall *(posttraumatic mechanical "winging").* Initially, the subtle winging is often missed in the face of captivating images of the fractured clavicle, as an uncompromising response by the surgeon to pain and anxiety of the patient, to prevent further displacement of the fragments and complications of the fracture.

If the clavicle heals with telescoping of the fragments or apex angled posteriorly and superiorly with ventral rotation, the space posterior to the clavicle is compromised. This will impede the clavicle's dorsal retraction and axial rotation, limiting the scapula's dorsal (*posterior*) tilting during the overhead elevation of the arm. As the arm descends, the attempted ventral *(anterior)* tilt of the scapula reciprocally elevates the inferior angle. Contractures of the deep cervical fascial layers and their reflections distort the brachial plexus and the encased subclavian vessels, causing symptoms of thoracic aperture syndrome. Defects in the morphology and morphometric alterations in the radii of the curvatures, with the medial curvature being the commonest site of the fracture, reduce the kinematic range, attended with pain due to traction of the brachial plexus on elevation and limited clearance at the medial curvature due to restricted dorsal axial rotation and the rolling of the clavicle.

In the young, with remaining growth, the altered angles of version and torsion, and the effective screw twist and pitch at the fracture site may improve with activity over time. Nonetheless, healing and remodelling may be affected by an accompanying neurovascular injury, which impairs the neurotropic influence on tissue healing, as C5, C6, and C7 nerve roots innervate most of the soft tissues, the clavicle and its joints involved at the time of the fracture. Loss of muscular equilibrium is often unrecognized clinically. The shortened Cleidobrachialis pectoralis prevents effective ventral rotation of the clavicle at the medial curvature in conjunction with the Occipitocleidal trapezius and Cleidobrachialis deltoideus during the "setting phase" at the time of arm elevation. The Pectoralis minor muscle, enclosed in the extension of the clavipectoral fascia, acting on the coracoid process, disturbs the force couple formed by it with the Serratus anterior and Trapezius, to optimally place glenoid fossa under the head of the humerus. In the young, it would affect the torsional angle of the humeral shaft, the version of the glenoid and humeral head, due to biomechanical forces growing up engaged in athletic and overhead heavy manual occupation. The neural injury and altered biomechanics of a malunited clavicle will follow the principle of "form follows function" in the young, leading to an altered path to maturity of the clavicle.

6.0 Vascular injury associated with fracture anatomy:

The Supraclavicular, Suprascapular and Transverse cervical vessels in the supraclavicular fossa, related to the posterior and superior aspect of the clavicle, and the Subclavian vessels and the brachial plexus trunks passing distally beneath the clavicle are vulnerable to a severe direct and indirect impact with traction injury, especially encountered in a motorcycle accident. In such cases, there will be neurological and vascular insufficiency. Failure to restore the length of the clavicle urgently will further compromise limb circulation. Because length of vessel is a function of perfusion, shortening with distortion causes vascular insufficiency(Kambhampati et al., 2006). During a high-velocity fracture, due to traction, compression, and oscillation of the tissues, intimal injury can occur to the medium- and large-sized arteries above and below the clavicle. An adventitial haematoma may form due to direct impalement of the sharp end of a fracture fragment within deep cervical fascial sleeves, with or without an aneurysm formation. An imminent injury to the brachial plexus cords, causing a neurogenic syndrome of the upper extremity, becomes highly likely due to traction at the time of injury.

7.0 Drooped shoulder complex - a virtually floating shoulder:

In the absence of normal resistance of the intact clavicle, the entire shoulder complex collapses. Gravity and reduced suspensory effort from the Occipitocleidal trapezius allow the shoulder "ptosis" to occur, reducing the standing shoulder height on the injured side. The weight of the shoulder complex and the upper extremity is hung from the soft tissues of the scapulothoracic synsarcosis, without the restraining joint capsule and ligaments. Protraction occurs due to the active participation of the scapulothoracic musculature, especially by the Serratus anterior and Pectoralis minor, assisted by the large muscles, namely the sternal and rectus heads of the Pectoralis major and the Latissimus dorsi. The posture of the shoulder complex is sustained by acute spasm of the muscles and the residual tone as the spasm gradually passes off.

8.0 Radiography of pathological anatomy of the clavicle fracture:

Radiological images in trauma practice are virtual, static representations of dynamic skeletal linkages and joints. When applied to the reconstruction of displaced fracture fragments, multiple two-dimensional plain radiographic views have limited value. Radiographic imaging of the three-dimensional anatomy of bones and joints comes with several optical errors. Plain radiography remains widely used for its ready availability, cost-effectiveness, and relatively low radiation dose, making it a preferred imaging modality for fracture management. It provides well collimated X-ray beam that can be angled through more than 180 degrees, depending on anatomical location, to obtain excellent multiple two-dimensional views. The semi-axial imaging technique for assessment of clavicle fracture has become the norm, even though the images are distorted in appearance.

Therefore, for morphometric evaluation, the plain radiographic images of a bone merely provide approximations of the actual values. These values can vary greatly depending on the projection techniques, patient positioning, understanding of the three-dimensional topographic anatomy, and the technologist's experience. The exact outcome of the reported normal and pathological anatomy depends on the radiologist's expertise in recognizing bilateral variations in anatomy and in accounting for the frequently observed genetic and geographical differences in cadaveric dry clavicles across diverse populations. Activity-related variations due to biomechanical forces acting on the bones and joints are rarely correlated.

8.1 Radiography of in-situ articulated clavicle bone:

The radiological anatomy of the clavicle is intricate because of its curvatures and angular orientation relative to the median and transverse planes. It is neither at right angle to the sagittal plane nor does it lie on the coronal plane. It is best visualized in anterior-posterior, posterior-anterior views or at an angle to the transverse plane by shifting the direction of the radiographic beam. For acquiring two standard orthogonal views, the principle of radiographic technique dictates that the X-ray beam should be perpendicular to the plane of the object under examination rather than to the cardinal planes. Multiple axial computed tomography views are stitched together to obtain a three-dimensional reconstruction and animated for better understanding. Plain radiographic multiple orthogonal views can be obtained at a lower radiation dose than computed tomography by manipulating the body or a body part to acquire customized views.

The clavicle is intercalated between two joints, embedded at the root of the neck at an angle, and varies between 10-20 degrees cranially to the transverse plane, and retracted 20 degrees posterior, relative to the mid-truncal coronal plane(Kapandji, 2005). The proximal ribs incline upward from anterior to posterior on an oblique plane that is steeper than the clavicle. The scapula is tilted anteriorly, overlooking the shoulder line, at 60 degrees to the clavicle, which tends to shadow the customary radiographic image of the clavicle in all planes and angles. This overlap of structures introduces shades of grey and optical errors, making it difficult to discern the fine details of the region of interest, particularly with an image intensifier during surgery.

The posterior-anterior radiographic view with 15 degrees of cephalic tilt to the transverse plane shows the best anatomy of the clavicle for morphometric analysis compared with the traditional anterior-posterior view(Smekal et al., 2008). This is true only if the imaging is performed with the patient protracting against the bucky, bringing the clavicles into the mid-coronal plane, perpendicular to the X-ray beam, with shoulders held down. However, this posture is neither practical for an acute fracture of the clavicle nor during surgery. Semi-axial oblique views taken at 10 to 45 degrees of cephalic and caudal beam can provide additional information about the clavicle anatomy and fracture pattern. Nonetheless, it is a desperate attempt to examine the transverse-plane anatomy of the clavicle to assess the medial and lateral curvatures, and the posterior-superior displacement of the fragments. What it shows is a distorted view of the clavicle. Still, it can be invaluable for understanding certain types of fracture patterns.

The anterior-posterior and posterior-anterior views provide the most desirable information about the fracture pattern, the amount of vertical displacement, intersecting crossover distance between the fractured ends of the medial and lateral fragments, and partial representation of superior and posterior-superior angular deformities, without much-needed exactness for surgical intervention. A careful examination may reveal axial rotational deformity of the diaphysis to a discerning surgeon with experience, allowing a proper assessment. Otherwise, it is not easy to tell whether the axial deformity of the medial fragment is due to rotation at the sterno-costoclavicular joint, and whether the axial rotation of the lateral fragment is at the acromioclavicular articulation or due to the protraction and drooping of the shoulder complex medially and inferiorly.

Although it is possible to report the rotational deformity of each fragment, it is labor-intensive and time-consuming for a cognizant radiologist. And whether it is worth reporting such details in the surgical workup for the surgeon to restore the anatomy of the clavicle, when there is currently a never-ending controversy over conservative and operative management based on simple aspects of correcting the overlapping fragments to attain the length and correct the angular deformity of the clavicle. The participation of a nervous, pained patient in 'decision making' is not a very meaningful basis as one of the evidence-based doctrines until the resolution of such elementary decision-making aspects of clavicle fracture deformity.

Neither anterior-posterior nor posterior-anterior views can deliver exact end-to-end or centre-line lengths. They fail to capture changes in the depth of medial curvature, which is the most common site of fracture and an ontogenetically conserved feature of the clavicle. The bidirectional asymmetry is primarily due to the greater chord length of the medial curvature. It is impossible to measure angles of torsion and version on any currently available plain X-ray views. The biomechanical consequences of these angular parameters have not yet been part of the clavicle's morphometric studies, which affect the overall functional outcome of the shoulder complex and the pectoral girdle following a clavicle fracture.

At the elementary level, before and after healing, understanding the pathological anatomy of the clavicle's fracture fragments and advanced knowledge of normal radiological anatomy in the coronal, sagittal and transverse (*axial*) planes are key to its surgical reconstruction and conservative treatment. As this gracefully bioengineered bone has curves and twists that are invariably distinctive in each patient, there is a need to further develop the three-planar imaging techniques to acquire its cortical and medullary anatomy on plain radiography.

This may not be entirely possible, the reason being that the clavicle is very neatly embedded subcutaneously in the root of the neck and cannot be moved independently like other appendicular long bones.

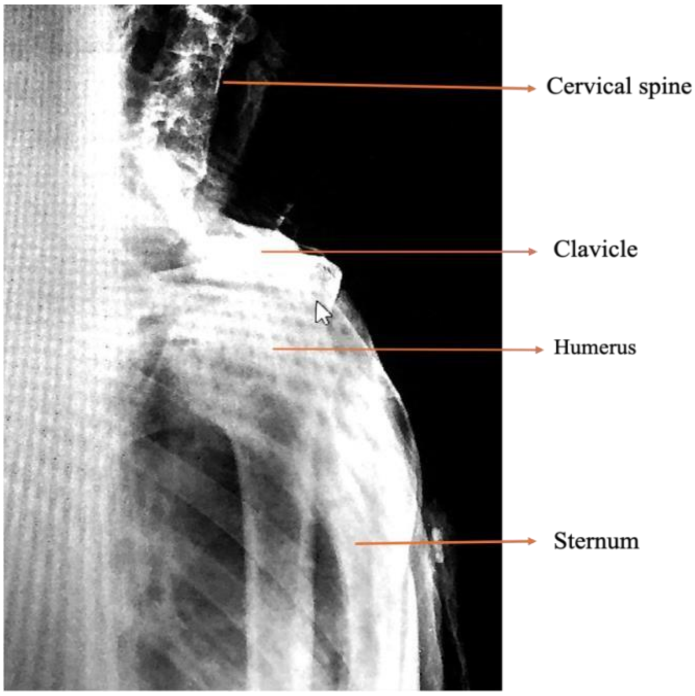

Figure 6. The author's attempt at an axial medial-to-lateral shoot-through view of the left clavicle, with an arrow at the acromial end of the clavicle.

A medial-to-lateral shoot-through foreshortened axial view of the clavicle is difficult to obtain, as it does not currently provide an intelligible image, being overshadowed by dense artefacts of the acromion and head of the humerus in the background (**Fig. 6**). The axial view shown here has never been tried before and requires further refinement and evaluation to determine its surgical role in clavicle fractures. Well-arranged anterior-posterior, posterior-anterior, and scapular views are essential as part of the clavicle trauma series. The full extent of correct clavicle shortening is not visible in any of these views, including the intact contralateral side for comparison. Nonetheless, the contralateral view can provide the shape, form of the clavicle, an estimate of the craniocaudal width, the thickness of the cortices along the projected length, the joints, and intra-articular fractures of the medial and lateral ends in rare instances. Consequently, the inclusion of the intact clavicle must be standardized, first to rule out any associated injury on the other side, and additionally, for morphological similarity and morphometric analysis based on shared optical errors, greyscale distribution, and unavoidable optical illusions.

The inclusion of the upper eight ribs and proximal humerus in the initial images provides orientation of the scapula, coracoid process and glenohumeral joint in a single frame, making the treating surgeon aware of the scapulothoracic and glenohumeral anatomy, as well as the importance of the former in returning the latter to full normal function during rehabilitation. The clarity of the greyscale and pixel grid of high image resolution across the whole image will help distinguish the cortices and medulla of the clavicle. There is a radiographically recognizable correlation between the intact clavicle and the orientation of the coracoid process when the clavicle and the scapula on the thoracic wall and the humerus on the glenoid surface are in their resting anatomical position (**Fig. 7**). As the shoulder tip drops, the displacement of the fracture fragments disturbs this relationship with the inferior, anterior and medial turning of the coracoid process. The tip of the coracoid process turns away from the glenohumeral joint line. With protraction of the scapula, the normal orientation of the coracoid process is altered in all the three planes.

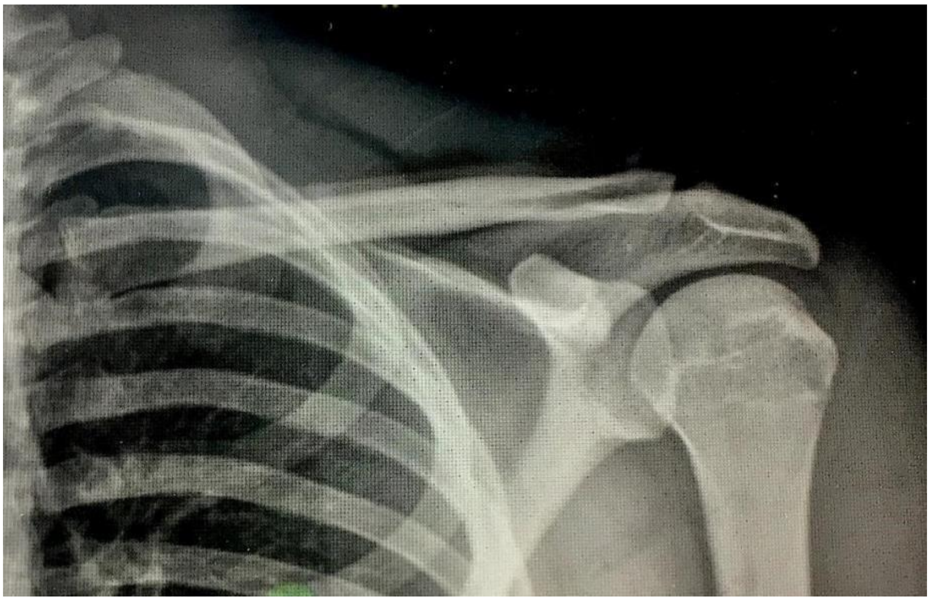

Figure 7. An anterior-posterior image of a normal clavicle shows the oblong appearance of the coracoid process with its tip (*true apex*) directed laterally over the edge of the glenoid fossa**.** Note that the slender hourglass outline of the clavicle's medulla has the narrowest section approximately at the inflection region between the curves. The medulla of the clavicle's lateral third almost matches the medulla of the acromion.

8.2 Intraoperative radiology for fracture reduction assessment:

Cortical thickness varies significantly across the five sections of the clavicle. The cortex is thin at the prismatic sternal and flat acromial ends. In the diaphysis, the cortex becomes thicker and denser as the cross-section becomes more circular in the third- and fourth-fifth sections of the clavicle. The ends are more trabecular than the central diaphyseal region. Unlike other long bones, the clavicle does not have a true medullary canal. As the trabecular anatomy of the clavicle is indiscernible on plain radiography, it appears to be a medullary canal. The shape and form of the medulla on anterior-posterior and posterior-anterior views taken perpendicular to the coronal plane also vary significantly. It tapers from the trabecular quadrangular sternal end, narrowest at the zone between the curvatures, and gently widen towards the flat acromial end, resembling the slender stem of a tall wine glass or a stretched-out hourglass. It may vary depending on the clavicle's angle of version and variable anatomy of the acromion.

Like any other bone fracture reduction technique, well-matched cortical thicknesses of the major fragments in two planes indicate satisfactory fracture reduction. Similarly, matching the medullary form of the two fragments, in conjunction with cortical matching, helps recognize adequate fracture reduction on the operating table. Uniform flow of the medullary flute from the sternal end to the acromial end, like the contralateral clavicle, indicates axial correction in the transverse plane on the anterior-posterior view. Repositioning of the scapula in its normal resting dorsolateral retracted position, equidistant from the midline and matching the contralateral scapula, indicates that the clavicle has been pulled to its original length. On inspection, the scapula's range of translation with passive humeral abduction and adduction, without visible incongruency of scapulothoracic synsarcosis, suggests resolution of mechanical winging of the inferior angle and that the clavicle has been placed in its preinjury orientation relative to the coronal and transverse planes. Accompanying reorientation of the coracoid process in relation to the glenohumeral joint line indicates correction of torsion and version around the screw axis. Nonetheless, these parameters are difficult to judge.

In summary, the distance of the vertebral border of the scapula at the level of its spine from the spinous processes of the vertebral column, and that of the coracoid process from the mid-sternal line, compared with the contralateral side, together with its reorientation, informs much about the dorsolateral repositioning of the scapula, the length and axial rotation of the clavicle.

9.0 Bilateral clavicle length asymmetry:

Morphometric studies have shown that the left clavicle is 5-8 mm longer than the right, and the right clavicle has significantly thicker cortices in mid-diaphyseal third-fifth and fourth-fifth sections(Bernat et al., 2014; Harrington et al., 1993; Kaur H & Sahni H, 2002). The length asymmetry is correlated with longer chord of the medial curvature. The left clavicle has a larger radius of curvature and is shallower than the right clavicle. Simply noting these few correlations can help get the best possible reduction of the clavicle. However, the currently available radiographic views do not show the exact size and the shape of medial and lateral curvatures on cephalic or caudal-directed oblique views.

There is no single plain radiological view that reliably helps correct the curvatures, angles of torsion and version, screw twist of the diaphysis and screw pitch length for a patient-specific clavicle. However, if the coracoid process reorients in all three planes, the clavicle's torsion, version and screw twist are likely corrected. If the alignment of medial and lateral curvatures, their offset, and their chord lengths remain uncorrected, one can be certain that the length, the screw twist and the screw pitch of the clavicle are uncorrected. The ratio correction between the radii of curvatures of the transverse and the inferior curvature in the coronal planes is critical for restoring the clavicle's cranking mechanism. Although dry bone and computed tomographic three-dimensional morphometry have revealed bilateral directional asymmetry, these differences are insignificant, and the concern is present in only one third of the population.

It is not clear what functional difference pulling the fractured clavicle to its original length would make to a healed clavicle, if other biomechanical parameters remain uncorrected during surgery or remodelling, when treated conservatively. A simple computer-based segmentation and registration technique can be applied to achieve greater accuracy in matching the two sides and reduce anatomical and biomechanical differences between them. The intact clavicle on a plain radiographic image can be segmented using appropriate software, virtually disarticulating and registered to the restored fractured clavicle. If the restored clavicle has attained its shape, form, length, cross-sectional anatomy, and curvatures, then the two clavicles should exhibit a high registration correlation, despite their right- and left-handed chirality. Some of these features may vary depending on whether the plate and screws or an intramedullary device is used to restore the anatomy of the clavicle.

10.0 Application of computer vision for the reconstruction of the clavicle:

Segmentation of the contralateral clavicle from plain radiographic views would be part of the surgical pre-planning and the registration process undertaken before wound closure. Applying the technique during early learning stages would entail extended time in the operating room, prolonged anaesthesia and higher costs. However, there would be greater surgeon satisfaction and better patient-based outcomes at the final follow-up. In the hands of an expert clinical biomechanical engineer, a well-trained radiologist, or a technologist, the segmentation and registration process should not take more than a few minutes after the anterior-posterior, and a second suitable view of the entire pectoral girdle (*bilateral shoulder complex*) is made available. No computer vision study is available for intraoperative assessment of resynthesized clavicle fractures. Initially, intraoperative plain X-ray-based registration may be a challenging bioengineering endeavour but achievable(Guéziec et al., 1998).

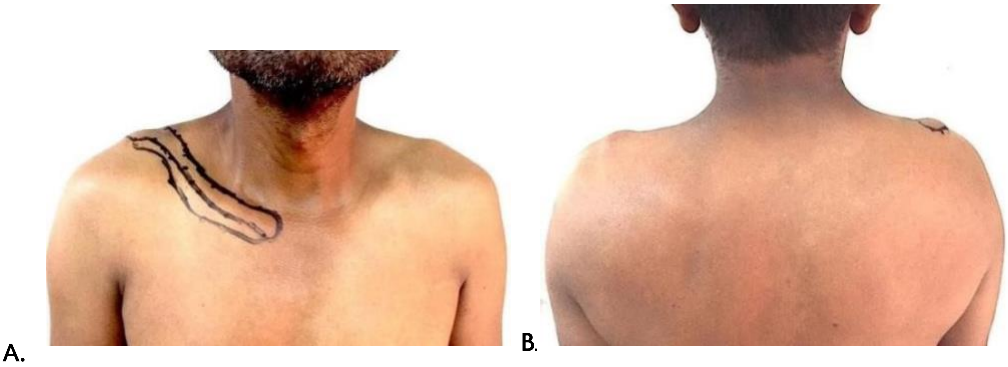

Figure 8. Both the clavicles are normal. Outline of the right clavicle on the cranial and anterior view (photograph by consent).

To reduce the radiation exposure of the pectoral girdle, compare the outline of the contralateral clavicle on the skin. The two planar drawing of the two-dimensional outlines are merged with the help of software as solid images and then converted into a three-dimensional virtual solid object (**Fig. 8**).

Alternatively, the intact and restored clavicles are radiographed. Then, segmentation and registration software are applied to verify the percentage restoration of the fixed clavicle. Several free open access, cost-effective photogrammetry, sketch-based modelling, and image-based modelling software, such as Autodesk Maya, Rhino, Fusion 360, and SolidWorks, etc., are available for converting two views of a three-dimensional object or two views of an object as two-dimensional sketches into a single three-dimensional object.

Based on intraoperative radiography, once the structural anatomy and biomechanical architecture are restored, also assess the orientation of the scapula to the thoracic wall with the humeral head resting in the glenoid by undertaking relevant shoulder radiographic views. Compare with the contralateral side to determine whether the coracoid process is repositioned to its original orientation on the anterior-posterior view and whether the scapula rests normally on the thoracic wall, equidistant from the spinous processes without winging.

The surgeon's satisfaction is achieved with the anatomical restoration of the clavicle and repositioning of the scapula. Move the glenohumeral joint through the full range of motion in coronal, scapular and sagittal plane arm elevation, while observing scapular movements before the patient wakes from anaesthesia. At the same time, watch and palpate the clavicle to assess the quality and strength of the fixed fracture. This approach reduces the surgeon's anxiety about future surprises of fixation failure and mechanical dysfunction at the scapulothoracic synsarcosis and glenohumeral articulation.

11.0 Anterior-posterior and posterior-anterior proximal thoracic radiography controversy:

Following a clavicle fracture, anterior-posterior imaging of the upper thorax, including bilateral clavicles, upper eight ribs, scapula, glenohumeral joint and humerus, performed in supine, erect or semierect (*beach-chair*) positions is done by projecting an X-ray beam perpendicular to the bucky *(receptor).* Posterior-anterior radiographic imaging of all relevant structures is possible in all patient positions except supine. The position in which the chest must rest against the bucky can be painful for a patient with an acute injury and during the early healing phase. In either set of positions, apply an axial cephalic or caudal tilt beam without adjusting the patient's position. In both positions, the scapula should preferably be protracted as in a routine chest X-ray. The beam must pass through the median plane, perpendicular to the bucky, to include both the clavicles for comparison and morphometric purposes.

The two views during follow-up differ in appearance due to variations in the positions and magnifications of the structures. Check the symmetrical positioning of the patient so that both the shoulders rest evenly against the bucky. The medial ends of the clavicles are equidistant from the median plane, passing through spinous processes of the vertebral column. On the posterior-anterior imaging, the patient hugs the bucky on the front, protracting the shoulders. A gentle hug will bring the clavicles closer to the coronal plane and perpendicular to the beam, reducing the optical errors. The relationship of the clavicles is better defined relative to the shafts of the ribs. However, the orientation of the coracoid process differs in both views. It must be carefully related to the intact and the fractured clavicles as an important anatomical landmark for assessing the correct orientation and axial rotation of the restored clavicle.

It is impossible to assess the anatomy of any curvature satisfactorily except for the inferior curvature on the anterior-posterior view. Whether the posterior-anterior view provides better morphometric length measurement is difficult to confirm, as in both methods, the beam is divergent due to the shoulders' width. Secondly, the beam passes at an angle unless the clavicles are in a protracted position to receive the X-ray beam perpendicular to it. Theoretically, the divergent rays passing through the substance of the clavicle are at various angles, generating a shadow of the clavicle of greater length than normal. The clavicle must be parallel to the detecting bucky to reduce distortion and unnecessary magnification of the image, and, for follow-up imaging, standardize the X-ray tube distance. Radiography for the clavicle would be repeated multiple times during follow-up visits. There is always a danger of extra-focal radiation dose to the radiosensitive organs such as the thyroid, eyes and breast tissue in juveniles and adolescents. Posterior-anterior imaging reduces the dose to these structures. Anterior-posterior unilateral radiography reduces the dose and extra-focal radiation by centralizing the collimated beam over the clavicle. In a survey of current practices of large teaching hospitals, 20% of the radiographers were performing a coned anterio-posterior shoulder view for clavicle fractures. 60% performed anterior-posterior 15 degrees cephalic angulation, 28%, 8% and 4% performed anterior-posterior cephalic oblique at 25 degrees, 20 degrees and 30 degrees, respectively(McEntee & Kinsella, 2010). The cephalic views demanded a high number of repeats. The traditional practice of anterior-posterior radiography has not changed significantly.

Posterior-anterior imaging is used less often because of limited experience and confidence in patient positioning, uncertainty about the anatomy, and the inability to include all relevant structures within the divergent beam(McEntee & Kinsella, 2010). To better define the fracture pattern, multiple anterior-posterior and oblique views at 20- and 45-degrees of cephalic tilt, and 45 degrees of caudal tilt are obtained to increase radiographic reliability for surgical management of clavicle fractures(Austin et al., 2012). For reliability, direct the beam perpendicular to the clavicle rather than at the shoulder joint. None of the current views adequately provide an essential cranial-caudal view of medial and lateral curvatures. Nor do the studies correlate with the patient's mechanical activities. It is not about procuring radiographic images but about meeting patient-specific requirements.

For the scapular plane and Garshey's (true anterior-posterior) view for the shoulder joint, the patient is rotated posteriorly by approximately 35-45 degrees against the bucky, or the beam is rotated to bring it perpendicular to the scapular plane and the bucky. Although the clavicle shaft appears distorted on this view, with limited visualization of the inferior curvature because the beam is oblique to the plane of the clavicle, a good view of the subacromial space shows the degree of its obliteration due to protraction and inferior displacement of the shoulder complex(Aydingoz et al., 2014). The scapular view has a limited value in the clavicle trauma series unless modified to show the whole length of the clavicle.

Fracture displacement with overlap of the fragments can vary when measured in erect and supine positions(Backus et al., 2012). On average, for mid-shaft clavicle fractures in an erect position, the vertical displacement is 17.0 mm. In the supine position, it reduces to 8.5 mm, as the shoulder complex falls backwards (*passively retracted*) under gravity. The reactive forces from the resting rigid surface increase the shoulders' width and height due to the retraction of the lateral fragment, reducing interfragmentary overlap. In the erect standing position, the vertical effect of gravity droops the shoulder, and the protracted lateral fragment is driven medially and lowered, thereby increasing the vertical displacement and telescoping of the fragments, reducing the observed length of the clavicle. The average observed length of the fractured clavicle in the upright position increases from 162 mm to 168 mm in the supine position. The difference of 6 mm is considered clinically insignificant(Backus et al., 2012). Such statistically derived numbers, based on static images, can be clinically significant and relevant in decision-making about whether to operate on a fragmented, displaced fracture or not.

Supposing the telescoping overlap of the fragments is 22 mm upright and reduces to under 20 mm in the supine position, the patient avoids an operative intervention, as the relative indication for surgery is 20 mm. This is based on almost 30 years of evidence that shortening by more than 20 mm carries a much higher risk of non-union and a poorer patient-based outcome(Hill et al., 1997a; Robinson et al., 2004). This criterion for surgery is not qualified by the clause about erect or supine posture and an arm, with or without a suitable shoulder immobilizer. Frequently, conservative treatment with a simple collar and cuff for fracture immobilization does not prevent shoulder ptosis. In contrast, a preferred broad arm sling supports the weight of the shoulder complex and arm, to help relieve acute pain. Figure-of-eight sacrifices patient comfort, and still, it fails to apply longitudinal traction and retract the lateral fragment dorsally for long. Applying sustained traction to reduce telescoping, vertical distance and angulation between the two major fragments with conservative methods is not practically feasible.

Resolution of acute pain gradually decreases the muscle spasm, which has thus far held the displaced fracture fragments, allowing them to return towards normal orientation in one or two planes. With further return towards normal resting muscle tone and the force couple taking effect, further influence the vertical and telescopic displacements of fragments. This improved position of the fracture pattern is what keeps the clavicle's fracture management controversy alive!

12.0 Parameters for cephalic and caudal-directed beam angle:

It is difficult to determine the exact clavicle length on traditional anterior-posterior plain radiography because of the distance between the X-ray head and the bucky, and the effect of patient positioning on accurate measurements. This difficulty is even greater in patients with a high body mass index, where soft tissue shadows reduce the image quality. It is compounded if the patient cannot hold the desired position long enough due to acute pain. If the anterior-posterior and semi-axial 25-45 degrees oblique views of a fractured clavicle, with a retracted and elevated medial fragment with a relatively protracted and depressed lateral fragment, are not parallel to the bucky and the beam is not perpendicular to the position of the clavicle, neither the fractured nor the intact clavicle will provide comparable morphometric numbers for surgical restoration. Therefore, there can never be a desired equivalence of lengths to compare the two sides.

Standard anterior-posterior and additional oblique semi-axial views are inadequate and can be misleading for making surgical decisions based on apparent rather than actual shortening(Smekal et al., 2008). A posterior-anterior view of the thorax is a better way to determine clavicle length, but it is rarely performed. In a comparative study of computed tomography served as a reference, and a posterior-anterior 15 degrees cephalad oblique view of the shoulder produced comparable results for determining clavicle length(Smekal et al., 2008). Nonetheless, bidirectional asymmetry is present in many paired dry bone and computed tomography morphometric studies. [4]On the other hand, anterior-posterior and oblique cranial and caudal views at 45 degrees provide reasonable information of fracture pattern, in addition to alternative views of the clavicle(Baraza & Wood, 2014; Harris & Latshaw, 2012). There is no consensus on angular cephalic or caudal tilt values. However, both views provide a distorted and inadequate anatomy of the curvatures.

13.0 Distinctive sex-based effect of clavicle length:

The original length of the clavicle and the threshold of shortening causing unsatisfactory outcomes differ significantly between biological sexes. In males, a decrease in length of the clavicle of more than 18 mm and in females of more than 14 mm results in unsatisfactory patient-based outcomes(Lazarides & Zafiropoulos, 2006). A study of plain radiographic imaging of dissatisfied patients treated conservatively showed a mean shortening of 15.2 mm (9.7%). More than 10% shortening in a fractured clavicle, as a proportionate measure rather than absolute loss of length, was considered clinically significant(De Giorgi et al., 2011). In certain cases, instead of following rigid 20 mm rule, it is worth considering statistical data carefully only as a guideline for surgical intervention. Radiological images are prone to optical and technical errors. Prevent malunion and kinematic disturbances of the clavicle, and of other associated linkages and joints, based on patient-specific clinical evaluation.

14.0 Comparability of plain radiography and computed tomography:

Plain radiography is not an accurate modality for measuring shortening of the clavicle for acute fractures(Omid et al., 2016). Radiography can measure the clavicle up to 8 mm longer on the fractured side and 6.42 mm on the normal side compared to computed tomography, indicating a poor correlation between the two modalities. Secondly, from the plain radiographic experience, the relative change from the erect to the supine position, and the supine positioning for optimal measurement during computed tomography, are questionable, as they too employ the same light principles for imaging. Therefore, when using computed tomography for clavicle reconstruction, oblique clavicle-specific slices are used to reconstruct 3-dimensional images for greater accuracy(Omid et al., 2016).

In another recent survey, measuring the length of the clavicle on the anterior-posterior and posterior-anterior thoracic X-ray views against computed tomography as a reference tool. The mean length on computed tomography was 149.30 mm. On supine anterior-posterior and posterior-anterior X-ray views, the lengths were 149.60 mm and 149.55 mm respectively. On an anterior-posterior 10 degrees cranial beam standing view, it was 150.98 mm, and on supine, it was 150.01 mm(Lima et al., 2022). The supine posterior-anterior view, closest to the computed tomography measurement, was considered the most reliable. However, in an acute setting, patient comfort is essential. All that is learnt about the fracture pattern and bone morphometry pre-operatively cannot be applied intra-operatively because computed tomography is not yet widely available in operating rooms for comparison with the intact contralateral side to achieve 100% restoration of the anatomy and biomechanical architecture of the clavicle, due to the concern about excessive radiation dose.

There is no study comparing preoperative computed tomography morphometric measurements with direct intraoperative morphometry of the fracture fragments and the length of the reconstructed clavicle using digital calipers.

15.0 Shifting the radiographic paradigm:

15.1 Towards a trauma series recommendation:

Currently, to assess the fracture anatomy of the clavicle, the trauma series includes anterior-posterior and cephalic or caudal oblique standing radiographic views of the clavicle, including the shoulder joint. The combination of one or more features of shortening, angular deformity, vertical displacement and bone fragmentation, is used to assess the risk of non-union and malunion and to guide surgical intervention. Vertical displacement exceeding 100% is associated with unsatisfactory outcomes. With excellent intra-observer measurement agreement across these standardized, reproducible multiple views, there is no statistically significant difference in vertical displacement measurements attributable to a particular radiographic projection in mid-shaft clavicle fractures(Hoogervorst et al., 2020). Accurate measurement of each fracture fragment and total shortening remains a concern.

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[4] Quesana F (1926) Technique for the Roentgen diagnosis of fractures of the clavicle. Surgery, Gynaecology & Obstetrics, 42, 4261-4281

For a trauma series, the radiological principles require that the collimated projected beam be directed perpendicular to the plane of the index structure at an optimal distance of 100 cm for reproducibility, to avoid magnification and reduce optical errors due to parallax, and with minimal divergence to avoid exposure outside the region of interest. For plain radiographic imaging of an intact or a fractured clavicle, the beam should be projected perpendicular to the plane of the clavicle, and the bucky should be parallel to and as close as possible to the clavicle and in its anatomical plane. As the beach chair position is the recommended position during surgical fixation of the clavicle, it is ideal for radiographic views of a fractured clavicle, with the arm resting beside the trunk in internal rotation, the elbow flexed at a right angle, and the forearm in the lap to relax muscles and ligaments of the shoulder complex, and those attached to the coracoid process.

For the posterior-anterior view of the clavicle, the patient should preferably sit comfortably on a stool, chin up, in a braced posture, whenever possible, with hands on the iliac crests. This position will partially restore clavicle's length with retraction of the shoulders if conservative management is considered. The suggested five-view clavicle trauma series (**Fig. 9**), including the traditional anterior-posterior, comprises A. Posterior-anterior of the upper thorax, beam at 15 degrees cephalic to match the elevated position of the intact clavicle, with shoulders braced to include both clavicles and glenohumeral articulations for morphometric comparison; B. posterior-anterior of the fractured clavicle, beam tilted to match the average displacement of the major fragments; C. trans-axial from medial to lateral shoot through; D. True anterior-posterior view, beam perpendicular to the clavicle, preferably in a beach chair position; E. Traditional AP view of the clavicle and shoulder extending to the eighth rib, providing a base line orientation of the scapula and the coracoid process relative to the clavicle, with optional 30-45 degrees semi-axial cephalic and caudal views. It is at the surgeon's discretion to choose a set of five or fewer views, depending on the severity of the trauma on inspection, and to follow through with the remainder after the traditional anteriorposterior view. Nevertheless, it is relevant to obtain all five views as a follow-up strategy when continuing with the conservative treatment or following unsatisfactory surgical fixation.

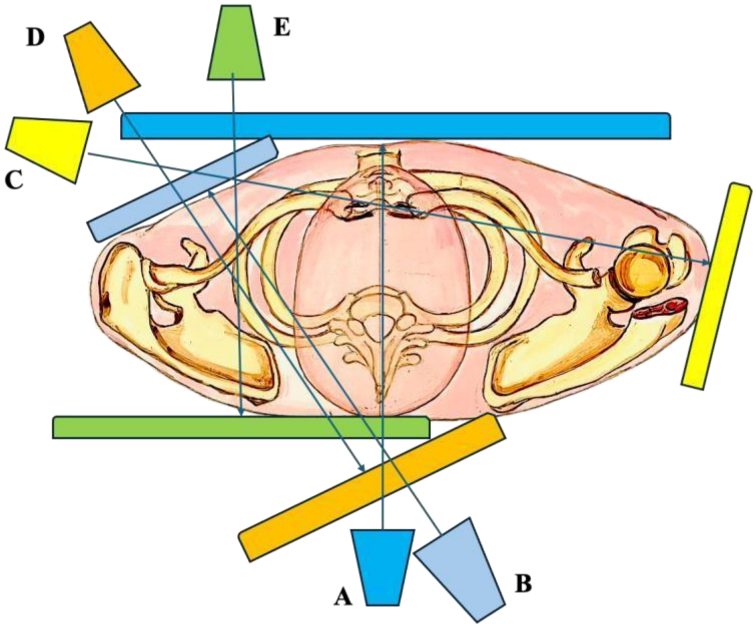

Figure 9. Five views trauma series – **A.** PA of the upper thorax at 15 degrees cephalic, **B.** PA of the clavicle, **C.** Medial to lateral axial shoot through of the clavicle, **D.** Perpendicular AP of the clavicle, **E.** Conventional AP of the Clavicle with or without the oblique cephalic and caudal views (artwork modified in PowerPoint).

15.2 Coracoid Cortical Ring Light up-G Sign (CCRL-G Sign):

Kinematically, the glenohumeral joint is quite versatile, yet much attention is devoted to restoring the proximal humerus using intricate fracture repair and replacement arthroplasty implants. Over the past two decades, greater emphasis has been placed on torsional anatomy of the proximal humerus. Surgeons seem less aware of the torsion and version angles, as well as the screw twist and pitch of the clavicle. They focus on correcting the length, a basic criterion for treating fractures of all long bones. Although pre-contoured plating systems have raised awareness, they improve certain angular parameters by default. Very often, a pre-contoured plate may need recontouring to fit an individual patient, or whatever fits well at surgery, is lately true for the clavicle, too. There is a lack of intentional effort to correct various radii of curvatures of the clavicle, bone surface variations, torsion and version angles. Neglecting these factors contributes to the incomplete restoration of biomechanical functions of the clavicle and the inability of the patient to reproduce the original kinematics and kinetics at the sterno-costoclavicular and the acromioclavicular joints, scapulothoracic and acromiohumeral synsarcoses and ultimately at the glenohumeral joints.

There is no described radiological sign for assessing the patient-specific correction of the medial and lateral curvatures, the offset between them, inferior curvature and axial rotation of the clavicle to help restore the dorsolateral relationship of the scapula to the thorax. As the sister bone, the scapula is affected by the displaced fracture of the clavicle, which displaces the coracoid process. This is seen on an anterior-posterior view of the shoulder, as the *'Coracoid Cortical Ring Light up On and Off Sign'* described here (**Figs. 10 and 11**). To hold the scapula in a stable and reproducible anatomical position, the shoulder complex and the humerus must rest beside the trunk in a neutral position, so that the coracoid process is held in an anatomically reproducible location and orientation, serving as an intraoperative guide to the reconstructed clavicle anatomy and for bilateral comparison.

15.2.1 Coracoid process: an anatomical landmark:

The coracoid process is a key anatomical landmark known as the "lighthouse of the shoulder" because of its relation to the axillary vessels and brachial plexus cords that run inferior to it(Matsen III et al., 2009; Mohammed et al., 2016). It can be an important X-ray landmark, for the patient-specific reduction of the clavicle fractures. The Lshaped coracoid process lies approximately 25 mm (*an inch*) below the clavicle at the junction of its fourth-fifth section and lateral one-fifth. It arises from the superior aspect of the scapular neck and is palpable at the lateral border of the infraclavicular fossa(Standring, 2016). It projects superiorly and simultaneously directed anteromedially, then bends laterally and is oriented transversely(Bhatia et al., 2007). The root and stem of the coracoid process form the inferior pillar, and the horizontal lateral projection is called the superior pillar. When the arm rests against the trunk, its tip (*true apex*) points laterally, anteriorly and slightly inferiorly, reaching the glenohumeral joint line, thereby showing the anterosuperior surface of the superior pillar on the anterior-posterior radiograph of the shoulder complex (**Fig. 7**). To the coracoid process are attached the pectoralis minor, the conjoint tendon formed by the short head of the Biceps brachii and Coracobrachialis; the coracoclavicular ligamentous complex, coracoacromial, coracohumeral, and transverse scapular ligaments. Thus, the coracoid process is a highly mobile and effective cantilever, with its muscle attachment acting like a door handle.

The coracoid process has two to three ossification centres. Ossification begins in the middle of the first year(Lambert, 2016). The second centre appears around the age of ten at the base of the coracoid process. The accessory apophyseal centre at the tip of the coracoid process appears around the age of 15. It is usually symmetrical on both sides. The subcoracoid centre at the coracoid base forms the upper third of the glenoid articular surface. It appears at age 8 to 10 years, extending towards the physis at the base of the coracoid. The process joins the rest of the scapula about the fifteenth year(Lambert, 2016). The physis at the base of the coracoid usually fuses to the rest of the scapula by the age of 18 years after it has fused with the subcoracoid centre(Aydingoz et al., 2014).

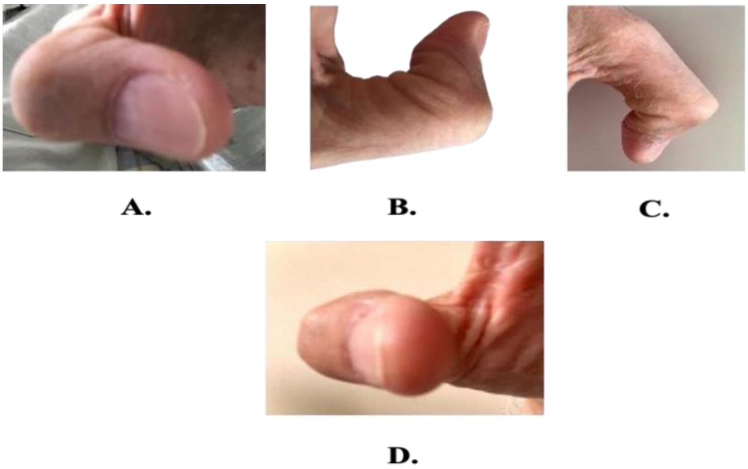

Figure 10. Gestured thumb modelling the coracoid process, showing its representative views. **A.** Anterior-superior view superior pillar (*distal phalanx*) directed laterally, **B.** superior view of both the inferior and superior pillars, **C** and **D.** apex aligned with the base and directed anteriorly, as seen in protracted scapula and shoulder ptosis following an ipsilateral fracture of the clavicle.

15.3 A binary On-and-Off light switch:

The *'Coracoid Cortical Ring Light up Sign'* is a binary on-and-off switch sign. In an intact clavicle, the anterosuperior surface of the superior pillar is seen as an oblong structure, with or without a crescent at the true apex, depending on the age, maturity and density of the ossification centre. Assuming that there are no preexisting pathologies of the coracoid process and shoulder complex linkages and the joints. Normally, on the side of the intact clavicle, the *'Coracoid Cortical Ring Light up Sign'* is absent (*off*). The superior pillar appears oblong. The sign is negative, and the binary light switch is considered turned off.

In an anterior-posterior radiographic view of a mid-diaphyseal clavicle fracture, with displacement, the gravity rotates the lateral fracture fragment along with the shoulder anteriorly, medially and inferiorly with protraction of scapula, with or without winging of the inferior angle. The base of the inferior pillar turns laterally, and the tip of the superior pillar rotates anteriorly and medially, reciprocally, spinning around a vertical axis passing through the base of the coracoid process. The anteriorly directed tip of the superior pillar lines up with the base of the coracoid process. The overlap of both the rings appears as a dense white ring. This accompanies a displaced clavicle fracture. The presence of a bright, dense white ring indicates that the binary switch is turned on. When the *'Coracoid Cortical Ring Light up Sign'* is turned *on*, the sign is considered positive **(Figs. 10 and 11)**.

The end-on appearance of the coracoid process varies with the severity of the fracture displacement. The oval cross-section of the apex tends to overlap, to a varying degree on the basal cortical ring of the inferior pillar. Where the apex of the superior pillar does not align with the base of the inferior pillar of the coracoid process, there may be two rings: a circular cortical ring at the root of the inferior pillar and an oval cortical ring formed by the apex of the superior pillar. The size and the density of the two rings will vary with maturity of the ossification centres. Immobilization of the shoulder complex is paramount to ensure the quality of the radiographic image and to define the exact posture of the displaced coracoid process.

Figure 11. Coracoid Cortical Ring Light up-G Sign: the sign is on. Compare to Figure 7. Note the rotation of the lateral fragment with an altered appearance of the medulla. Note the inset for comparison. (The image was taken from the public domain and modified to clarify the key features).

There are normal anatomical variations in which the coracoid process arises from the costal surface of the scapula at the root of the acromion, above the glenoid fossa. The CCRL-G sign is best visible only on an anterior-posterior projection when the X-ray beam is perpendicular to the coronal plane for imaging the shoulder, including the whole length of the clavicle. The sign is sensitive to the quality of the patient's resting position. The presence of two cortical rings indicates variable protraction and an inferomedial drop in the shoulder. The apical ring lying on the lateral half of the basal cortical ring suggests less shoulder protraction and ptosis. When the apex of the coracoid process turns more medially, the oval apical ring will appear on the medial half of the basal cortical ring of the inferior pillar. If the apical cortical oval ring lies on the inferior half of the basal cortical ring, the lateral fragment is rotated anteriorly and inferiorly (*ventrally*) with greater anterior tipping of the scapula.

Be careful when applying longitudinal traction to reduce the clavicle fractures in all three planes. The fracture reduction traction load should be applied gradually, considering the viscoelastic nature of the muscles and the neurovascular structures at the root of the neck to prevent iatrogenic neuropraxia. The reduced clavicle should lie dorsal to the mid-coronal truncal plane, retracted 20-25 degrees and elevated 10-20 degrees to the transverse plane, matching the contralateral side. With three-dimensional reduction of the clavicle, the coracoid process will follow the clavicle anatomy and the dorsolateral repositioning of the scapula, restoring its apex over the edge of the glenoid fossa, switching *off* the *Coracoid Cortical Ring Light up Sign*.

The author has noted the CCRL-G sign in several published studies of patients with clavicle fractures treated conservatively. Those studies which refute surgical intervention, particularly among adolescents with minimal shortening and axial rotational deformity of the clavicle, the representative published images show that the 'Coracoid Cortical Ring Light up Sign' is switched off at the last follow-up imaging. The medulla of the clavicle nearly matches the contralateral side (**Fig. 12**). Despite vertical displacement and measurable shortening with correction of the torsion and version angles, over time, the glenohumeral joint movements should approach their full range. In contrast, there is a greater likelihood of limited recovery in the range of glenohumeral joint motion, particularly in overhead coronal and scapular plane abduction, despite surgical treatment, when residual linear and angular deformities persist.

Figure 12. Bilateral comparison following a healed mid-diaphyseal fracture of the clavicle, in an adolescent, showing that the 'Coracoid Cortical Ring Light-up-G Sign' is turned off. (Image was taken from the public domain and modified to clarify the key features).

The orientation of the coracoid process is often difficult to assess due to poor-quality images. Generally, during the final visit, the focus is on a rapid review of the image of the implanted clavicle rather than a thorough examination of the regional anatomy and kinematics of the clavicle and associated joints.

The coracoid process is a key technical landmark for restoring the original length and achieving axial correction of the clavicle at the time of its surgical fixation. The sign can help assess the evolution of gradual self-correction of the clavicle deformity in cases of conservative management of third- and fourth-fifth sections clavicle fractures. The corrected position of the coracoid process will return to its normal excursion from the infraclavicular fossa deep to the clavipectoral fascia towards the rotator interval in the subacromial space of the acromiohumeral synsarcosis. This will prevent the coracohumeral impingement in the long-term, following a displaced clavicle fracture.

In summary, do the anterior-posterior view of the regional bony anatomy of the shoulder complex for comparative assessment of the clavicle fracture follow-up and the status of the coracoid process, applying the binary *Coracoid Cortical Ring Light up On-Off Sign*. An observation that requires specificity and sensitivity studies. The fluted shape of the medulla, like a stretched-out hourglass at the junction of the medial and lateral curvatures of the clavicle, is another useful sign to assess the relative rotation of the fragments. A semi-axial cephalic or caudal 30 to 45 degrees tilt on an anterior-posterior views in the clavicle plane for visualization of transverse plane deformity of medial and lateral curvatures and fracture pattern can be helpful when compared with the intact contralateral side. The erect posterior-anterior with 15 degrees cephalic tilt view of the upper thorax for relative shortening of the fractured clavicle and morphometric comparison has proponents. Still, its accuracy requires further work to remove the optical errors due to the divergence of the X-ray beam. The trans-axial medial-to-lateral shoot-through can be a significant technique for visualizing the serpentine flow of the clavicle, the posterior-superior angulation, vertical displacement, offset between the medial and lateral curvatures, axial rotation of the fragments, the height of the infraclavicular space and scatter of bony fragments. It is a challenging radiographic endeavour and needs further refinement.

16.0 Malunion – Pathological anatomy and prevention of malunited clavicle fractures:

Malunion means badly united. The pathological anatomy of a badly united fracture is always three planar, whether the bone is parallel to the median plane or horizontal. The misaligned fractured fragments often appear markedly different from their original form due to overlap, malrotation, and other angular deformities. Fragmentation of the fractured ends adds complexity to the fracture pattern and deformity, owing to associated soft tissue injury and contractures during healing. In addition to good quality plain radiographic images, a 3-dimensional computed tomography helps to visualize the distribution of fracture fragments within the soft tissues. An MRI and even an angiogram may become necessary if there are neurovascular symptoms of the upper extremity. These imaging modalities will assist in developing a safe surgical approach without damaging the already injured soft tissues, particularly the periosteal blood supply to the clavicle. A meticulous surgical approach, without aggressively teasing the network of the small nerve fibres, veins and lymphatics in the fascio-cutaneous envelope will prevent tissue ischemia and delayed healing of this subcutaneous bone.

16.1 Ultimately, all fractures heal:

It is acceptable to allow the acute tissue oedema to settle down, and the fracture ends to take advantage of fracture healing elements in the fracture haematoma. At surgery, do not wash out the resolving fracture haematoma. Its congealed material can be carefully peeled away along with the soft tissue envelope and periosteum, preserving the periosteal blood supply to the fractured ends. It is a matter of finding the correct plane, and it easily peels off due to the residual oedema in cases of delayed intervention. A meticulous approach is part of “damage control” to help with healing. A patient-specific (*topographic anatomy, site of fracture, fracture pattern, regional pathological anatomy of the soft tissues, and associated injuries*) and surgeon-specific (*experience, implant selection, quality of fracture reduction, fixation and secondary immobilization techniques*) regime should guide rehabilitation from the earliest possible stage, rather than an evidence-based time range applied to a cohort of a variety of patients. In this regard, surgical management includes a rehabilitation programme based on patient-appropriate medicine (*patient’s age and physical characteristics, co-morbidities and risk factors delaying fracture healing, patient expectations, occupation and leisure activities*)(Gandhi, 2022). Ultimately, all fractures heal sooner or later in the city and jungle, whether treated conservatively or surgically(Apley & Solomon Louis, 1982). Over the last 75 years, the primary surgical goal has been to prevent malunion in all bones and types of fractures.

The pathological anatomy of a clavicle malunion can be classified as badly united when the bone fragments are set in longitudinal, angular or axial rotational deformity in any of the three cardinal planes, whether treated conservatively or surgically. A plain radiographic view will show one or more deformities at the site of a united fracture. Torsional or axial rotational deformity can be inferred from a patient’s clinical history and examination. Further plain X-ray views are necessary for planning corrective surgery. Reserve the 3-dimensional reconstruction of computed tomography and magnetic resonance imaging for complicated regional pathology, such as neurovascular injury induced by the fracture and malunion during healing. Usually, the healing of clavicle fractures is relatively faster than other long bones due to their trabecular medullary morphology and periosteal vascularity. The interfragmentary strain is widely distributed across the trabecular network, as finite-sized individual microfractures healing simultaneously to accelerate the process, unlike the slow healing at the Haversian level hierarchy of the cortical bone.

16.2 Rationale for operative arbitration in implant selection:

The clavicle has a cortical envelope of variable thickness along its entire length, enclosing trabecular plates and beams. A rudimentary medullary canal in the mid-diaphyseal zone has a circular cross-section and thicker cortex. Surgical intervention is the only means of preventing malunion of a significantly displaced clavicle fracture. Loadbearing rigid fixation implants impair Perren’s 2% interfragmentary strain, which is required for the maturation of the provisional fracture callus. The slow-healing process occurs at the Haversian level through the “cone-cutting” mechanism, which can take more than 3 years. This process of fracture union requires prolonged implant presence, which can lead to stress shielding. If removed within 12 to 18 months of surgery, there is a well-recognized risk of refracture upon implant extraction before the bone remodelling process is established. Avoid such a mishap by practising the use of a load-sharing intramedullary implant to realign and immobilize the fracture. Technically, this may seem an impractical proposal for a curved bone, however, selecting an optimally rigid intramedullary implant allows the required interfragmentary strain as the fracture healing proceeds. The technique of closed intramedullary implant insertion also helps protect the fracture ends against damage to their already tenuous periosteal vascularity. Only minimal reaming is needed to create a 2-3 mm accessway through the trabecular medulla of the clavicle to accommodate a 3 to 5.5 mm diameter intramedullary implant for an interference fit, when planned within a few days of the fracture.

16.3 Outcome-based necessity of surgical indication:

Currently, surgical indications are relative in most patients. The aim is to avoid an expected malunion, defined by longitudinal and vertical displacement criteria, which would lead to final shortening and result in moderate to poor outcomes in terms of pain, delayed union, strength, power, limited recovery of range of motion, early fatiguability, and restricted function at the glenohumeral joint. Malunion of a fractured bone occurring in any of the three planes affects its kinematics at the relevant articulations and at other secondary articulations. This is especially true in clavicle fractures, because the clavicle has extremely variable three-dimensional anatomy and biomechanical architecture. Secondly, it shares three-dimensional kinematics with the scapulothoracic and acromiohumeral synsarcoses to position the glenoid under the moving humeral head, compounding the problem. Malunions of the clavicle will always affect all the associated linkages and the joints. It is analogous to the carriages of a moving train on the railway tracks. A single misaligned carriage will distort the movement of the rest of the carriages in the train. The ride will be uncomfortable and painful, affecting the velocity and acceleration, resulting in a loss of time to reach the destination, financial loss and a higher incidence of future mishaps.

17.0 Long-established anatomy of malunited fractures:

In a fascinating study of 73 pairs of malunited clavicles (56 males and 17 females) out of a total of 1430 clavicles, mainly longitudinal and vertical displacements were noted(Edelson, 2003).

Fifty of these had fractures in the middle third (Allman type 1). All clavicles were from adult skeletons aged 27 to 80 years, from an early *twentieth-century* museum collection. The specimens showed *shortening* of 10 mm or more, compared with the opposite side, with altered *angulation in the transverse or coronal planes*, exceeding 20 degrees in 22 specimens. There was *displacement of one shaft diameter or more* in 15 specimens, and *hyperabundant callus* with a circumference of more than 125% in 28 specimens. There was considerable *angulation of the lateral fragment, apex posterior*.

In the middle third fractures, the *lateral fragment was invariably displaced posteriorly relative to the medial fragment*. In the medial third fractures, [5] *the lateral fragment was displaced anteriorly relative to the medial fragment.* The shortening in 24 of the 36 specimens was attended with angulation. The angular deformity was more pronounced when the fracture was more lateral, with *maximum angulation occurring at the coracoclavicular ligament*. The study did not report a fragmented fracture pattern. It is likely that in case of a fragmented fracture, even if it had healed with marked shortening, was enclosed by the callus, with little remodelling, without any visible signs of fragmentation. Thus, there can be two kinds of noticeable displacements in two or more planes, longitudinal and vertical, leading to shortening and angulation. Within these two types of fracture displacements, there can be varying degrees of fragmentation at the fracture site, depending on the force causing the fracture and how the force dissipates. The response of the resisting muscles and final resting displacement of the fragments is visible on initial plain radiographic imaging. Interestingly, no observation was made on the rotational deformity between the two major fragments.

17.1 Longitudinal fracture displacement - a space occupying issue:

In a healing and a healed clavicle fracture, on an anterior-posterior view of the shoulder complex, the overlap of the medial and lateral fragments results in longitudinal and craniocaudal or dorsoventral displacements, producing a bayonet-type of deformity. The residual appearance of the malunited clavicle is a result of continuous telescoping motion of the fragments during the early healing phase of inadequately reduced and immobilized unstable fractures. It is not surprising that, in addition to a sudden increase in its diameter, there is always a proud, rapidly forming subperiosteal cuff of callus. The deformity's size and shape also depend on the degree and direction of angulation. The topographic anatomy of the clavicle is extremely intricate with major neurovascular bundle passing posterior and inferior to it. The optimized anatomical space leaves no room for sudden appearance of these displaced fracture fragments, and remain in-situ, despite the expandable skin and subcutaneous tissues. In the following weeks, the callus further obliterates this space. Given the time required for the callus to grow, the surrounding tissues gradually accommodate it until it begins to regress. However, the deformity due to the overlap and angulation is never completely resolved(Edelson, 2003). In its early stages, the fracture pattern can be the cause of concern if it is associated with extensive soft tissue damage to the fascial layers and contusion of muscles, leading to fibrotic contractures that act like tension

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[5] The longer lateral fragment was pulled anteriorly and inferiorly by the Cleidobrachialis pectoralis and the Subclvius, while the smaller medial fragment either remained in its position relative to the lateral fragment or was pulled posteriorly by the Cleidomastoid. Given the vector of action of these muscles, there is a likelihood of both fragments rotated ventrally.

bands, restraining the movements of the clavicle and tugging on neurovascular structures. In parallel, this causes peripheral signs and symptoms, that resolve only partially over time, unless the deformity is corrected surgically.

17.2 Functional longitudinal shortening:

When the shortening of the clavicle is less than 15 mm, the functions of the clavicle, scapulothoracic synsarcosis and the glenohumeral joint are preserved(Eskola et al., 1986; Hill et al., 1997b; Ledger et al., 2005). However, current plain radiography and computed tomography techniques often show up to 5 mm of morphometric inaccuracy. In addition, there is up to 8 mm of bidirectional asymmetry in the clavicle. A 10% shortening of the clavicle leads to mispositioning of the scapula and altered scapular kinematics(Kim et al., 2017; Matsumura et al., 2010). Therefore, a 10% loss in the length of the clavicle due to an uncorrected fracture is a relative indication for surgical intervention. Shortening is only acceptable in the immature, where it is expected to grow and remodel with return of the normal biomechanical functions. In a sedentary, mature adult population, there will be an adaptation to task limitation characterized by a reduction in arm range of motion in all planes.

17.3 Altered curves and twists:

The medial, lateral and inferior curvatures cannot be ignored within the longitudinal shortening concept. The clavicle fractures of the third-fifth and fourth-fifth sections involve the medial curvature. In conservatively and surgically treated clavicle fractures, shallower residual curves would increase, while deeper curves would decrease the final length. Contrary to the residual shorter, deeper curve due to the malunion, the longer, shallower medial curve, which adds length, affects the biomechanical function of the clavicle. Technically, a longer curve with a longer radius of curvature has a greater mechanical advantage because of the longer lever arm.

The angles of torsion and version, screw twist, and screw pitch of the clavicle alter with the collapse of the fragments. Both the torsion angle and pitch of a spring changes with distraction and compression, changing its mechanical properties. Neither biomechanical studies nor mathematical models are available to substantiate these alterations in malunion of the clavicle. During growth and development, the degree of screw twist and pitch distribution vary due to continuous changes in the biomechanical forces. It is unknown how varying clavicle's length and the distributed screw twist and pitch along its length affects its anatomical features and biomechanical functions. The curves and twists embedded in the biomechanical architecture of the clavicle require simultaneous attention when correcting the length to restore its 3-dimensional anatomy.

17.4 Angular displacement:

If longitudinal deformity is of functional concern, the angular deformity is fraught during the acute stage of the injury. The angular deformity with convexity directed superiorly in the supraclavicular fossa pierces the superficial fascia, causing skin tenting. There is always a risk that skin penetration will convert a simple closed fracture into an open fracture through contused, tenuous tissues, thereby increasing the incidence of deep wound infection if left too long. It is an acute surgical liability for a caring surgeon. When such urgency is least likely, and the angulation is non-threatening, it is often treated conservatively, with the expectation that it will improve with indirect traction on the angulated fragments. An extrinsically visible angular deformity is readily discernible on standard trauma radiographic views. In contrast, superior and posteriorly directed apex is clinically least visible, and altered curvatures, angles of torsion and version, the screw twist and altered screw pitch are imperceptible on X-rays, and least appreciated.

How the flattening or exaggeration of the curves may affect the mechanical advantage of the clavicle function needs clarification. Flattening of the inferior curve compromises the volume of the infraclavicular space(Gieger et al., 2016). This effect can become exacerbated if the angulation is directed inferiorly and posteriorly due to the collapse of the main fragments, further complicating the fracture pattern. It can compress the neurovascular structures as they pass in and out of the thoracic aperture. The contents of the infraclavicular space are pinched cyclically between movements of the clavicle and the first rib, particularly with a proud callus during abduction and in sustained overhead posture of the ipsilateral arm. Mispositioning of the scapula affects the force couple formed between the Trapezius and the Serratus anterior and Pectoralis minor, limiting the kinematics of the scapulothoracic synsarcosis(Andermahr et al., 2006). Uncorrected protraction, with the shoulder ptosis and ventral rotation of the lateral fragment, results in altered torsion and version, misplacing the glenoid fossa under the humeral head and affecting the glenohumeral kinematics.

18.0 Concern over expansile callus and neurovascular injury:

In the case of a clavicle fracture, progressive weakness of the Biceps brachii, Triceps brachii and forearm muscles, with paresthesia, following conservative treatment and internal fixation, a computed tomography-based angiography combines the advantage of diagnosing compression of the neurovascular structures in the infraclavicular space, pathological anatomy of the fracture callus, and iatrogenic injuries during osteosynthesis(Gieger et al., 2016). Take advantage of the computed tomography imaging to assess the diameter of the callus, the size and direction of the angular deformity, and the diaphyseal curvatures. At the same time, check the offset between the medial and lateral curvatures, the angles of torsion and version, alterations in segmental screw twist and screw pitch, and the mechanical axis relative to the anatomic axis of the clavicle to undertake corrective surgery.

Mispositioning and disturbed kinematics of the scapula following linear and angular malunion of the clavicle distorts the cervicoaxillary sheath extending from the prevertebral layer of the deep cervical fascia(Lambert, 2016). During arm elevation, stretching and narrowing of the axillary fascial tube reduce venous return, obstruction of lymphatics and disturb neural perfusion, resulting in pain, paresthesia and dysthesia. The distortion of the axilla and anterior axillary fold is associated with contracture of the clavipectoral fascia, tugging at the dome of the axillary fascia, which is noticeable with overhead abduction.

19.0 Concern over pain, strength and range of motion:

Malunion of the clavicle diaphysis may be associated with fixed superior angulation at the sterno-costoclavicular joint, with relative elevation of the medial fragment due to the buttressing effect of the lateral fragment, fascial contractures and the failure of the Subclavius muscle. Simultaneously, the malposition of the scapula on the thorax shows the altered angular relationship of the scapular spine to the midline spinous processes of the vertebral column, due to rotation of the scapular body (Basamania & Rockwood, 2009). A large angular displacement and reorientation of the scapula on the injured side, hanging from the skull and the vertebral column, automatically affects the contralateral shoulder complex, reducing the biomechanical performance of the entire pectoral girdle around the truncal anatomy. The altered, bilaterally shared biomechanical effort due to the malposition of the scapula leads to early fatigue, loss of strength, power and velocity of the entire girdle.

The cervical musculature, including the Trapezius and Sternocleidomastoid has proprioceptive and the sensory receptors(Lambert, 2016). The ptosis and protraction of the shoulder on the side of a displaced clavicle fracture cause imbalance between the shoulder heights. At the level of the central nervous system, there is a constant muscular struggle to readjust the vertical posture of the body triggered by the imbalance, to maintain a horizontal gaze, the main reason there are compensatory changes in scoliosis. The physical effort to throw an object or carry a heavy load beside the body engages the trunk and pectoral girdle musculature on both sides of the body. Therefore, the malunion of the clavicle fracture not only leads to definitive adverse influence on the ipsilateral shoulder complex, but also on the entire circumferential pectoral girdle anatomy and the truncal balance. The dysfunctional biomechanics of the pectoral girdle is further driven by abnormal transmission of the kinetic chain energy arising from ground reaction forces, ending at the throwing hand.

In a study of 196 children aged 3 to 18, 21 patients with an initial displacement of more than 20 mm were treated conservatively with a figure-of-eight brace or a sling(Bae et al., 2013). Following fracture union, adjusted for hand dominance, forward flexion (-7.30 degrees), abduction (-6.50 degrees) and external rotation (-2.50 degrees) of the humerus were negatively affected by the fracture. The +4.25 difference in internal rotation of the humerus was likely due to the persistent scapular protraction on the injured side. This study demonstrates a definite influence of malunion on the biomechanical function of the glenohumeral kinematics. In a three-dimensional biomechanical analysis, following surgical fixation of mid-diaphyseal clavicle fractures, the shoulder complex showed increased protraction and decreased retraction of the scapula at the lower and higher angles of abduction, respectively, with significantly reduced clavicle retraction(Hung et al., 2021). Similar changes were observed on the uninjured side, suggesting a symmetrical bilateral compensatory mechanism of the pectoral girdle that restricts glenohumeral kinematics, a restriction that may become more evident with conservative treatment.

As glenohumeral articulation is the proxy joint for the kinematics of the clavicle, a pain free peak range of shoulder motion and strength are of significant concern for successful delivery of a projectile, underhand throw, and sustained overhead manual labour, following clavicle fractures. More than 20% of patients experience considerable pain, reduced strength and dissatisfaction over a mean period of 2 years(Bae et al., 2013). Statistically calculated averages often overlook and fail to highlight patients with a lower-than-average range of motion. In another study of 30 patients aged 19-67 years treated conservatively, flexion strength endurance was 81% and 75%, and abduction strength endurance was 82% and 67%, respectively, on the healthy and injured sides(McKee et al., 2006). This is a wake-up call to prevent upper-extremity disability, particularly in a growing and young adult population. The deformity of a shortened clavicle (15.9 – 33.4 mm) with a greater resting coronal plane angulation (7.12 – 14.28 degrees more than the uninjured side at the sternoclavicular joint) will translate and rotate the inferior angle of the scapula through a greater arc and increased protraction (anterior scapular version 2.48 – 9.72 degrees more than the good side)(Ledger et al., 2005). Normally, the glenoid surface has up to 10 degrees of retroversion relative to the plane of the scapula(Saha, 1971). The glenoid fossa with a persistent drop in the shoulder tip causes increased muscular effort, limiting the range of motion at the glenohumeral joint(Ledger et al., 2005). The deformity of the clavicle significantly reduces peak shoulder abduction velocity on the ipsilateral side, a patient-specific problem. The strength of the glenohumeral joint is related to malunion of the clavicle rather than being comparable to an issue of arm dominance(Murray et al., 1985).

An absolute shortening of more than 14 mm (9.4%) in females and 18 mm (10%) in males is associated with pain, evidence of thoracic aperture compression symptoms on hyperabduction, and kinematic disorders at the shoulder complex linkages and joints when treated conservatively(Lazarides & Zafiropoulos, 2006). Even though some of these studies are not the most recent and surgical intervention has become more common, controversy and significant resistance to surgery persist. Worldwide, many patients continue to suffer with pain, reduced shoulder function, with a loss of nearly a quarter of its strength and performance, irrespective of limb dominance. Therefore, it is time for patient-specific and patient-appropriate medicine to be put into practice(Gandhi, 2022).

20.0 Linear and angular measurement discrepancies and deformity problems:

Unlike younger populations with minimal displacement, adults treated conservatively are expected to develop some shortening and angular malunion in almost every case. If left unattended, significant symptoms are attributable to the angular malunion rather than clavicle's length decrement alone(Nowak et al., 2005). However, shortening does influence the shoulder kinematics in the lower ranges of glenohumeral joint motion(Stegeman et al., 2015). To date, there is no single definitive method for measuring the exact length of the clavicle other than computed tomography. The clavicle length measured on the posterior-anterior beam with a 15-degree cephalic tilt to the coronal plane on a panoramic view of the upper half of the thorax approximates the computed tomography(Smekal et al., 2008). Proportional shortening can be measured as the horizontal distance between overlapping major fragments, using the formula(Smekal et al., 2008) _

Proportional shortening = (measured shortening) / (measured shortening + total length of major fragments) × 100.

To measure the percentage difference in proportional length between the two sides_

Percentage difference in proportional length = (difference in lengths of the two sides/length of the intact clavicle) × 100.

Clinically, on a radiograph with X-ray beam perpendicular to the clavicular plane, the clavicle length is the distance between the most medial articular edge of the sternal end and the most lateral point on the acromial end. On computed tomography, 72% have bidirectional symmetry, whereas 28% have bidirectional asymmetry between 5 and 10 mm, and 7% have a length difference of more than 10 mm, in a cohort of 102 patients(Cunningham et al., 2013). A computed tomography study of clavicles in individuals over 30 years old showed that males differ significantly in all dimensions; female asymmetry is more variable, and there are differences at the medial and lateral ends of the clavicle(Abdel Fatah et al., 2012). There is minimal curvature asymmetry in males, and in females, there is right and left curvature asymmetry. The female clavicle has a notable twist near the mid-shaft, which is not evident in the male clavicle. In a recent retrospective study of 15 males and 15 females who had computed tomographic angiograms for non-trauma purposes, differences in clavicle measurements were observed between biological sexes(Krishna S et al., 2023). The length and craniocaudal thickness on average, respectively, were 154 mm (+/- 0.7) and 13.1 mm (+/- 1.3) in males, and 140 mm (+/- 0.9) and 10.8 mm (+/- 1.9) in females. Surprisingly, there was no significant difference between their right and left clavicles, right 148 mm (+/- 0.9) and 12.2 mm (+/- 1.6), and left 146 mm (+/- 1.1) and 11.5 mm (+/- 2.2). This outlying study showing bidirectional symmetry is limited by the size of its examined cohort, compared to much larger dry bone forensic and imaging studies. Cohort size and statistical averages can be very deceiving!

When clavicle fractures in patients aged 1 and 80 years are treated in a much-preferred arm sling, half of those with an initial shortening of 5 mm or more develop progressive shortening malunion until it stabilizes itself in a woven callus(Nordqvist et al., 1997). According to the Edinburgh classification, nearly 73% of the cases have midshaft clavicle fractures; of these, 65% with displacement develop malunion(Robinson et al., 2004). Ultimately, only half of the patients achieve pain-free function with functional shortening. This is likely only when the major fragments are well aligned in all three planes, with a little loss of length. It is not surprising that the little-to moderately active younger population will not experience a significant loss of function due to the shorter clavicle.

Apart from the muscle length-tension relationship and operational length of the lever arm causing a reduction in effective turning force during concentric contraction, every millimetre loss of the clavicle length and diaphyseal misalignment results in increased mispositioning of the scapula, disturbing kinematics of the scapulothoracic synsarcosis and its end articulation. Protraction, repositioning of the glenohumeral joint, a greater translation and rotational arc of the inferior angle of the scapula and posterior tilt result in complex 3-dimensional kinematic irregularities of the scapulothoracic synsarcosis, with variable glenohumeral articulation dysfunction depending on quantitative linear and angular malunion.

The end-to-end length of the clavicle has a measurable correlation to the chord length of medial and lateral curvatures. A computed tomography study revealed that shorter people have shorter, more curved clavicles, whereas taller people have longer clavicles with shallower curves(Fontana et al., 2020). Therefore, the absolute loss of the clavicle length cannot be applied directly for surgical intervention. Instead, the proportional length and percentage shortening difference formulae for measuring bilateral length differences are more tenable. These formulae for measuring bilateral length differences cannot be applied where there is an angular deformity with telescoping of the fragments in any of the radiographic views, unless each of the fragments is complete and the segments are radiographed in the plane of the segment for measurement by summing up to provide the 'true' original length.

Instead of maintaining strict criteria of 20 mm longitudinal shortening and 100% vertical displacement as the sole determinants for surgical decision-making in all patients, consider proportional shortening, patient-specific fracture pattern and patient-appropriate medical factors for management. To minimize radiation exposure, avoid computed tomography, whenever possible. For linear measurement in a case with angular deformity of the clavicle, get a posterior-anterior radiographic view with a 15-degree cephalic tilt to the plane of each fracture fragment separately to apply the proportional percentage formula confidently for the shortening of the clavicle. Calculate the total length of the fractured clavicle accurately by adding up the lengths of two or more fracture segments rather than measuring the overlap to judge shortening.

In an older study, the calculated average sum of the medial and lateral curvatures on the right was 292.94 degrees and on the left 296.42 degrees having a difference of 3.48 degrees(Terry, 1932). In a more recent study, on average, the sum of the curvatures on the right was 292.55 and 297.18 degrees, with a difference of 4.63 degrees(Kaur H & Sahni H, 2002). Supposing each degree on the angular scale corresponds to 1 millimeter, then bilateral directional asymmetry is due to the size of the curvatures. Neither of these studies measured the inferior curvature. The latter and the other two curvatures are associated with dorsolateral and inferior scapular placement in modern Man(Voisin, 2006). There is a positive correlation between the length of the clavicle, the radius of medial curvature measured from centreline of the clavicle(Bachoura et al., 2013). The functional anatomic centreline length passing through the mid-point cortical diameter following the curvatures is longer than the end-to-end length.

In a cadaveric study examining clavicle shortening 0 to 20%, it was found that, across a range of clavicle lengths of 144.0 to 176.4 mm, during arm elevation there was a significant decrease in protraction of the scapula(Matsumura et al., 2010). On average, in 10%, it is 8 degrees, 15%, 11 degrees, and 20%, 14 degrees. On average, there is a decrease by 4 degrees in posterior tilt of the scapula with 20% shortening of the clavicle. There was no significant change in translation and rotation of the inferior angle of the scapula during arm elevation. With clavicle shortening, the loss of its strut effect jeopardizes the normal arc motion at the sternoclavicular joint, not only disturbing the posture of the scapula but also the kinematics at the acromioclavicular joint, scapulothoracic and acromiohumeral synsarcoses due to increased anterior tilting and decreased posterior tilting of the scapula. This results a decrease in subacromial space volume, leading to loss of concentric motion between the acromion and humeral head, causing subacromial impingement symptoms.

With clavicle shortening of more than 10%, the resting position of the scapula shows a reduction of 7 degrees of lateral rotation of the inferior angle and 8 degrees of abduction (control 137-160 degrees, shorter clavicle 126-157 degrees). At rest, the scapula has a greater anterior tilt than the normal range of 4-9 degrees. The posterior tilt in the normal is 24 degrees (range 18-29 degrees), and in the shortened clavicles, it is 16 degrees (range 9-28 degrees). The scapular protraction is 8 degrees (6-11 degrees) more than usual. These reported changes were observed when abduction exceeded 100 degrees(Kim et al., 2017). Any change in the resting position and end-position would mean that the clavicle and the scapula never gather and store sufficient strain energy to reach their normal peak strain energy during an overhead throwing task and reacquire initial position fully, returning in time for the next throw.

Longer delays in surgery results in deterioration in the scapulothoracic relationship. The functional outcome of corrective surgery for a malunion is inferior, even when the clavicle's length is restored(Rosenberg et al., 2007). This is due to the formation of contractures leading to altered tensegrity of the deep cervical fascial layers, and inability to restore the soft tissue anatomy. Delaying surgery denies many patients good to excellent functional outcomes. This is benign disregard for the expected patient-based outcome.

In summary, an angular malunion with more than 10% shortening of the clavicle, is associated with pain, reduced global shoulder strength and endurance, and early fatigue during an overhead task due to altered kinematics at all the involved linkages and joints of the ipsilateral shoulder complex and the entire pectoral girdle. Often, there is a deep regional ache due to altered tensegrity of the deep cervical fascia, and occasionally, neurovascular signs and symptoms.

The clavicle is the 'steering mechanism' of the scapula. It controls vectors (*direction and magnitude*) of the scapula, enabling it to predictably and uniformly slide on the thoracic wall, and positioning the glenoid fossa under the humeral head with precision and in a timely manner. At its lateral end, it articulates with the pivoting acromion to allow concentric motion of the humeral head at the acromiohumeral synsarcosis. The clavicle is not just a linking bone, but a machine made up of three or more curved levers forming a compound cranking system and individual specific curves, varying torsion across its entire length, version angle, and screw pitch. Therefore, re-establishing the anatomy and biomechanical architecture of the clavicle that matches the contralateral clavicle would complete the functional structure and mechanism of the pectoral girdle.

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