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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 5 Frustum, a Geometrical Deformity of a Malunited Clavicle Fracture

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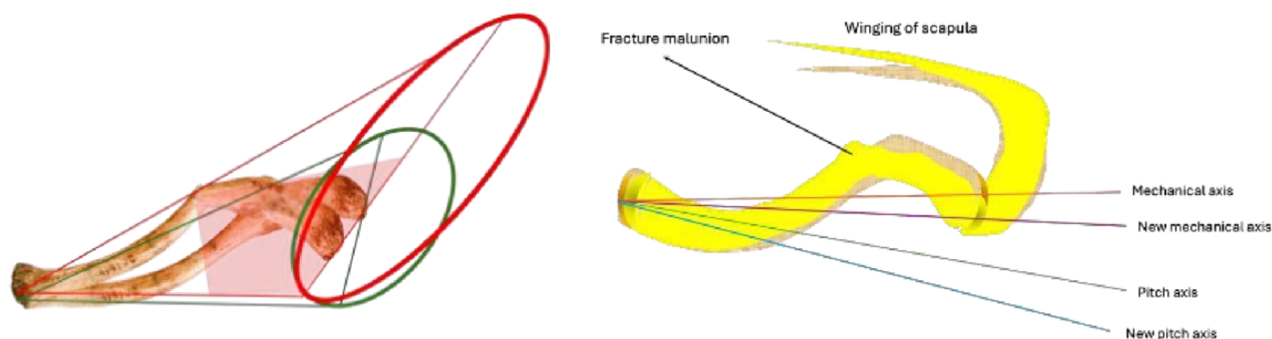
Highlights: Fractures of the clavicle within the shoulder complex are a two-bone problem, as the forces from the clavicle are mediated through the scapula to the glenohumeral joint. An angular malunion in the third-fifth and fourth-fifth sections of the clavicle from the sternal end often results in a frustum following conservative management of its fractures. This is reflected in subtle or gross winging of the scapula and dyskinesis, which affect the glenohumeral articulation.

How biomechanical forces stimulate linear bone growth, which is mostly under compression, and correct torsional deformity at the cellular level in a mature callus remains poorly understood. Whatever the 'normal' range of motion return in the adolescents with malunited clavicles, it is limited by remodelling potential and physical adaptations during recovery of muscle-length tension.

This part of the study delves into the fundamentals of kinematic biomechanics pertaining to a malunited clavicle.

Graphic abstract:



Keywords: Clavicle fracture, Clavicle malunion, Frustum formation, Clavicle kinematics, Scapular kinematics, Scapular winging, Two-bone problem, Biomechanics

1.0 Frustum formation and disturbance of scapular kinematics:

The normal anatomy of curves and twists is essential for the biomechanical performance of the clavicle and normal dorsolateral and inferior resting position of the scapula. Normal kinematics of the clavicle allow the scapula to protract and rotate on the thoracic wall, and to tilt vertically posteriorly, thereby correctly positioning the glenoid fossa during arm elevation and overhead activities. The velocity and acceleration at the glenohumeral articulation are imparted by a combined mechanical advantage generated by clavicle's multiple curved lever system that actively transmit its screw motion and cranking force. In the event of malunion, there is an extrinsic angular (*surface feature seen directly and on a radiology image*) and intrinsic angular *(cellular arrangement and helical flow of collagen embedded in mineral deposits in the substance of a healthy bone, and at the callus during remodelling of a bone)* deformity. The intercalated clavicle, being the first transmission link to the glenohumeral joint, its malunion and misalignment jeopardizes the generation of sufficient force and power for aiming and delivering a projectile at a target.

The clavicle is a cantilever suspension bar from which the scapula and, in turn, the upper extremity suspend. It is analogous to a fishing rod. The cord of the fishing rod is the arm, and the hook is the hand. Mechanically, a shorter fishing rod is less efficient and more tiring for the fisherperson. If the rod has a frustum *(a geometrical term, where there is a physical and/or functional dissociation of the stable (fixed) proximal end from the mobile (free) distal end with an angular deformity in between them)*, then controlling the movements and throwing the bait at the desired target will be challenging!

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An angular malunion at the clavicle's third-fifth or fourth-fifth section from the sternal end frequently creates the [1]frustum (**Figs. 1 and 2**). Biomechanically, the angular malunion at the zone of frustum isolates the clavicle's medial segment from the lateral, misaligning the cantilever function and reducing its overall cranking effect. Ultimately, the frustum becomes a three-dimensional two-bone problem, as the next link in the chain is the scapula, which acts

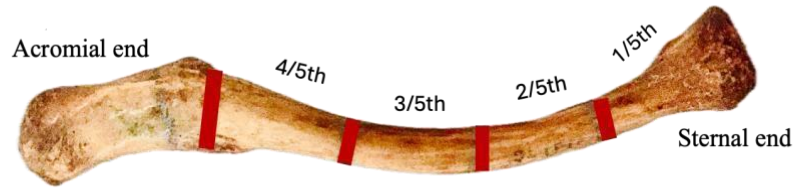

Figure 1. One-fifth segmentation of the clavicle

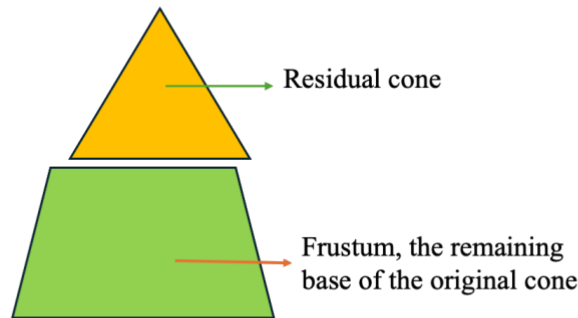

Figure 2. Frustum formation (created in PowerPoint).

as an intermediate unit between the clavicle and the humerus. Imagine a cone with its base at the acromial end and its apex at the centroid of the clavicle's sternal end articular surface. Biomechanically *(functionally),* the plane passing through the frustum divides the clavicle into medial and lateral segments. Although these two units are physically united but functionally disconnected at the plane of the frustum. The planes passing through the malunion and at the acromioclavicular articulation cannot have the same alignment relative to the normal intact clavicle, because of the new anatomical development and the changed biomechanical architecture of the malunited clavicle (**Fig. 3**).

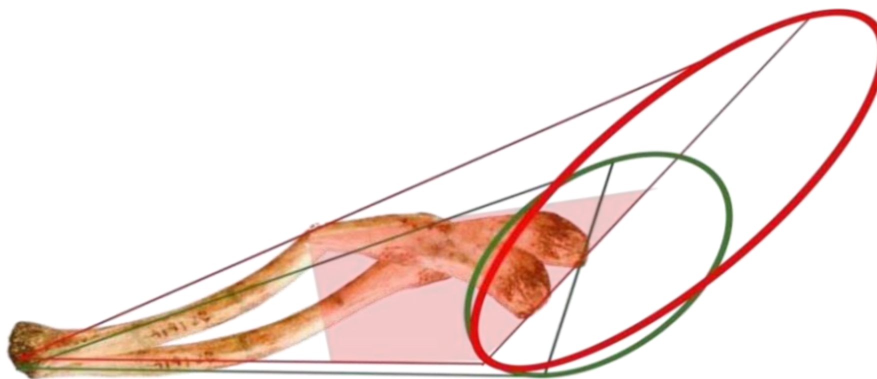

Figure 3. Frustum formation - The changed anatomy and geometry of the biomechanical architecture of the malunited clavicle, with shortening. The green cone-section triangle enveloping the intact clavicle, which normally circumscribes a symmetrical oblique elliptical base, shown in a disarticulated clavicle (created in PowerPoint).

[1] Frustum in Latin means a piece. In geometry, it is part or a remaining segment of a cone-shaped solid left after the top has been cut off by a plane parallel to the base, or between any two cutting planes, especially between two parallel planes.

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The skeletal deformation creates two segments of completely different geometries, dividing the original normal biomechanical architecture into distinct structures: a new cone and a quadrangular or any other prismatic space, depending on the fracture malunion. Each will have a very elusive kinematic outcome! The resulting asynchronous motion between the newly formed bone segments will impede the movement of the next bone in the link. Therefore, the malunited fracture of the clavicle is a two-bone problem, which is not very different from that of the radius and ulna in the forearm and tibia and fibula at the ankle.

When there are shortening and angular deformities of the clavicle, of whatever size, take care of it no differently from the two-bone relationships of the forearm and the lower leg bones. The clavicle is not an isolated unit of the skeleton. The task may be demanding, but restoring the clavicle's original anatomy and biomechanical architecture is paramount. Unnecessary controversy over conservative and surgical treatment has continued far too long, like Pott's fracture of the ankle and Colle's fractures of the wrist. Apply the same fracture treatment principles used for the two-bone problems of the forearm and lower leg fractures to advance the clavicle fracture management to prevent unwanted malunion and adverse biomechanical outcomes. There is a need for greater exploration of the extrinsic anatomy and intrinsic hierarchy distribution of microstructure throughout the entire bone. A greater effort is required to convert 2-dimensional plain radiographic images into 3-dimensional images, and to introduce Clinical biomechanical engineers alongside the surgical team in the department of surgery.

2.0 Frustum, a two-bone problem:

The clavicle is fine-looking and graceful,

With it, the scapula moves graciously.

At the acromion, it holds the scapula with sleight,

So, the humerus climbs to its height.

A broken clavicle becomes a two-bone problem,

With the malunion comes frustum.

By a crooked clavicle,

The hand never reaches its pinnacle!

The clavicle and the scapula act simultaneously and synchronously to elevate the arm. Their articulation at the acromioclavicular joint is similar to that of the distal radio-ulnar joint and tibiofibular syndesmosis with limited range of movements. Failure to restore normal anatomy of the clavicle leads to further injuries and pain due to the poor adaptation. Therefore, functionally, the fracture of the clavicle is a two-bone problem requiring early restoration of its anatomy and biomechanical architecture (*design of extrinsic anatomy and intrinsic hierarchy with distinctive inherited mechanics*), based on individual variations in its morphology and morphometric anatomy.

Unlike the problem of the two parallel bones in the forearm, the two-bone problem of the clavicle and the scapula is far more complex because of their topographic anatomy and the horizontal orientation of the clavicle, which pairs at almost right angle to the scapular blade, moving simultaneously in the different planes. The divergent clavicle and the scapula, hinged at the acromioclavicular joint, form an ever-changing dynamic angle, sliding over the thoracic wall along an ellipsoidal path. The angle between them varies with the coronal and sagittal diameters of the thoracic frame during abduction and forward flexion of the arm. The relationship of these linkages changes remarkably, given that their growth varies from year to year in the young.

The two bones adapt to each other, and to the elliptical circumference of the thorax. The acquired anatomy of the two bones in everyone alters over time, developing a specific biomechanical architecture to generate constant velocity and powerful motion at the glenohumeral joint. The performance of the glenohumeral articulation is entirely dependent on the individually optimized biomechanical architecture of the clavicle, which directs the motion of the scapula and adjusts the glenoid articular surface beneath the head of the humerus. The simultaneously moving linkages synchronize with the eyes and the hand to throw a projectile— with precision —at the chosen target, such as a bowler throwing a ball at wickets, in a game of cricket. As the anatomy of the clavicle adapts to the topographic anatomy, so does its biomechanical architecture to the demanding kinematics of the glenohumeral articulation, along with that of the scapula and humerus, under the influence of biomechanical forces.

The clavicle is distinct from other bones in its functional anatomy and biomechanical architecture, and in how it has evolved across species and developed in each during growth. The compound lever system of the clavicle, as part of the cleidoscapular mechanism is more prone to often ignored biomechanical failure than other bones. The scapula

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is constantly struggling to keep up with the humerus and to follow the directions of the clavicle, with rapidly changing tasks, frequently and without limit. They jointly experience the transmitted ground-reaction forces of the kinetic chain acting on the pectoral girdle, along line of gravity, on either side of the median plane. As a result, the links and joints of both shoulder complexes respond simultaneously and synchronously to a task.

3.0 Review of the cleidoscapular kinematics:

Movements of the clavicle and the scapula occur at paired joints, sharing the acromioclavicular joint, and the scapula shares its glenoid fossa with the humerus. The clavicle, uniquely intercalated between the sternocostoclavicular and acromioclavicular joints in series, is rooted in the clavicular fossa of the manubrium sterni, forms a continuum with the axial skeleton. The clavicle rotates around its mechanical and screw axii between the two joints. The sternal end of the clavicle has a much larger articular surface, which is incongruent, supported by the intra-articular disc, stabilized by the thick circumferential capsule and ligaments, reinforced by the extraarticular costoclavicular ligament and dynamically stabilized by the Subclavius muscle, during its simultaneous three-dimensional movements.

The acromioclavicular joint is more than just a uniaxial hinge because of its variable structure and relatively lax inferior capsule and ligaments. The coracoclavicular ligamentous complex reinforces and stabilizes the acromioclavicular joint during conjunct movement of the clavicle and the scapula, and its tautness assists in final axial rotation of clavicle. The clavicle makes rotatory and rolling movements to direct the scapula each time the arm is elevated. The shared movements of the clavicle and scapula are reflected in definite motion ratios between the cleidohumeral and scapulohumeral rhythms, which vary throughout depending on the load and rate of the arm elevation.

During circumduction, an articulated clavicle moves at the sternoclavicular joint enclosing a conical space with its apex at the sternal end and an asymmetrical elliptical oblique base, or a partial arc at the acromial end, subtending an angle of 30 degrees during abduction of the humerus(Lambert, 2016). The virtual conical space circumscribed by the rotating and rolling movement of the clavicle during abduction is the motion cone with an oblique base (**Fig. 3**). The elevating acromial end of the clavicle reaches its maximum height when the posterior-inferior conical projection of the prismoid sternal end of the axially rotating clavicle, acting as a cam, engages with the upper surface of the first costal cartilage. The costoclavicular ligament complex, acting as a pivot, restrains and stabilizes the elevating clavicle along with the Subclavius.

The acromion protracts and retracts in the transverse plane and tilts in the sagittal plane during coronal translation of the scapula on the thoracic wall. The scapula tilts posteriorly and swivel at the acromioclavicular joint. These movements occur in concert with those of the clavicle during arm elevation. Any mechanical interference from pathological anatomy of the clavicle results in loss of synchrony between the two bones. Therefore, any restraint to the clavicle's axial rotation and rolling motion will automatically limit abduction and forward flexion of the arm. The disturbed motion of the clavicle due to a frustum formation at the malunion leads to dyskinesis of the scapula, affecting the kinematics and kinetics of the humerus.

In the clinical settings, following the Cartesian axii, during the first 90 degrees, for every 10 degrees of arm elevation, there are 4 degrees (2.5:1) of clavicle elevation at the sternoclavicular joint. Above 90 degrees, the motion of the clavicle in this plane is almost negligible(Inman & Saunders, 1946). Not forgetting that the cam-effect at the sternal end due to the posterior-inferior projection can add another 5 to 10 degrees of clavicle elevation. On average, the scapulohumeral ratio is 2:1 (120 degrees of the humeral elevation is accompanied by 60 degrees of scapular rotation). The clavicle retracts 35 degrees and rotates dorsally by 45-55 degrees, limiting abduction to about 120 degrees(Inman & Saunders, 1946). The tightening of the conoid component of the coracoclavicular ligament helps with final dorsal rotation of the clavicle to reach maximum achievable arm elevation(Abbott & Lucas, 1954; Inman & Saunders, 1946). The scapula tilts posteriorly by 20 degrees during abduction between 0 and 145 degrees, and to adjust the glenoid fossa under the humeral head, it swivels dorsally by 10 degrees during the first 90 degrees of abduction, and then 6 degrees ventrally beyond 90 degrees(Kapandji, 2005).

4.0 The cleidoscapular bond: analogous to the radio-ulna:

The two-bone motion of pronation and supination in the forearm is an inverse rotation of the radius relative to the ulna between the paired proximal and the distal radio-ulnar joints. The two bones are also hinged by the spanning interosseous membrane, with most of its fibres running obliquely from radius to the ulna, proximally to distally, to help dissipate the violent reactive forces across the two bones in a Z-direction towards the elbow. The mechanical axis of supination and pronation is non-axial to the anatomic axis of either of the bones, running obliquely between the centroid of the radial head and that of the ulnar head, for synchronous movement of the proximal and the distal

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radio-ulnar joints. The radial head turns in the radial notch of the ulna, and the capitulum of the humerus proximally, and the ulnar head is in the radial notch distally. The paired-joint system of radius and ulna distally articulate at the wrist joint, increasing the kinematic and kinetic capabilities of the hand. The articulation of the radius at the humerus and the multiaxial carpus transmits a much greater load proximally, bearing most of the force, sustaining fractures more often and of much greater severity than the ulna.

The radius rotates around the pronation-supination mechanical axis, sharing forces with its weight-bearing anatomical axis across the oblique fibres of the interosseous membrane, which dampens the effect along the anatomical axis of the ulna, resulting in simpler fractures of the shafts than at the ends. The vertical height of the torque point is constant at the elbow joint or below it is determined by the applied load at the wrist(Burman, 1953). The resulting fracture strain of the radius is often greater than the ulna to cause oblique or a long spiral fracture, with or without comminution, depending on the amount of the torsional force. A hyperpronational torsional injury during a fall, causing a twisting fracture at the neck of the ulna, will apparently displace the distal fragment dorsally and in supination due to the secondary torsional force of the muscles, and is best reduced and immobilized in pronation, as in the case of a Colle's fracture(Burman, 1953).

Attempting to supinate the radius against the deceptively supinated distal fragment of the ulna will result in axial malunion, limiting pronation and supination. The confusing configuration of the fracture fragments of the forearm bones, due to secondary torsion, can make reduction and immobilization challenging, even with varying supination or pronation manoeuvre. Often, the malunion of the bones can be corrected by performing osteoclasis of the radius, provided the ulnar malunion is elastic. The force transmitted across the interosseous membrane at manipulation and immobilization will reverse the radial side correction until osteoclasis of the ulna is also performed, where its callus is already maturing. The supposedly corrected linear axial, sagittal and coronal angular deformities will leave behind the torsional deformity, limiting pronation and supination of the forearm. The residual torsional deformity of the radius and ulna is often overlooked during open reduction and fixation of fragmented fractures leading to malunion. The residual malunion of one or the other bone obstructs full pronation and supination of the forearm because, in motion, it is a two-bone problem. Each bone has an independent proximal and distal articulation, bound in a paired-joint system and joined by the interosseous membrane. The outcome is worse if there are frustum formation and torsional deformity of either bone, especially the radius, following conservative treatment of the forearm fractures, where the torsional deformity may not get fully corrected with remodelling alone, even in the young.

The forearm bones in the paired-joint system resemble a closed 'safety pin' design with almost two parallel struts joined at the proximal and distal radio-ulnar joints. By comparison, the divergent design of the clavicle and the scapula is much more intricate, where the key component, the clavicle, is intercalated between two joints, like the radius between the carpus and the capitulum, suspending its sister bone, the scapula, at the acromion. The twobone relationship of the clavicle and the scapula is that of a dynamic *'open clasp'*, clutching across the elliptical thoracic wall with several muscles. The open end of the osseous clasp is closed via the first rib articulation between the manubrium sterni and solely to the first thoracic vertebra completing the bony framework of the pectoral girdle on both sides of the vertebral column, as the final loading bearing site. The 60-degree clasp angle changes as the clasp opens and closes during the excursion of the scapula, in response to change in the cross-sectional diameters of the thoracic frame. Just as the malunion of the radius affects the kinematics of the forearm around the ulna, the kinematics of the scapula are altered in varying proportions depending on the type and severity of the malunion of the clavicle fractures. Thus, the kinematics of the clavicle directly affect the kinematics and kinetics of the scapula.

Alongside the altered kinematics of the clavicle and scapula, the humerus also exhibits kinematic and kinetic changes at the glenohumeral articulation, however, it compensates well because of the shallow and a longer radius of curvature of the glenoid fossa, unlike more constrained radiocarpal articulation. In non-anatomic reverse total shoulder arthroplasty, the biomechanics of the scapula and the clavicle are dramatically affected(Kim et al., 2020; Schneider et al., 2024). There is reorientation of the scapula, altered kinematics of the scapulothoracic and acromiohumeral synsarcoses, and an inversion of the loading conditions from the glenoid to the sternocostoclavicular joint, with compensatory changes in their kinematics. This can cause stress fracture of the acromion and clavicle, apart from their osteoporosis(Cronin et al., 2025). The altered loading conditions may also cause degenerative changes at the first costovertebral joint. In this regard, at the shoulder complex, the two-bone problem of the clavicle and scapula becomes a three-bone problem. Nonetheless, it remains a two-bone problem because the two are hinged directly and joined through the circumferential pectoral girdle mechanism as part of the biomachinery for overhead and underhand movements of the hands.

5.0 Trapezius muscle: an analogue of the interosseus membrane of forearm:

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The superior component of the Trapezius, Occipitocleidal trapezius and the middle section dynamically bind the clavicle to the scapula, unlike the virtually static flexible fibrous interosseous membrane that hinges between the radius and ulna. The coracoclavicular ligament complex actively contributes to this function of the Trapezius. The thin, extensive sheet of Trapezius muscle arising from the superior nuchal line and thoracic spinous processes inserts into the superior surface and posterior border of the clavicle's lateral curvature, acromion, and spine of the scapula sharing ground reaction forces like interosseus membrane in the forearm, co-ordinating the movement of the scapula and clavicle. The Trapezius muscle forms an important force couple acting on the scapulothoracic synsarcosis with the Serratus anterior and the Pectoralis minor from the "setting phase" onwards, sustaining scapulohumeral rhythm throughout the process of high-speed arm elevation.

6.0 Advanced functions of the clavicle related to its normal anatomy:

By spreading the shoulders to maximum width, the presence of bilateral clavicles acts like a balancing pole while walking a tight rope, making the shoulders wider than the pelvic skeleton. One reason the clavicle begins its development first is to set the pace for rest of the locomotor skeletal system and finishes growing last is to achieve maximum width relative to the pelvis. Apart from the vertebral column, how the synergy of pectoral and pelvic girdles' musculature is neurologically mediated connecting with the balancing apparatus, vision, and postural reflexes to form a reflexive kinetic chain during gait has received the least attention(Yoo & Mihaila, 2022). The lateral Vestibulospinal tract facilitates muscle activity in the trunk and limbs, and Medial Vestibulospinal tract controls neck and axial muscles to stabilize the head during movement, which in turn influences the orientation of the pectoral girdle. How the retracted and elevated posture of the clavicle by 20 degrees to transverse and 10-20 degrees coronal planes, relates to the field of vision, forming a panoramic view arc of 210 to 220 degrees, when looking straight ahead with a fixed gaze, is less well known (**see Part 1 of the series**). Consider the linear and angular parameters when managing a clavicle fracture carefully rather than leaving the individual in a state of covert widespread neuromuscular imbalance.

This degree of field view range, with postcranial descent of the pectoral girdle, formation of the neck and the bipedalism, was a necessary, well-coordinated phylogenetic and ontogenetic elaboration of the sensory-motor feedback at the higher level central nervous system during evolution. On top of that, there are morphological and morphometric variations in the anatomy and biomechanical architecture of the clavicle that correspond to claviculate species and individual needs during growth. This kind of development in the clavicle design, with its specific anatomical orientation, is a vital survival kit built into everyone's skeleton. With this view of the evolutionary concept of the panoramic field view, the clavicle's retraction angle to reach the mid-truncal coronal plane limits the lateral rotation of the cervical spine, where everyone's chin stops, except in people with collagen disorders. The lateral rotation of the cervical spine can also be one of the criteria for Beighton's list, including the extent to which the chin turns from the mid-mandibular plane, and how far it goes past the palpable anterior surface of the clavicle, and the total arc it forms between the two clavicles, usually between 130 and 166 degrees. The clavicle marks the lateral boundary of the forward-looking panoramic view and the mechanical space of an observer to keep the object in hand within the field of view around the body during circumduction.

In summary, within the pectoral girdle machinery, as a two-bone problem, the failure of the clavicle due to the formation of a frustum is not limited to the disturbed function of the upper extremity's distal linkages but also involves mediolateral perturbance of the truncal balance. The restraint to the rotation of the intercalated clavicle will be no different than that of a malunited fractured radius. If left untreated, the angular and torsional deformities of the clavicle, with shortening produce unrecognized multiaxial and multidimensional kinematic abnormalities to which many seem to adapt over time.

The scapula hinged at the acromioclavicular joint of a malunited clavicle, will remain mispositioned and misaligned, losing its normal excursion path on each elevation of the arm. Both bones will move differently, blocking each other's motion like one of the two panels of a swing door off the hinge. Until corrected, the function of the entire pectoral girdle will continue to suffer.

7.0 Muscle length-tension disparity and constant velocity sternoclavicular joint problem of a frustum:

In the presence of a frustum, muscle length-tension disparity creates disequilibrium among several force couples acting on the scapulothoracic synsarcosis. The clavicle does not merely oscillate between the paired joints to shuffle the acromion and tilt the scapula posteriorly and anteriorly under the humeral head. Instead, it is elevated and retracted simultaneously, realigning the moving scapula on the changing curvature of the thoracic wall under the influence of several force couples acting simultaneously, to turn the glenoid face cranially to support the head of the abducting humerus at a task-specific speed. This multiplanar, combined clavicular motion of elevation, retraction and dorsal rotation occurs at the sterno-costoclavicular joint, at a constant velocity, maintained by a wellbalanced

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muscle length-tension equilibrium. This motion is made possible by the toroidal sternocostoclavicular joint with the intra-articular disc, which allows the clavicle to rotate and translate rapidly through various angles at a constant speed, reciprocating with the acromioclavicular joint, acting like a constant velocity joint in an automobile for a differential motion between the inner and outer wheels without jamming.

A frustum formation of the clavicle alters the conjunct motion, displacing the multiple axii, obliterating the constant velocity function of the sterno-costoclavicular joint, and altering the kinematic velocity of the scapula and the humerus. At the same time, the acromial arch loses concentricity at the acromiohumeral synsarcosis, continually impeding the humeral head, and colliding with it, causing extrinsic compression and shear of the rotator cuff. The scapular dyskinesis and malposition of the glenoid fossa introduce misalignment of the long-head tendon of the Biceps brachii muscle. The altered oblique path of the tendon like a windscreen wiper, rubbing harshly against the intrinsic surface of the glenohumeral joint capsule and the tendon of the Supraspinatus muscle initiate intrinsic rotator cuff abrasion (**for details see Part 3 of the series**).

Altered tension in the prestressed coracoacromial ligament, modifies the excursion of the coracoid process between the infraclavicular fossa and the rotator cuff interval. The altered tension in the ligament also affects the capsuloligamentous thickenings of the glenohumeral joint, causing subtle incongruency and loss of concentricity, shifting the centre of rotation during rapid abduction and rotation of the humerus. Thus, linear and angular shortening of the clavicle with the formation of the frustum causes no less biomechanical harm than is seen with the frustum formation of the radius, obliterating pronation and supination. In both cases, there is a loss of range of motion, velocity, strength, and power due to altered relationship between multiple articulating surfaces, which blocks the normal cranking effect of the curved lever mechanism of bones, resulting in varying degree of impingement upon the neighbouring structures.

8.0 Strain energy storage by the clavicle and the scapula:

When the arm is repeatedly abducted for high-velocity activity without a sufficient resting phase in between each manoeuvre, the clavicle rotates fully on its screw axis, turning the inferior surface facing anteriorly. Tension in the conoid ligament helps rotate the clavicle dorsally to its zenith. The clavicle's compound rolling movement *(elevation, retraction and dorsal axial rotation)* around its pitch and mechanical axii and the longitudinal screw axis tightens longitudinally running spiral collagen bundles that form the screw twist, stores elastic strain energy. This stored energy helps to return the clavicle to its resting position. Maximum strain energy storage and release are possible only in the presence of the normal anatomy of the clavicle and restoration of its biomechanical architecture following a fracture.

The clinically invisible screw twisting rotation is the winding and unwinding effect of a normal clavicle as a torque machine, gathering and releasing the variably distributed elastic torque strain energy, like a helical spring, along its length during a high-velocity projectile delivery. As the scapula tilts posteriorly by dorsal rotation of the clavicle, the scapular blade also stores elastic strain energy by unfolding its concave costal curve, with the scapular spine as its fulcrum. The efficiency of the shoulder complex and pectoral girdle musculature depends on the intact normal clavicle with patient-specific curved levers, torsion and version angles. Therefore, frustum and shortening will adversely affect the function of the shoulder complex, preventing the repositioning of the clavicle and the scapula to their initial positions for each subsequent movement. The scapula receives the elastic strain energy generated at the clavicle via the acromion. The acromion has a torsion angle similar to the version angle of the clavicle(Zenker et al., 2022). This biomechanical relationship between the clavicle's acromial end and the acromion prevent the loss of energy transmission at the acromioclavicular articulation.

9.0 Loss of torsion, version and kinematic behaviour of the clavicle between the paired joints:

It is unclear whether the major fracture fragments of the clavicle rotate in the opposite or the same direction, thereby tightening or unravelling (*unreeling*) the screw twist and diaphyseal torsion, and how much is regained at maturity of the callus, particularly in cases of rigid fixation and conservatively managed malunited fractures. In a malunion, if there is only partial or no recovery of the patient-specific torsion and version angles and the angular alignment of the fragments, and the clavicle does not return to the correct screw twist and pitch, then axial rotation of the clavicle will be limited or defunct. The uncorrected torsion and version angles automatically reduce the range of rotation at both the screw axis and the mechanical axis, ultimately affecting the rolling movement around the pitch axis of the clavicle. When a disarticulated clavicle is rotated through 360 degrees around its mechanical axis, it generates a physiological motion cone due to the offset between the medial and the lateral curvatures, at the acromial end. However, as this never happens, the articulated clavicle oscillates around its mechanical axis and rolls around the pitch axis as it elevates and retracts simultaneously. It generates an elliptical arc at the acromial end, which is only a segment of the motion cone (**Fig. 4**). Instead, if the motion

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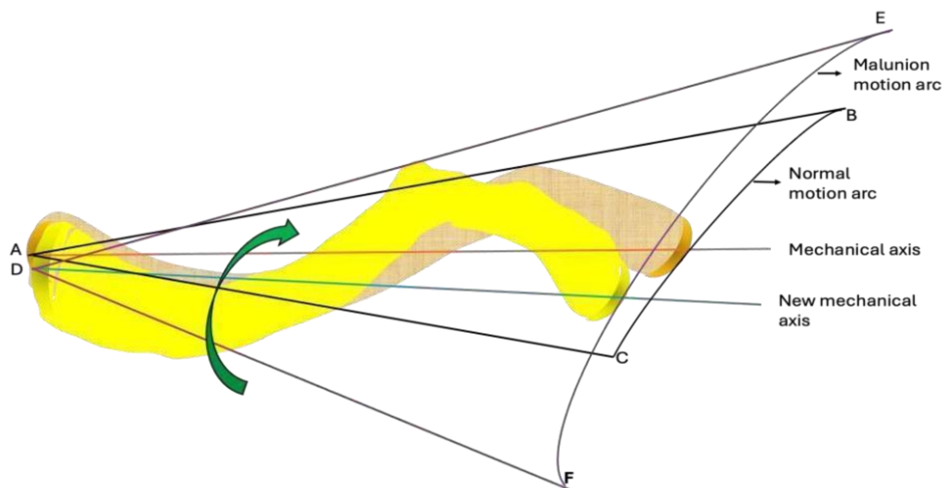

Figure 4. Motion arc at the acromial end and motion triangle ABC in a normal clavicle and DEF in a malunited clavicle with frustum formation. An articulated clavicle traces a motion arc around the mechanical axis during rotation and around the pitch axis during rolling (created in PowerPoint).

cone is viewed in two dimensions, the asymmetrical arc forms a motion triangle during dorsal and ventral rotation of the clavicle, normally subtending an angle of approximately 30 degrees. The base of one-half of the motion triangle is the weight-bearing mechanical axis of the clavicle. **1**

10.0 Compound kinematics at the multi-curvature (saddle-shaped or toroidal) articular surface of a linkage; understanding surface joint motion and the shifting instantaneous centre:

The Reuleaux method for locating the instant centre of a moving articulating surface is much simpler than the recently described method of stereophotogrammetry(Reuleaux, 1876). The surface joint motion can be expressed in any plane of a joint except the transverse plane. The instant centre location method describes the relative uniplanar motion of two adjacent linkages of the skeleton, and the direction of displacement of their contact points as the joint surface of the dynamic link moves on the joint surface of the static link. At any time during the motion, the point on the moving link moves relative to the point on the static link.

10.1 Instantaneous centre of motion:

It is unclear whether the major fracture fragments of the clavicle rotate in the opposite or the same direction, thereby tightening or unravelling (*unreeling*) the screw twist and diaphyseal torsion, and how much is regained at maturity of the callus, particularly in cases of rigid fixation and conservatively managed malunited fractures. In a malunion, if there is only partial or no recovery of the patient-specific torsion and version angles and the angular alignment of the fragments, and the clavicle does not return to the correct screw twist and pitch, then axial rotation of the clavicle will be limited or defunct. The uncorrected torsion and version angles automatically reduce the range of rotation at both the screw axis and the mechanical axis, ultimately affecting the rolling movement around the pitch axis of the clavicle. When a disarticulated clavicle is rotated through 360 degrees around its mechanical axis, it generates a physiological motion cone due to the offset between the medial and the lateral curvatures, at the acromial end. However, as this never happens, the articulated clavicle oscillates around its mechanical axis and rolls around the pitch axis as it elevates and retracts simultaneously. It generates an elliptical arc at the acromial end, which is only a segment of the motion cone (**Fig. 4**). Instead, if the motion cone is viewed in two dimensions, the asymmetrical arc forms a motion triangle during dorsal and ventral rotation of the clavicle, normally subtending an angle of approximately 30 degrees. The base of one-half of the motion triangle is the weight-bearing mechanical axis of the clavicle.

Within the dynamic link, there is a point that does not move and thus has zero velocity. This point is an instantaneous centre of motion or instant centre. The instant centre can be located by identifying the starting point on the articular surface of the static link and the initial point of contact on the articular surface of the dynamic link. These points can be located and marked by identifying them radiographically. As the dynamic link is displaced through a chosen range of motion, a second point is marked. On the surface of the dynamic link, draw the tangent lines at the first and second points and raise the perpendicular lines (**Fig. 5**). The intersection of the perpendicular lines, within the substance or outside of the dynamic link, represents the virtual instantaneous centre of the surface joint motion.

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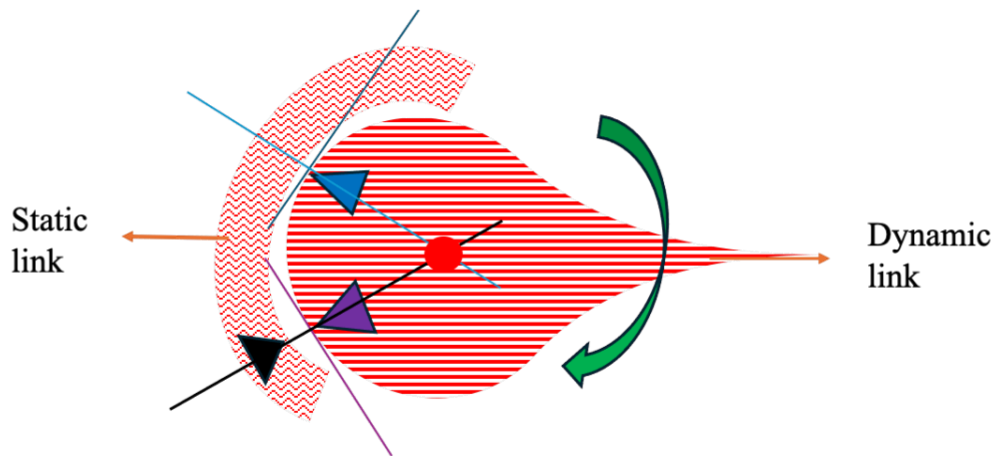

Figure 5. Joint surface motion between a static and a dynamic link. Instantaneous centre of rotation (red dot) for the movement between the purple and the blue triangles (created in PowerPoint).

Depending on the asymmetry of the articular surfaces, as the dynamic link displaces, so does the instantaneous centre of motion, indicating the direction of displacement relative to the static link. This suggests that the contact points are tangential to the direction of the load on the load-bearing joint surface, producing translatory motion during displacement. At other times, rotation and rolling motion do occur as well.

The concept of surface motion must not be confused with the range of motion of a joint occurring at the other end of the link, which is a clinical experience. The limitation of the Reuleaux instant centre technique is that it cannot be applied where the surface joint motion exceeds 15 degrees in any other plane(Nordin & Frankel, 1989).

10.2 Type of movements the articulated clavicle experiences at the sternoclavicular and the acromioclavicular joint:

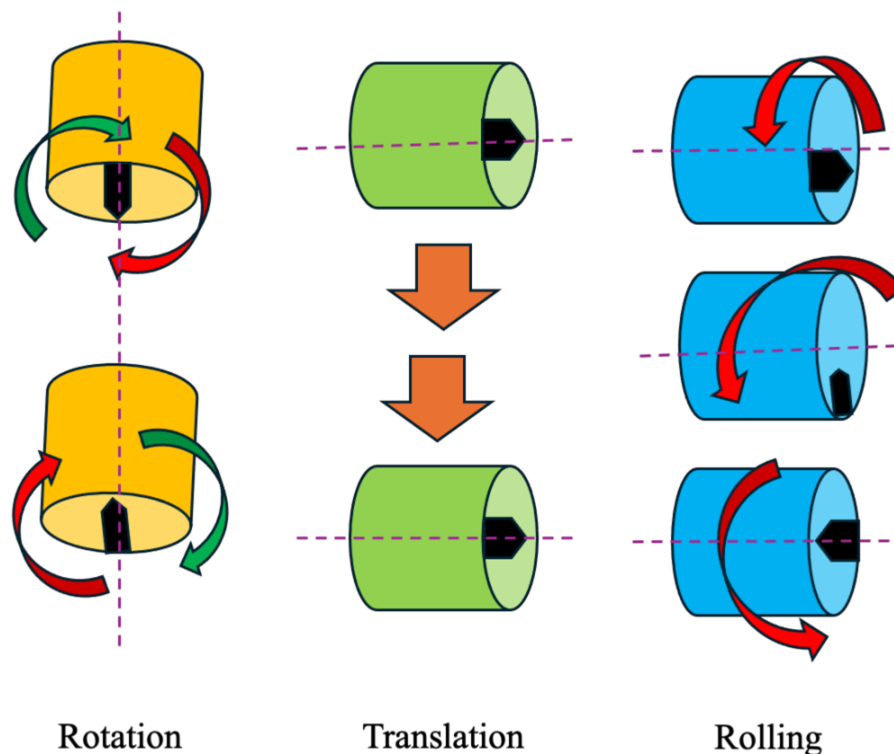

Figure 6. Modes of articular surface motions (created in PowerPoint).

Three types of surface joint motions exist: translation, rotation and rolling (**Fig. 6**). They apply to the clavicle kinematics at the sternoclavicular joint surface. These movements frequently co-occur between the saddle-shaped articular surface of the sternal end of the clavicle on the articular disc, and (or) between the articular disc and the clavicular fossa of the manubrium sterni.

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Translation is the movement of a body in the plane of the joint surface without rotation or angular displacement. The articular surface of the moving clavicle retains the same orientation to all axii. The contact point of the moving surface, remaining the same, is continually in contact with the stationary surface.

Rotation is a circular motion of a link on a joint surface. The acromial end of the clavicle rotates relative to the sternal end about a given point, line or axis at a fixed angle about its origin (**Figs. 6 and 7**). During rotation, the contact point on the stationary surface remains constant, while the contact point on the joint surface of the moving link changes the position. The rotation of the clavicle occurs around its straight mechanical axis, with a screw twist around the screw axis between the centroids of the sternal and acromial end joint surfaces.

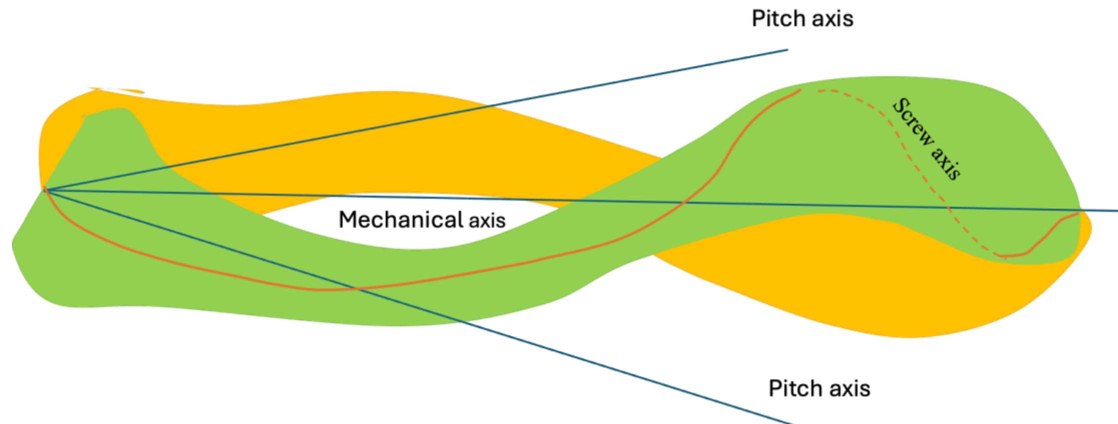

Figure 7. Rotational motion of a clavicle articulated between two joints (created in PowerPoint).

Rolling is the movement of a part around a centre or an axis or one complete turn in a circle. During rolling, the contact point on the joint surface of the dynamic link changes by an equal amount of turning with forward motion relative to the contact point on the joint surface of the stationary link. The rolling motion of the clavicle takes place substantially around the pitch axis and other axii, with simultaneous elevation, retraction and rotation, so that the acromial end of the clavicle displaces cranially and posteriorly (**Fig. 8**).

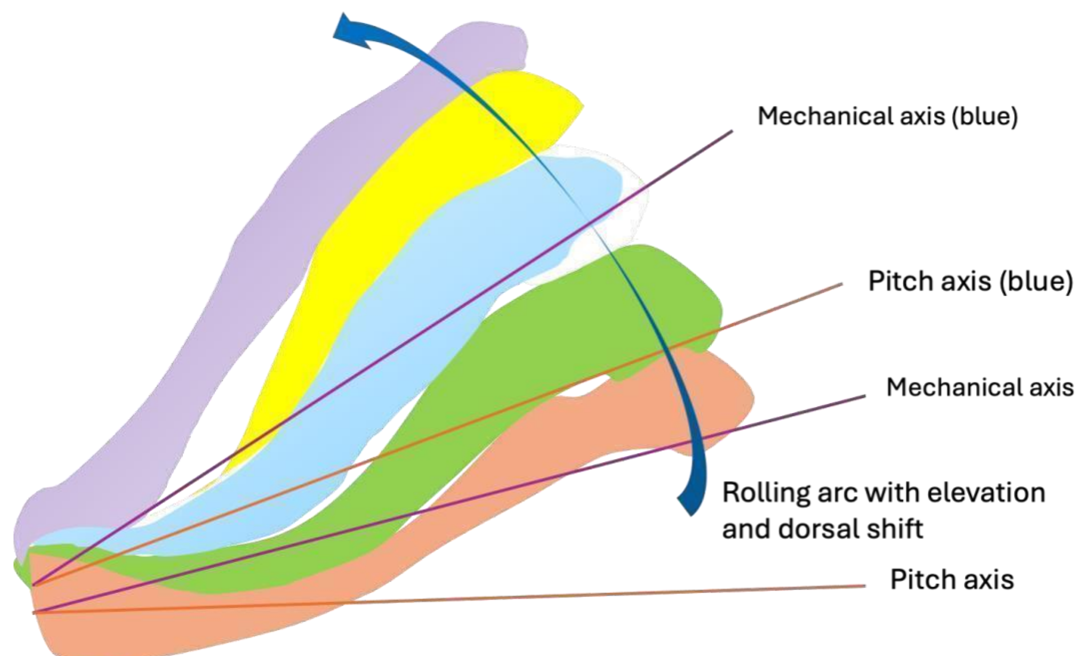

Figure 8. Rolling motion of a clavicle at the sternoclavicular joint, with the acromial end tracing an arc from ventral to dorsal position (created in PowerPoint).

11.0 Kinematic dynamics of the clavicle:

In its dynamic state, when the clavicle moves at the sternoclavicular joint, the eccentric centroid at its sternal articular surface is fixed, while the instant centre of rotation shifts according to the type of motion at a given moment. The virtual screw axis, mechanical, and the pitch axii, partly or wholly, lie within the medial curvature originating at the

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centroid (*the point on the joint surface where two maximum orthogonal diameters cross each other*). Thus, the clavicle rolls around these axii at the centroid of the sternal end's articular surface. However, as the lateral curvature offset from the medial curvature, the three gradually diverge from each other. The screw axis follows the centreline, spiralling the anatomic axis, and the straight mechanical axis passes through the centroid of the articular surface of the acromioclavicular joint. The most divergent and variable pitch axis, following a straight path, exits the medial curvature aligned to the centroids of its cross-sectional diameters at an angle that deviates from the lateral curve, due to the offset.

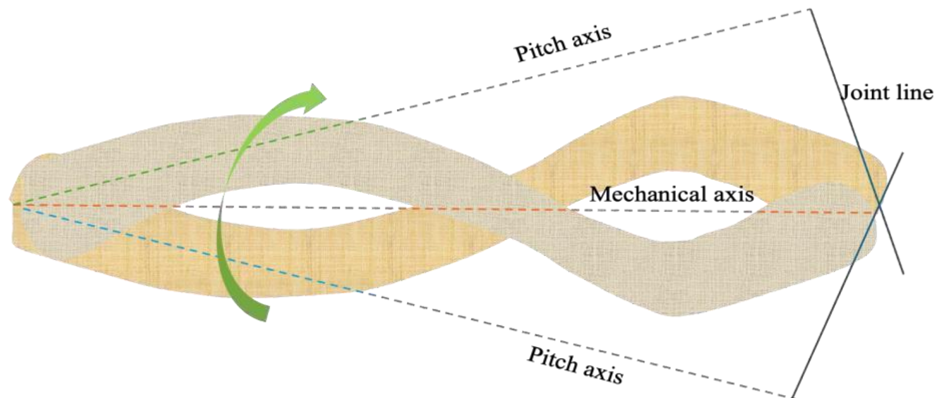

Figure 9. Formation of a motion triangles with ventral to dorsal rotation of a normal clavicle (created in PowerPoint).

A cone is a surface generated by the revolution of a straight line passing through the origin of the three-coordinate system, making a given angle with the axis around which it revolves. In geometry, the hypotenuse of a right-angled triangle sweeps out the cone. The articulated clavicle's straight mechanical axis and the screw axis, acting as fixed leg and the base of a triangle, and the pitch axis as the hypotenuse forms a virtual near right-angle triangle with the line passing through the joint line at the acromial end. With sweeping motion, the pitch axis *(hypotenuse)* shifts from ventral to dorsal and vice-versa, tracing an oblique arc of an asymmetrical cone base. This forms similar triangles as a part of the oblique base of a three-dimensional asymmetrical cone (**Fig. 9**). The motion of the acromial end of the rolling clavicle traces an oblique path, with conjunct motion of rotation around the mechanical axis. At the joint surface of the sterno-costoclavicular articulation, the acromial end elevates vertically and rolls dorsally with axial rotation around the mechanical axis. Simultaneously, it makes translatory motion, such that there is reciprocal anterior and posterior motion between the sternal and the acromial ends, respectively. Only an intact clavicle will form similar triangles when rotated and rolled from ventral to dorsal position, shifting the sweeping pitch axis along with the medial curvature of the clavicle.

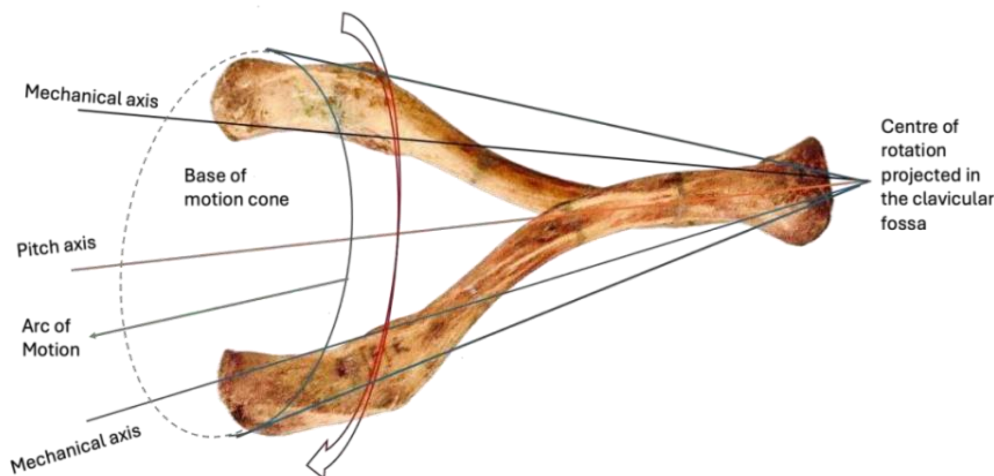

Figure 10. Tracing of the motion cone by the acromial end around the pitch axis sweeping the mechanical axis in a disarticulated clavicle (created in PowerPoint).

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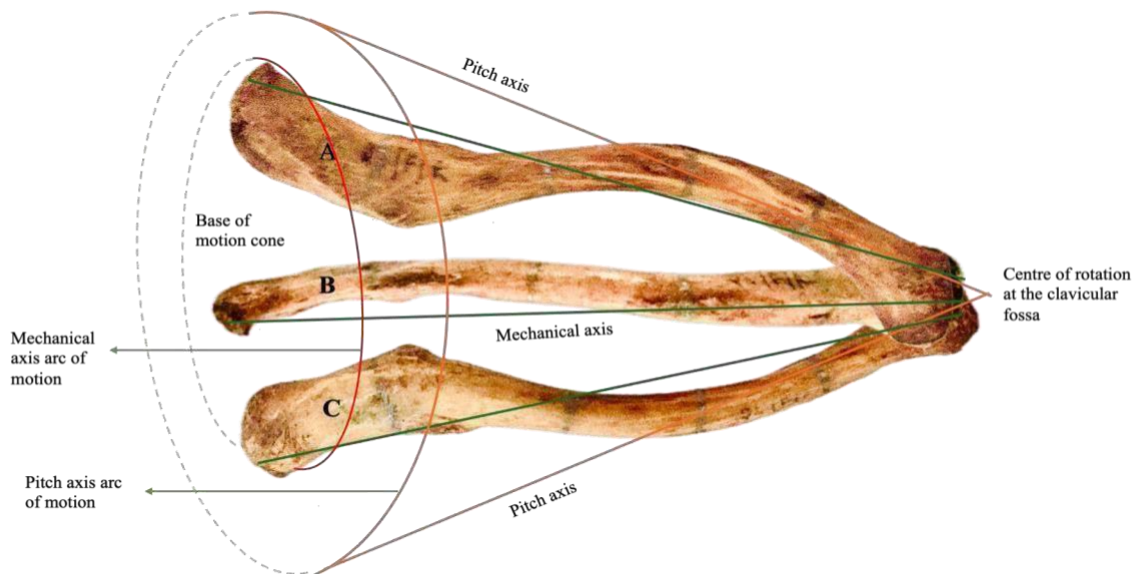

Figure 11. Tracing of the motion cone by the acromial end around the mechanical axis by sweeping the pitch axis in a disarticulated clavicle (created in PowerPoint).

During abduction of the humerus, the upward and backward rolling of the clavicle is a combined motion of translation, rotation and rolling at the sterno-costoclavicular joint surface. While the reciprocal movement of the acromion traces a part of an ellipse, changing the direction of its superior surface posteriorly **(Figs. 10 and 11)**. Unlike a disarticulated clavicle as a free body in space, at the centroid of the sternal end's articular surface, the acromial end of the articulated clavicle, with the pitch axis, traces only a part of an oblique ellipse, making an arc of 45 to 55 degrees at the base of the motion cone. The arc extends to 65 degrees, which includes the initial 8-10 degrees of anterior-inferior rotation of the acromial end, starting with the "setting phase". Hypothetically, a disarticulated clavicle can trace a complete cone either around the pitch axis or the mechanical axis (**Figs. 10 and 11).**

11.1 Screw twist and motion of the clavicle:

Given the complex geometry of the clavicle design, the screw axis *(helical axis)* following the clavicle's centreline anatomic axis form one and a half to one and three-quarters (1.5-1.75 twists) of the screw twist between its ends. Medial, lateral and laterally concentrated curvatures are aligned neither on a straight linear axis in the coronal plane nor the transverse plane. At rest, the mechanical axis runs beside the screw axis. During maximum roll of 55-65 degrees of rotation_

1. As the pitch axis shifts from ventral to dorsal along with the medial curvatures of the clavicle, the magnitude of the shift relative to the lateral curvature depends on the offset between the two curvatures.
2. The screw axis tilts relative to the mechanical axis due to the screw twist between the paired joints. The screw twist changes direction approximately between the third-fifth and fourth-fifth of the diaphysis. The screw twist has a smaller pitch at the shorter lateral curvature than at the longer medial curvature, making the clavicle a differential screw machine.

The respective clockwise (right-handed screw motion) and counterclockwise (left-handed screw motion) movements of the left and right clavicles, as seen from the acromial end will affect_

1. Axial displacement along the longitudinal screw axis between the paired joints varies due to differences in radii of curvature and offset.
2. Radial displacement is perpendicular to the screw axis.
3. Torsional displacement follows the twist around the screw axis.

The intercalated clavicle rotates simultaneously at both the sterno-costoclavicular and acromioclavicular joints, as medial curvature cannot move separately from the lateral curvature, as it translate and roll at the sternocostoclavicular joint across the articular disc. It is hard to say if the screw axis shifts within the flat and wider acromial end because of the change in screw pitch and offset of the lateral curvature, like the instantaneous centre of rotation. The location of the screw axis will average around the anatomical axii following the centreline. It will oscillate relative to the other axii, seeking a stable location to prevent vibration and wobbling of the clavicle at a

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higher rate of arm elevation. The distance between the axii will also vary depending on the cross-sectional chord length and the radii of curvature of the curves, as the cross-sectional shape and diameters of the clavicle change. The eccentric paths of both the screw axis and the mechanical axis depend on the regularity of the curvatures, torsional and version angles, which vary in everyone. The key factors that will influence the position and radial distance of the mechanical axis and the pitch axis from the centreline screw axis will be:

1. Radii of medial and lateral curvatures of the clavicle
2. The angle of the screw twist, sectional torsion angles of the diaphysis and version of the acromial end relative to the sternal end.
3. Amplitude of oscillatory arc during rotation and roll of the clavicle.
4. Density distribution along the length of the clavicle, which defines sectional stiffness to allow bending and torsional deflection during motion.

As a result, there will be a variable stress distribution along the length of a clavicle. Axial compression, translational and torsional shear at the articular surfaces will be higher if the clavicle does not align between its paired joints during motion. In a malunited clavicle, expect micro-vibration, loss of stored elastic strain energy, and greater effort to complete a task in hand. There is early fatiguability and a gradual decrease in speed.

Following a malunion of the clavicle, deficits in range of motion with energy loss leading to fatigue are mitigated only by reoptimizing the clavicle's three-dimensional anatomy and biomechanical architecture. This will redistribute the displaced bone mass back toward normal around the centreline anatomical axis, normalizing and repositioning the screw, mechanical and pitch axii. It will tend to reduce the clinically unnoticeable micro-vibrations of the constrained clavicle. A corrective osteotomy of the clavicle can only partially achieve these goals because there are currently no definite imaging techniques and methods available to evaluate the uncorrected biomechanical errors. Secondly, partially remodelled intrinsic tissues, particularly the spiral path of the provisional collagen bundles embedded in the newly laid bone mineral, will take time to remodel, if at all.

11.2 The relationship between mechanical axis, screw axis and the anatomical axis:

Understanding the motion of an intercalated bony linkage in paired joints, such as the tibia-fibula and radius-ulna, and the management of their fractures can help resolve the kinematic complications of the clavicle-scapula mechanism and to resolve other deficits associated with the malunited clavicle. To correct a three-dimensional deformity of the clavicle, control each fracture segment separately, realigning them mechanically to their kinematic axii between the paired joints in all the three coordinates and, also, at appropriate angles to the cardinal planes of the body.

The straight line of the mechanical axis of the clavicle does not pass through the centre of the medullary tube corridor from the centroid of one joint surface to that of the other. The vertically standing disarticulated clavicle's ends have much greater offset on a plumbline hung perpendicular from the proximal centroid of motion through the diaphysis than most of the long bones. In an intact clavicle, the mechanical axis is a stable common weightbearing axis *(the base of two right-angle triangles within the motion cone)* around which the stable pitch axis leg *(hypotenuse)* rotates, tracing a reproducible ellipse as the base of motion cone or part of it as an arc forming the motion triangle. During supination and pronation, a similar arc, say 165 degrees, is formed by the radial styloid of the radius around the common mechanical axis of the radius and ulna. In case of the clavicle, the arc traced at the base of the cone by the acromial end for its full range of rotation-cum-rolling motion from ventral to dorsal is 65 degrees of arc, with elevation and retraction, starting from the "setting phase" to 120-degree abduction. The turning of the inferior angle of scapula following the acromial end of the clavicle at a constant velocity, depends on the constant velocity function of the sterno-costoclavicular articulation. It is because of this and the differential reciprocal motion between the sterno-costoclavicular and the acromioclavicular joints that during a high-velocity throw, the sternal end of the clavicle never jams.

During the screw twist motion, the acromial end of the clavicle rotates elliptically around the mechanical axis, and the mechanical axis around the screw axis embedded in the substance of the clavicle, while the pitch axis traces its own motion arc. There are arcs of widening radii and spreading waves of motion from the beginning to the final moment when throwing a projectile in hand, generating enormous torque, imparting angular acceleration to the object. In a clavicle with the normal biomechanical architecture, the radial arrangement of increasing radii of the various axii meeting at the same centroid prevents the sternal end of the clavicle from jumping out of the clavicular fossa of the manubrium sterni and triggering arrhythmic motion at the glenohumeral articulation. Everyone optimizes

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the biomechanical architecture of the clavicle around these axii, developing specific morphometric parameters, including radii of curvature, torsion and version angles, lengths and diameters, and bone density distribution.

The pitch axis traces two physiological motion triangles around the mechanical axis, for the transverse medial curvature, when moving dorsally, then ventrally. A separate pitch axis passing between the centroid of the sternal end and the inferior curvature in the coronal plane, traces its own two physiological motion triangles during rotation. Although biomechanically, transverse-plane medial and lateral curvatures and the coronal-plane inferior curvature, offset from each other, are separate entities, they are anatomically merged back-to-back, forming a compound hyperbolic paraboloid around which the screw axis winds within the substance of the clavicle (**Fig. 12**).

Figure 12. Hyperbolic paraboloid structure of the clavicle (created in PowerPoint).

The only way to test the combined motion of the clavicle's rotating curvatures tracing the elliptical circumferential path of cone motion is either by computer modelling or by strategically applying micro-sensors to analyze with a high-speed motion-tracking system(Twin Arc Legacy life, 2025). The screw axis follows the centreline of the curves around the anatomical axis and the length of the mechanical axis passing between the paired joints' centroids equals the clavicle's effective length. The centreline length carrying the screw axis, central to the biomechanical architecture of the clavicle, is the most relevant parameter of its biomechanical function. Unlike a log in a stream, a straight, flat or rodlike clavicle without curves and twist, and a space-occupying malunited clavicle would experience much higher drag against the fluid-filled tissue resistance, muscle tone and the fascial tension to initiate rotation-cumrolling motion. Secondly, would require much longer length like a machine shaft to achieve equivalent mechanical advantage. The mobile branches of trees are at an angle, optimally curved to minimize wind resistance, act like dampers to dissipate wind energy, reducing the load on them; and improved aerodynamic effect
(**Fig. 13**).

Figure 13. A segment of a tree branch with hyperbolic paraboloid curves like the clavicle (created in PowerPoint).

12.0 Loss of alignment of the axii in a constrained intercalated clavicle with frustum formation:

Typically, a motion cone is formed when the anatomic and screw axii align with the centreline and the clavicle has a normal effective length, intercalated between the two joints. Following a clavicle fracture, there is a mechanical loss of intercalation. With frustum formation between the malunited fragments, there is loss of alignment of the axii and, with it, the concentricity between the screw axis and the pitch axis. The acromial end traces an abnormal motion arc, failing to form the normal similar right-angled triangles on ascent and descent of the arm **(Figs. 3 and 9).**

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The frustum of an intercalated clavicle distorts the normal motion arc, spanning a much larger arc during rotation and rolling, impinging on surrounding soft tissues **(Fig. 4)**. The absence of a typical motion triangle at the acromial end compromises motion of the scapula and jeopardizes precision in projectile delivery, at a much higher energy cost.

Similarly, in the dislocation of the clavicle at the acromioclavicular joint, the clavicle loses the intercalary function. Release of the acromial end causes biomechanical failure and non-surgical claviculectomy. Depending on the type of acromioclavicular joint disruption, the relative displacement of the clavicle's acromial end from the scapula, causes loss of the normal alignment of the mechanical, screw, and pitch axii of the paired joint system, creating adverse kinematics of the clavicle, scapula and the humerus. The benign negligence of a surgeon in treating lower grades of acromioclavicular dislocations can still eliminate normal kinematics of the sterno-costoclavicular and acromioclavicular articulations, as well as of the scapulothoracic and acromiohumeral synsarcoses, ultimately leading to kinematic dysfunction of the glenohumeral articulation.

13.0 Callus remodelling and obstructive motion of the scapula at the scapulothoracic synsarcosis:

The fundamental rule of an intercalated linkage motion within a paired joint system and its sister bone is synchronization of their movements. When one of the linkages sharing a common joint break this rule by obliterating or limiting the biomechanical function, it affects the function of the sister linkage as well. The distorted motion triangle formed by the clavicle malunion will be transmitted to the scapula, tracing a distorted arc at its inferior angle. Geometrically, the difference between the normal and the malunited clavicle's motion triangle would be translated into almost an equivalent degree of mechanical scapular winging at rest. This would be worse if the fragments overlap and angulate, distorting the medial curvature, changing the offset of lateral curvature, and affecting the biomechanics of the lateral and inferior curvatures. This applies when an uncorrected malunited clavicle is left with residual deformity following conservative treatment, especially in patients older than age 12, after which the remaining growth of the clavicle is only 20%. This is akin to a spinal motion segment between paired facet joints of adjacent vertebrae that experience similar biomechanical disturbances, as in 3-dimensional deformity of scoliosis, of various aetiologies, which fails to realign with growth and shows relentless progression of the deformity throughout life if left uncorrected.

How the biomechanical forces stimulate linear growth and correct torsional deformity at cellular level in a mature callus during remodelling is poorly understood. As shown in the rabbit bone model, the likely mechanism that corrects the angular deformities in children's fractures occurs at the physes through asymmetric, helicoidal growth under the triaxial biomechanical forces during the post-fracture period, realigning the bones and joints(Murray et al., 1996). However, the rotational deformity correction is very limited. Linear growth following a fracture result from hyperaemia at the fracture site and the physes, and tensile forces when long bones are treated in traction(Shapiro, 1981). The remodelling potential in growing bones is inversely proportional to the age, with the highest potential in neonates. It is believed that most malalignment correction occurs at the physes due to Heuter Volkman's law (1862), with the remainder due to Wolfe's law (1892) and Pauwel's theory of elasticity (1965) during healing and remodelling of the maturing callus(Maquet, 1992; Naik, 2021).

Despite limited remodelling potential in adolescents, depending on the pathological anatomy and altered biomechanical architecture, the degree of altered motion of the clavicle will manifest as scapular dyskinesis. This will ultimately reflect as altered stability and the kinematics of the glenohumeral articulation, affecting its range of motion, strength, power, endurance, fatiguability and the ability to hit a projectile at the bullseye. At the minimum, telescopic shortening forming a bayonet and angular deformities in any plane represent a significant change in the regular geometry of the clavicle, demanding a prolonged intensive retraining programme until it remodels to match the functional demands of an individual, at a lower-level performance or compensating through engagement of the contralateral half of the pectoral girdle. Whatever the 'normal' range of motion return in the adolescents with malunited clavicles, is later a matter of physical adaptation and adjustment of muscle-length tension, with the formation of a new vector between the origin and insertion points of the muscles, at higher energy expenditure.

14.0 Formation of an altered quadrangular motion space within the motion triangle reconfigures the structures at the root of the neck:

There will undoubtedly be a radial deviation of the lateral fragment in the presence of an angular malunion and shoulder ptosis, with or without significant linear shortening of the clavicle's effective length. Nevertheless, functional shortening will occur as the two clavicle ends come together. There will be an equivalent shortening of the chord at the medial and lateral curvatures, with a change in their radii of curvature. In the presence of angular deformity in the same orientation as the original curvature, the curves will deepen due to the pulling force of a functioning Subclavius muscle or contracture of the fibrous tissue during the early healing phase.

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Depending on the site of the fracture, whether at the third-fifth or four-fifth sections, the severity of the angular deformity will vary. It is worst when more lateral and closer to the inflection point(Edelson, 2003). The length and shape of the base of the motion triangle (cone) will change with the degree of angular malunion. So will the quadrangular space occupied by frame of the clavicle (**Fig. 14**). The projected motion cone will be completely distorted. The cleidoscapular angles at the acromioclavicular joint and the respective angles to the fore and rear coronal planes will also alter, at rest and during motion.

Functionally, the formation of the **frustum** (*the portion of a three-dimensional cone or a pyramidal structure that remains after its upper part is cut through a plane parallel to its base*) or the truncation (*sectioning the top portion of the cone or a pyramidal structure from its base*) of the motion cone, functionally divides the lateral curvature of the clavicle from the medial curvature. Even though the two curvatures, moving around two sets of axii, still have the apex of the distorted motion cone unchanged or very close to each other at the centroid of the clavicle's sternal

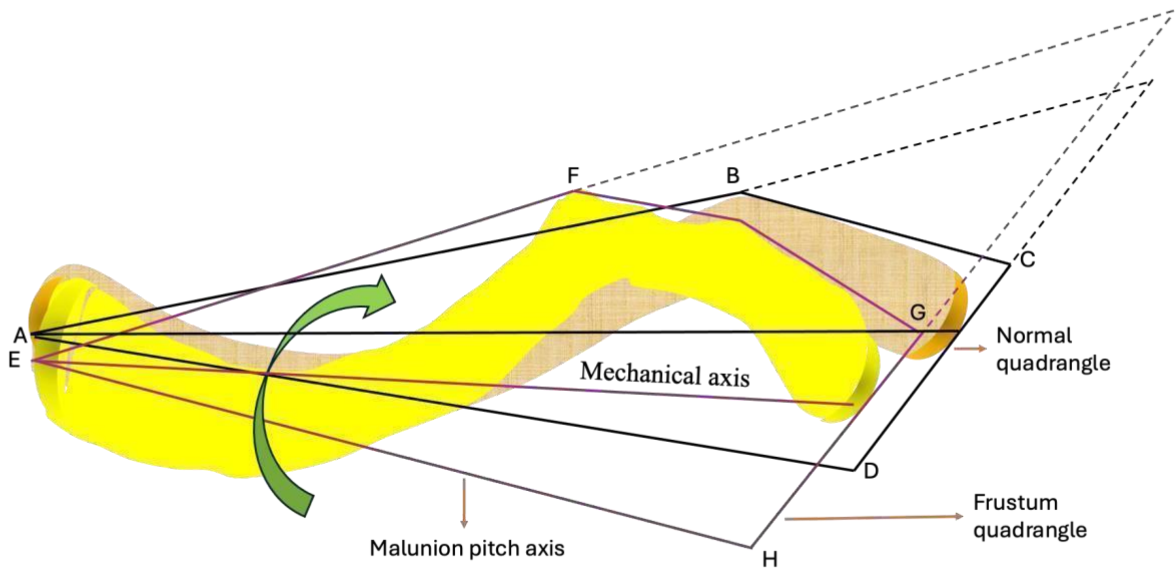

Figure 14. The formation of a new quadrangular space due to the frustum (created in PowerPoint). end.

With the frustum or truncation of the motion cone formed by the angular malunion, the clavicle rotates around new mechanical, pitch and screw axii. The clavicle rolls around the new pitch axis, elevating and retracting dorsally along a new arcuate path traced by the acromial end. With the angular malunion, the screw twist, angles of torsion and version, screw axis and pitch axis all conform to the deformity, shifting proportionately and embedded within the frustum. The direction of the anatomical and screw axii originating at the sterno-costoclavicular joint follows the misaligned centreline across the fragments.

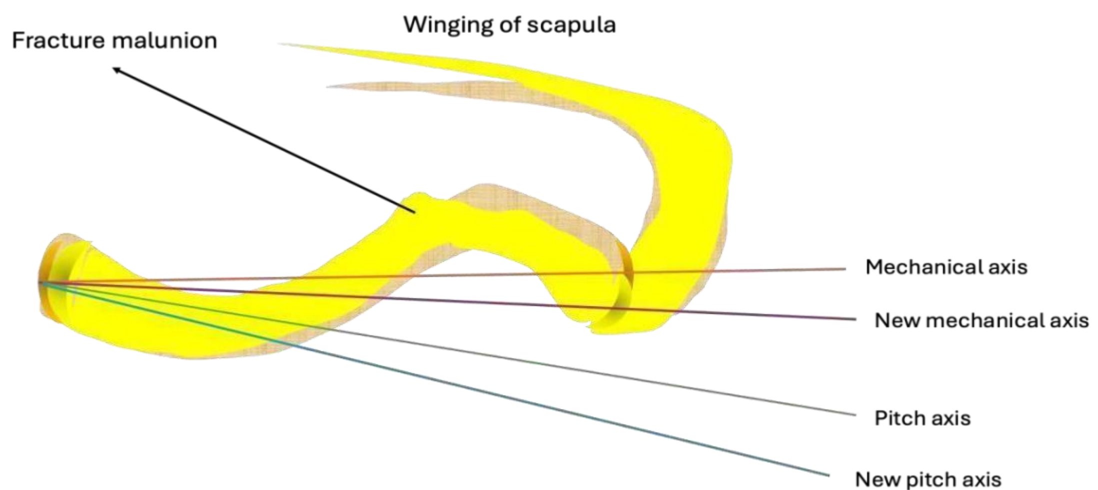

Figure 15. Winging of the scapula (yellow) following the frustum formation (created in PowerPoint)

With the clavicle's shortening and changed geometry, the relationship of the scapula is altered with the thoracic wall. The inferior angle of the scapula is lifted with or without lifting the medial vertebral border, depending on the angle

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at the frustum, limiting translation of the scapula. Geometrically, conversion to the new motion triangle, new motion quadrangular space and arcuate path introduces equivalent "winging" of the scapula (**Fig. 15**).

However, as the scapula is a highly mobile linkage, the protraction by the Serratus anterior pulls in the inferior angle conforming against the thoracic wall curvature masking the winging associated with smaller angular malunion. During abduction in the coronal plane, in contrast to forward flexion, with cranial elevation, dorsal rotation and rolling of the clavicle, despite limited posterior tilting of the scapula, the subtle inferior angle winging, which may not be clinically perceptible and is hidden by the shifting of the scapula due to the posterior superior angulation deformity, becomes apparent during descent of the humerus. With higher degrees of frustum, the resulting shortening, protraction, and anterior tilt of the scapula shorten the functional excursion of the articular surface at the acromioclavicular joint. The entire vertebral border of the scapula then lifts off the thoracic wall. Scapular winging and dyskinesis are worse when accompanying traction neuropraxia of the long thoracic nerve due to inability of the Serratus anterior to effectively counter the middle component of the Trapezius. Theoretically, the winging angle will be nearly equivalent to the angular shift at the acromioclavicular joint, quantifying the 'mechanical' winging present at rest.

The scapular winging is analogous to the subluxation of the ulnar head in a shortened and angulated radius, or dislocation of the radial head in malunited fractures of the ulna, presenting as a problem of an intercalated twobone system.

Scapular winging may not be clinically apparent if a thick subcutaneous coat is present. It is more alarming in a slim patient with less-developed muscles. The medial fragment, as the apical segment of the cone, is cut off at the frustum from the base of the motion cone (*lateral fragment*), biomechanically isolating the sterno-costoclavicular joint from the acromioclavicular joint. The well-packed regional anatomy at the root of the neck does not allow space-occupying geometrical elements, such as expansion of quadrangular frame and motion triangle of the deformed clavicle with altered kinematics. In a smaller angular malunion, the force couples work hard to prevent and mask the scapular dyskinesis by compensating for the deformity. A significant superior-posterior angular malunion acts as a mechanical block to the rotation and rolling of the clavicle.

Theoretically, however small the movements are at the frustum, they stretch the deep layers of the cervical fascia and clavipectoral fascia along with the intermediate tendon of the [2] Omohyoid muscle, and neurovascular structures related to the posterior and inferior aspects of the clavicle in both supraclavicular and the infraclavicular fossae. The sustained deformation of the fascial layers due to scarring and mechanical block caused by the frustum is responsible for deep-seated ache and neurovascular signs and symptoms originating at the root of the neck during hyperabduction activities. The contracted clavipectoral fascia tugging at the dome of the axillary fascia, caving the axilla deeper, is an unrecognized intermittent cause of symptoms similar to the classical syndrome of thoracic aperture compression. In the early stages of fracture healing, it can only be relieved by correcting the malunion by restoring the anatomy of the clavicle. With the delay in corrective osteotomies, the patients experience residual symptoms because of the soft tissue contractures. The unrectified soft tissue contractures lead to altered tensegrity forces between the structural links and fascial reflections over the neurovascular structures.

15.0 The scapula does not compensate well:

The frustum geometry of the clavicle is not much different from the well-recognized frustum after an angular malunion of the radius in the forearm. The scapula's only advantage over the ulna is its greater freedom to translate over a large, well-conformed thoracic frame and to tilt dorsally and ventrally in the sagittal plane, compensating for [3]*'frustrum',* its hidden dysfunctional kinematics. The compensation reduces scapular dyskinesis, helping put the glenoid fossa successfully under the moving humeral head However, the scapula loses the normal torque advantage of elastic strain energy transfer from the clavicle, as it would typically provide. Secondly, due to reduced posterior tilting of the scapula from its new state of resting anterior tilt caused by protraction, it fails to acquire sufficient elastic strain energy by effectively unfolding the costal concavity. If it does manage to store enough elastic strain energy, it tends to lose a part due to increased interfascial friction and an altered path of motion.

In summary, an angular malunion of the clavicle shortens the chords and deepens the medial and lateral curvatures, forming a frustum. In the presence of a frustum, the scapula fails to reach its maximum kinematic capability, initiating

[2] The intermediate tendon of the Omohyoid is enclosed within the deep cervical fascia, connecting directly to the clavicle, the first rib, and the carotid sheath, containing the Common carotid artery, the Internal jugular vein and the Vagus nerve, affecting venous flow. Proximally, its attachments to the Hyoid bone and Larynx influence swallowing and breathing.

[3] Frustration in motion

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its motion late after the "setting phase," and there is a delay in acquiring and releasing sufficient strain energy. How the scapulohumeral rhythm changes following a malunited clavicle is unknown. High-velocity, respective overhead activities with early fatigue; the scapular drag causes thermal tissue damage, leading to chronic subscapular pain.

Reduced radii of curvature diminish the cranking effect. The mechanical and pitch axii shift anteriorly and inferiorly, depending on the degree of deformity. The altered arcuate path of the acromial end widens the base of the motion cone and transforms the motion geometry. The mechanical block caused by the angular malunion limits the arc of rotation-cum-rolling of the acromial end. The posterior-superior apex of the angular malunion, directed towards the posterior triangle of the neck, does not impinge on the subclavian vessels and the brachial plexus trunks often because most mid-diaphyseal fractures occur in the third-fifth and fourth-fifth of the clavicle, thereby increasing the lateralized focal volume of the infraclavicular fossa. Nonetheless, the apex may overlap the trunks of the brachial plexus as they descend between the anterior and medius Scalene muscles, causing symptoms when the clavicle fully rolls dorsally. The contracted fascial layers of the supraclavicular fossa pull on the contents of the carotid sheath and the apical fascia of the lung, and of the Clavipectoral fascia at the axillary sheath and axillary dome.

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References:

Abbott, L. C., & Lucas, D. B. (1954). The function of the clavicle; its surgical significance. *Annals of Surgery*, *140*(4). https://doi.org/10.1097/00000658-195410000-00014

Burman, M. (1953). Primary torsional fracture of the radius or ulna. *The Journal of Bone and Joint Surgery. American Volume*, *35 A*(3). https://doi.org/10.2106/00004623-195335030-00013

Cronin, J. T., Curtis, K. B., Richards, B. W., Hibbard, J. N., & Skedros, J. G. (2025). Acromion and Clavicle Stress Fractures After Reverse Total Shoulder Arthroplasty Reflect Failure to Address Osteoporosis: A Case Report and Literature Review. *Cureus*, *17*(3). https://doi.org/10.7759/cureus.79993

Edelson, J. G. (2003). The bony anatomy of clavicular malunions. *Journal of Shoulder and Elbow Surgery*, *12*(2). https://doi.org/10.1067/mse.2003.2

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

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

Kim, E., Jang, T., Park, H. J., Ikemoto, S., Murase, T., Sugamoto, K., & Hong, S. W. (2020). In vivo threedimensional scapular kinematic alterations after reverse total shoulder arthroplasty. *Journal of Orthopaedic Surgery*, *28*(2). https://doi.org/10.1177/2309499020921979

Lambert, S. M. (2016). Shoulder Girdle and arm. In S. Standring & R. Birch (Eds.), *Gray's Anatomy: The Anatomical Basis of Clinical Practice* (41st ed., pp. 797–836). Elsevier.

Maquet, P. (1992). Iatrophysics to biomechanics. From Borelli (1608-1679) to Pauwels (1885-1980). *The Journal of Bone and Joint Surgery. British Volume. 74-B(3), 335-339.* https://doi.org/10.1302/0301620X.74B3.1587872

Murray, D. W., Wilson-MacDonald, J., Morscher, E., Rahn, B. A., & Käslin, M. (1996). Bone Growth AND Remodelling After Fracture. *The Journal of Bone and Joint Surgery. British Volume*, *78-B*(1), 42–50. https://doi.org/10.1302/0301-620X.78B1.0780042

Naik, P. (2021). Remodelling in Children's Fractures and Limits of Acceptability. *Indian Journal of Orthopaedics*, *55*(3), 549–559. https://doi.org/10.1007/s43465-020-00320-2

Nordin, M., & Frankel, V. (1989). Biomechanics of the Knee. In M. Nordin & H. V. Frankel (Eds.), *Basic Biomechanics of the Musculoskeletal System* (2nd ed., pp. 115–134). Lea & Febiger.

Reuleaux, F. (1876). *The Kinematics of Machinery: Outlines of a Theory of Machines* (A. R. W. Kennedy, Ed.; Ed). MacMillan And Co.

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Schneider, B. S., Hao, K. A., Taylor, J. K., Wright, J. O., Wright, T. W., Pazik, M., Schoch, B. S., & King, J. J. (2024). Influence of acromioclavicular joint arthritis on outcomes after reverse total shoulder. *JSES International*, *8*(1), 111–118. https://doi.org/10.1016/j.jseint.2023.08.014

Shapiro, F. (1981). Fractures of the Femoral Shaft in Children: *The Overgrowth Phenomenon*. *Acta Orthopaedica Scandinavica*, *52*(6), 649–655. https://doi.org/10.3109/17453678108992162

Twin Arc Legacy Life, P. -411033, I. (2025, July 25). Studying Moth Flight Dynamics with Particle Image Velocimetry (PIV) Analysis.Ix-Cameras.com

Yoo, H. & Milhaila, D. (2022, November 7). *Neuroanatomy, Vestibular Pathways.* StatPearls [Internet]. Treasure Island (Fl): StatPearls Publishing; 2025.

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

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