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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 7: Biomechanical architecture and the Cranking system of the Clavicle

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Highlights: The anatomy of the clavicle and pectoral girdle evolved for flying, brachiation and overhead projectile delivery. To attain these functions, the clavicle acquires the *'claviform'* architecture beginning in the embryo through foetus to maturity in adulthood.

The engineering design of the clavicle and its functional form is like an aeroplane propeller, or a propeller mimics the clavicle. The less recognized features of the clavicle include variable torsion, version, and screw twist with a differential screw pitch. The strength, power generation, and energy storage are enabled by its hyperbolic paraboloid architecture, making the clavicle a precision, force-generating cranking system.

The various curves and screw motion augment muscle force to lift, throw and accelerate a projectile. The mechanical properties of a hyperbolic paraboloid clavicle confer greater strength due to the optimal ratio of its longitudinal curves, which react to tension and compression simultaneously, thereby distributing loads more evenly along its length.

Graphic abstract:

Keywords: Clavicle fracture, Clavicle malunion, Crank, Hyperbolic paraboloid, Biomechanics, Architecture, Projectile delivery

1.0 Redesigning the biomechanical architecture of the clavicle to repurpose the glenohumeral articulation:

Phylogenesis and ontogenesis have enabled the elevation of the arm possible by freeing the forelimbs from cursorial and fossorial functions. This has allowed the unique, evolving mechanism of the shoulder complex for abduction and circumduction of the upper limb in the parasagittal plane. Although in birds and insects the wings serve entirely different purpose, kinematically they are only marginally different from the upper extremities of the arboreal primates and Homo sapiens.

The anatomy of the pectoral girdle and forelimbs evolved for flight in birds and for high-speed mobility and brachiation in terrestrial quadrupedal primates. Among Homo erectus, throwing a high-speed projectile to kill for food and, more recently, among humans for overhead lifting and projectile delivery for athletic purposes. To perform these essential high-speed functions of mobility, survival, and pleasure-seeking activities against air resistance, the evolving animal needed a new skeletal element in the postcranial forelimb— a well-optimised skeletal linkage between the axial and the appendicular skeleton, the clavicle. In the aclaviculate, the existing well-developed scapula, forming the scapulothoracic synsarcosis, already had the advantage of sliding over a large thoracic framework formed by the extensions of the central axial column, the ribs. Ribs were introduced to facilitate lateral swimming motions in limbless fish and, in claviculate lizards, to improve mobility and breathing on the ground. The scapulothoracic synsarcosis already had powerful musculature for advanced scapulothoracic kinematics and kinetics, enabling the repurposing of the pectoral girdle.

The birds evolved a one-piece skeletal element with spring mechanism, the furcula, or "wishbone," of varying morphology between the scapulae to store energy during flight. Phylogenetically, it behaved as fused clavicles in the midline(Kardong, 2002; McGonnell, 2001). The need for quadrupedal primates to run fast on the ground, brachiate, and swing in all directions through the trees redesigned the furcula anatomy into articulating bilateral clavicles intercalated between the manubrium and the scapulae. At the same time, there was a gradual change in the thoracic cage configuration from its greater median plane (*mid-sagittal*) diameter to the increment of coronal plane side-to-side diameter shifting the scapula on the dorsolateral aspect of the thorax(O'Brien et al., 2009). The pectoral girdle, surrounding the upper thoracic ribcage like a belt, helped distribute forces across the midline, balancing the right- and left-side kinematics during progressive bipedal gait, and dampen compressive forces for high-velocity projectile delivery.

From primates to Homo erectus and Homo sapiens, the clavicle has been progressively redesigned to repurpose the functions of the glenohumeral articulation, with modification of its biomechanical architecture by altering curves and twists, to reposition the scapula for parasagittal and overhead movements. In humans, the signs of transformation and repurposing of the entire pectoral girdle and thoracic cage in cursorial, fossorial and brachiating primates are still visible during the growing years. Notably, subtle variations in the anatomy and its biomechanical architecture support crawling in babies and the digging and brachiating play of the juveniles. There is a rapid, broadening of the shoulders during early adolescence, distinct from that in primates.

Numerous morphometric, anatomical, biomechanical and radiological studies corroborate the structural development of the clavicle until maturity. This part of the study examines how variations in the redesigned curves and twists of the clavicle increase the mechanical advantage, amplify kinematics and kinetics, maximise the range of scapulothoracic synsarcosis, and increase the speed, and efficiency, thereby generating power at the glenohumeral articulation to perform simple and complex activities.

2.0 Recapitulating the embryogenesis and development of the clavicle:

The clavicle is the first bone apart from the mandible to appear in the sixth embryonic week, reaching full maturity at any time between the ages of 24 and 31 years(Singh & Chavali, 2011; Webb & Suchey, 1985). Developmentally, the clavicle retains the *'claviform'* architecture from the embryo through the foetus to adulthood. Much of the anatomy of its curves and twists is conserved throughout life, with observable variations in terms of its length proportional to the height of an individual, variations in the external diameters along its length, depth of its medial and lateral curvatures, torsional and version angles, etc., leading to bidirectional asymmetry in many studied cohorts **(for details see Part 2 of the series).** The gender and handedness differences follow biomechanical forces arising from individually acquired functions rather than geographical and racial differences that reach morphometric significance.

3.0 More than simply an S-shaped, sigmoid or a *f* musical key:

Anatomically, the clavicle's gross appearance and surface features are standard among all human beings. The clavicle does not have the shape of an S, Greek sigma ζ, or the appearance of the musical key *f*. The clavicle has little resemblance to any of these; is uniquely claviform or clavate, from the Latin *clava* meaning club, something with the thicker end uppermost. The uppermost refers to the proximal club-shaped prismoid sternal end. Technically, considering the engineering design of the clavicle bone, its functional form is closer to an aeroplane propeller, having a shank with a broad circular cross- section at its fixed end, changing from oval-shaped cross-sections of its shaft to a flat apex (**Fig. 1**). The propeller blade has an optimised angle of torsion and screw pitch, with the twist changing direction approaching the apex. Recent developments in the design of the propeller are not very different from the clavicle, such as the ability to change the pitch angle of the blade during flight, depending on the type of aeroplane and its purpose, as the clavicle by rotating in the clavicular fossa of the manubrium sterni at the sternoclavicular joint. Variations in the design of individual clavicle anatomies are noteworthy differences in their biomechanical architecture.

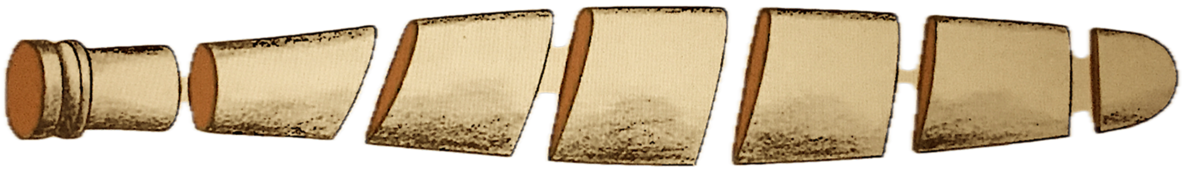

Figure 1. An airplane propeller

4.0 Trabecular and bone density distribution:

The clavicle, a clavate-shaped tubular bone, exhibits variable cortical thickness. The intracortical space contains optimally distributed trabeculae throughout its medulla in the form of plates and pillars(Shah & Routal, 2015). Cortical thickness ranges from 1.3 to 3.0 mm, with minima at the sternal and acromial ends, where trabecular density is higher, and maxima in the third- and fourth-fifth sections of the diaphysis from the sternal end. A short, rudimentary medullary canal is present in the middle section, in some cases.

Cortical thickness, like trabecular distribution, is optimised around the circumference of the bone at various sites based on the bone growth principles of Wolff's law, Heuter-Volkmann's law and the piezoelectric effect on the bone, with accretion and erosion of bone material under the impact of biomechanical forces. The broad quadrangular prismatic sternal end with thin cortices, the oval to circular cross-section at its second-, third- and fourth-fifth diaphyseal sections with thicker cortices, and the craniocaudally flattened acromial end with an elliptical or rectangular cross-section have extremely variable, moderately distributed density(Harrington et al., 1993; King et al., 2014; Walters et al., 2010).

5.0 Recapitulating surface anatomy, curvatures and twists of the clavicle:

The clavicle is not a simple weight-bearing bone like a rod **(Fig. 2)**. It is a specially designed axle, incorporated into the shoulder complexes on either side of the vertebral column, for the transmission of movements and forces. The most salient features of the clavicle are medial and lateral curvature, with the inferior curvatures concentrated laterally, the latter being orthogonal to the former two. The less recognised yet biomechanically important feature is variable torsion along its diaphysis. The screw twist, with a differential screw pitch and angle of version between sternal and the acromial ends, occurs around the clavicle's longitudinal screw axis. The medial curvature is convex anteriorly, and the lateral curvature has an opposing convexity facing posteriorly. Among these angular features, the medial and lateral curvatures have been well studied and reported in

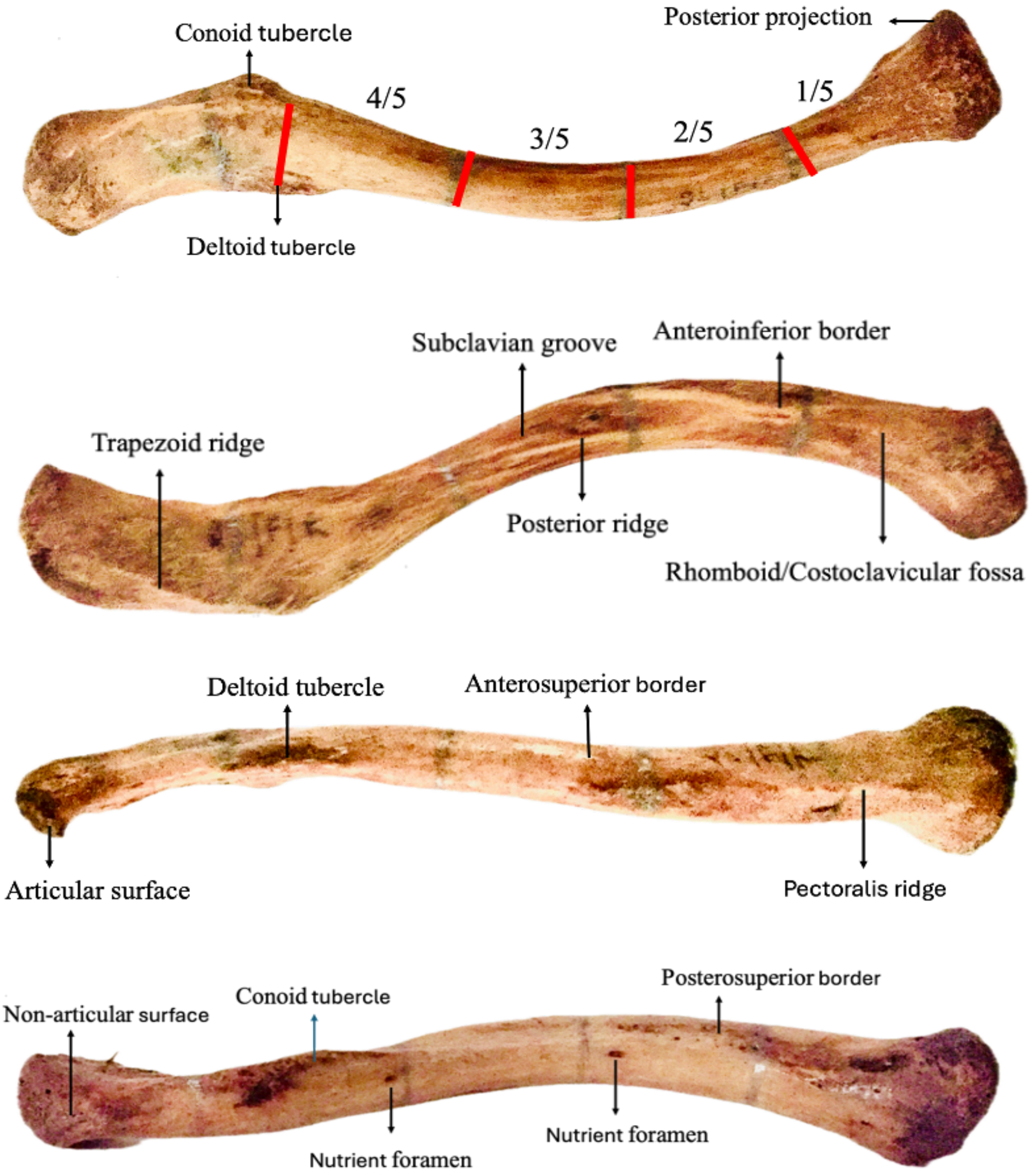

Figure 2. Superior, Inferior, anterior and posterior views of the clavicle.

anthropological, human anatomical, and radiological imaging literature. However, there is a lack of measurements evaluating diaphyseal sectional torsion angle, screw twist, screw pitch and angle of version.

The effects of variations in these parameters on the biomechanical function of scapulothoracic and glenohumeral kinematics to generate and conserve energy, are unreported. These angular variations likely play a significant role in transmitting motion and kinetic chain ground reaction forces across the sterno-costoclavicular and acromioclavicular joints, and scapulothoracic and acromiohumeral synsarcoses to the upper extremities during a throw. It is difficult to assess how well the version angle at the acromial end of the clavicle matches the described torsion angle of the acromion, as only limited information is available(Zenker et al., 2022). No reported biomechanical studies have measured torque transmission from the clavicle to the scapula during arm elevation in both normal and malunited clavicle.

The surface anatomy and angular features of the clavicle are highly variable. The sternal end's one-fifth, acting as the shank of the clavicle, is broad and prismoid in shape. The middle three of the five sections are oval to circular, and the acromial fifth is ellipsoid to rectangular. The cross-sectional anatomy varies, with the superior, anterior, inferior, and posterior surfaces poorly defined by variably marked borders due to the biplanar curves and twists (**Fig. 2**).

5.1 Borders and surfaces:

The superior surface is separated from the posterior surface by a posterosuperior rounded border that begins at the sternal end and merges with the posterior surface of the lateral curve at the conoid tubercle. No distinct border separates the superior surface from the anterior surface, except for the pectoralis ridge in the metaphyseal region of the sternal ends' one-fifth section, which extends to form a poorly defined, rounded anterosuperior border ending at the superior border of the lateral fifth past deltoid tubercle. The anteroinferior rounded border, skirting the rhomboid or costoclavicular fossa anteriorly, separates the anterior and inferior surfaces, becomes sharper laterally, and continues as the inferior border of the lateral fourth-fifth and the terminal fifth of the lateral curve. The posterior-inferior border, starting at the posterior-inferior projection of the sternal end, skirting the rhomboid fossa posteriorly as a ridge forming the posterior border of the subclavian groove, continues into the conoid tubercle and the trapezoid ridge, separating the inferior surface from the posterior surface. The inferior surface has the rhomboid fossa in the medial one-fifth, and the middle three of the five sections are occupied mainly by the subclavian groove. The smooth posterior surface remains broader up to the conoid tubercle and narrows laterally towards the acromial end **(Fig.2)**.

The markings on the superior, anterior and inferior surfaces show significant variation depending on manual and leisure activities. There is a definite nutrient foramen on the posterior surface and another on the inferior surface. The subclavian groove on the inferior surface, for the insertion of the Subclavius, extends from the middle of the medial curvature to the inferior surface of the lateral curvature. The inferior surface medially has a raised area, or a fossa called the rhomboid fossa, for the attachment of the costoclavicular ligament. The muscle attachments cover three sides of the clavicle, except for the central third-fifth and the posterior surface. From the medial to the lateral end are subtle to easily recognisable footprints of Sternohyoid, Sternocleidomastoid, Cleidobrachialis pectoralis, Subclavius, Occipitocleidal trapezius and Cleidobrachialis deltoideus. The Platysma drapes over all these muscles when present.

5.2 Curvatures and twists:

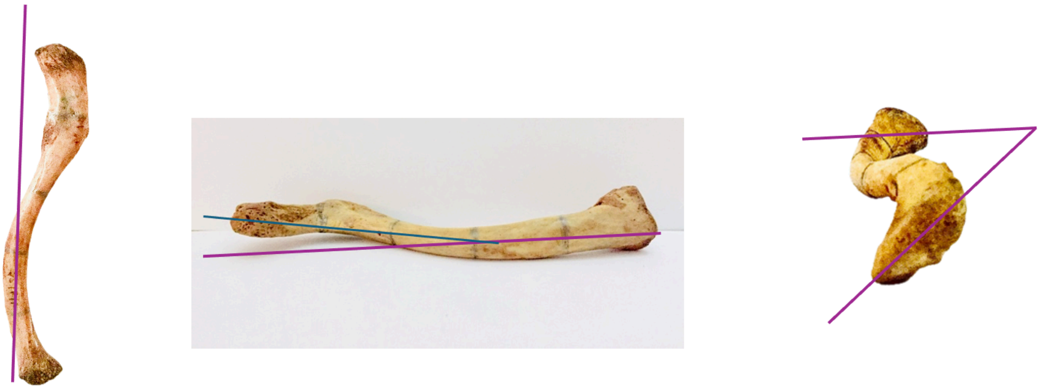

Figure 3. The disarticulated right clavicle shows the lateral curve offset to the medial curve, inclination angle, and the version angle at the acromial end (created in the PowerPoint by the author).

The longer medial curvature has a greater chord length and a longer radius of curvature than the shorter and deeper lateral curvature. The lateral curvature is offset from the medial curvature, a feature more readily apparent when a disarticulated clavicle is stood vertically (**Fig. 3**). When laid on its superior surface, the acromial one-fifth and fourth-fifth do not always lie in the same plane as the rest of the clavicle, forming an inclination angle, in addition to the laterally concentrated inferior curvature. At the same time, when seen end-on, there is a notable version angle at the acromial end relative to the transverse plane passing through the centroid of the sternal articular surface.

The changing torsion angle and the overlying screw twist can be palpated between the second-fifth and fourth-fifth sections of the diaphyseal surface using the discerning finger pulps, and the direction of the twist changes as the medial curvature continues into the lateral curvature. The screw twist extends between the sternal and the acromial ends, roughly following the anteroinferior and the posterosuperior borders, with a long pitch spiralling the anterior surface of the medial curvature to the superior surface, and then a shorter pitch spiralling the posterior and inferior surfaces of the lateral curvature towards the acromial end articular surface. Looking from the acromial end, in a left clavicle, it is a right-handed screw twist. The changing torsion angle begins at the metaphysis, between the anteroinferior and the posterosuperior borders, which form the most palpable boundary features enclosing the anterior and the superior surfaces, and it carries a measurable torsion angle along the diaphysis **(for details see Part 2 of the series).** The point where the torsion changes from the anterior to the superior surface is the site of change in the pitch of the screw twist. The spiral course of the screw twist is akin to the thread of a machine screw. As the spiral changes its surface at the inflexion zone, the longer proximal and the shorter distal pitches of the spiralling twist become tighter around the lateral curvature, forming the version angle. This makes the clavicle a differential screw system. The longitudinal axis of the clavicle, around which the torsion and the substance of the clavicle form the screw twist, is the screw axis.

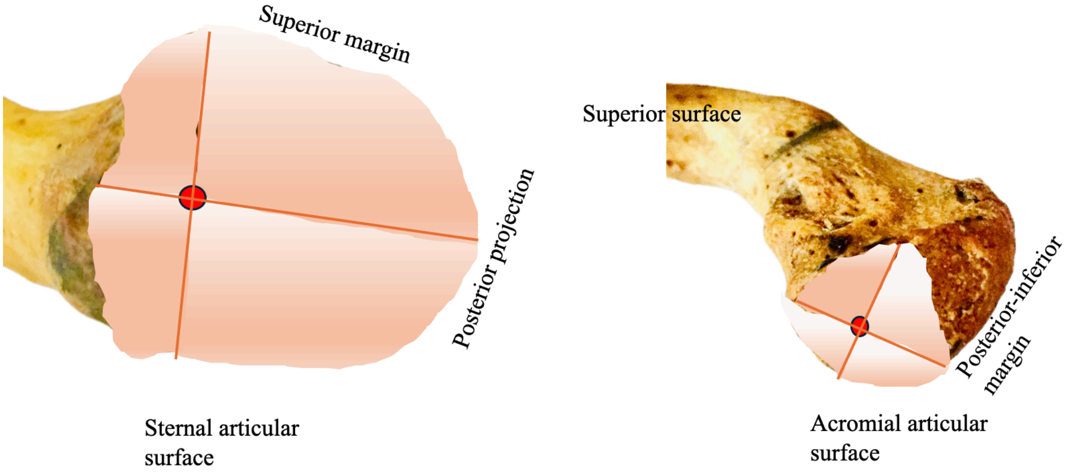

Figure 4. The centroids are shown as red dots on the sternal and acromial articular surfaces, where the two maximum orthogonal diameters intersect (created in PowerPoint by the author).

Unlike other long bones, the centroid of the sternal articular surface does not align with a straight horizontal line to that of the centroid of the articular surface at the acromial end due to the curvatures and the offset (**Fig. 4**), The screw axis follows the centreline anatomic axis, spiralling around it, and extends between the two eccentrically placed centroids, creating an advancing screw motion. The mechanical axis does not pass through the diaphyseal centre of the medial and lateral curvatures because of the offset and the inclination angle due to the inferior curvature. A para-axial virtual line passing from the centroid of the sternal end through the mid-medullary plane (*centreline*) of the medial curvature is the pitch axis. The offset and other angular features are better appreciated in the profile of a disarticulated clavicle (**Fig. 3**). It is difficult to discern the angular features on the anterior-posterior and oblique false axial radiographic images of an articulated clavicle, even less so following a fracture of the clavicle, for immediate 3D reconstruction in one's brain.

The clavicle rolls around the pitch axis by simultaneously elevating and retracting dorsally, with axial rotation around its straight mechanical axis, between the two centroids at the articular surfaces **(for details see part 2 of the series).**

6.0 Similarities of the clavicle to an aeroplane propeller:

As the biomechanical architecture of the clavicle is analogous to the basic design of the aeroplane propeller, which enables a plane fly against air resistance in all weather conditions, it is an excellent aeronautical engineering device to model for the clavicle's biomechanics. The clavicle has evolved and been redesigned to deliver a handheld projectile to attain a high-velocity in both favourable and unfavourable airflow conditions, through an entirely different kinematic mechanism operating within the viscoelastic tissue medium. The propeller's primary role is to convert the torque generated by the engine into a linear force that propels the fuselage of an aeroplane forward against air resistance. The twist at the tip of a propeller blade advances faster than the centre of the propeller, compensating for the speed difference between the shank and the apex, producing forward thrust(Kramer, 2022).

As the propeller moves through layers of air, it produces force, just like a wing of a bird or an insect, and so does the arm. The arm acts against gravity while lifting the weight of a projectile overhead to produce thrust *(forward force),* counteracting drag *(rearward force)*. Like a propeller, the clavicle is not a true airfoil, as the arm provides the forward movement. Still, as a significant component of the transmission system, the clavicle, because of its similar mechanics, gathers thrust at the root of the shoulder complex. The remaining transmission system comprises the acromioclavicular joint, the scapulothoracic and acromiohumeral synsarcoses. The viscous synsarcoses generate additional force and smooth the delivery like a door closer. The force generated by the clavicle begins at the sternoclavicular joint, where the clavicle is fixed by the broad-based sternal end, like the propeller's broad shank to the engine at the hub. The aeroplane propeller has two blades akin to the bilateral clavicles forming the front of the bilaterally represented well-balanced pectoral girdle, if viewed through this analogy!

Like the propeller, the torque and rotational speed transmitted through the substance of the clavicle are not the same along its length. They vary according to the cross-sectional diameter and outline, the trabecular arrangement, the changing torsional angle along the diaphysis, the differential screw pitch, and the version angle at its acromial end. With an in-built differential screw twist pitch within the substance of the clavicle, the acromial end of the clavicle travels faster, thrusting against the acromion and transmitting the forces along it to the scapula. To prevent excessive direct compression, the articular surface of the clavicle at the acromioclavicular joint is placed eccentrically with variable configurations and variable version angles between the acromion and plane of the scapular blade. How the varying torsion angle of the clavicle, version at the acromial end, and the acromial facet relate to torsion of the acromion is unclear. During the growing years, angular parameters of the clavicle are optimised in terms of weight, length, cross-sectional anatomy, cortical thickness, density, distribution of type and number of trabeculae, radii of curvatures of the medial and lateral curves, etc., to match individual physical demands.

Individual segmental variation in the angle of torsion, screw twist, and pitch likely account for the force generated during the delivery of a projectile in hand. The Wright brothers introduced the concept of a propeller twist. The scimitar curve near the apex, akin to the inclination angle (*inferior curve*) at the acromial one-fifth, was introduced much later to improve performance and reduce the noise produced by the propeller. Aerodynamic characteristics, such as cross-sectional chord length and twist at several stations along the blade, define the shape of a propeller blade. Due to the biomechanical forces, the clavicle develops variable cross-sectional shapes at various biomechanical stations. These features influence its biomechanical energy-storing function during screw motion, and ventral-to-dorsal rotation and roll.

Change in its end-to-end length due to bending and in screw twist may be insignificant to be recognised clinically. They can be measured ex-vivo by placing strain gauges at strategic points on the clavicle. These changes are elemental for storing elastic strain to return the clavicle to its resting state, while being assisted by the muscles at a low energy expense. As a three-dimensional body, it undergoes screw motion and torsional deflection, so some parts of the curves and twists wrap around the screw axis more than others.

During arm elevation, the simultaneous elevation and dorsal retraction of the clavicle, together with axial rotation, the roll and translation at the sterno-costoclavicular articulation, causes the longitudinal mechanical axis and the screw axis to move further away from the pitch axis. Theoretically, although the axii follow one another, the pitch axis diverges with elevation and retraction of the acromial end accompanying axial rotation from the transverse plane toward the coronal plane, due to the offset between the major curves and the inclination angle. However small it may be, this shift in the pitch axis changes the length of the lever arm at all cross-sections, at both the lateral and the inferior curvatures, gathering mechanical advantage with lesser force.

Figure 5. Cross sections of the clavicle showing the shift in the direction of the chord lines. The holes are left over after the removal of an intramedullary implant (created in PowerPoint by the author).

The chord line subtending at each cross-section is defined from the posterosuperior border to the anteroinferior border or, based on the shape along the screw or anatomic axii is the line at the maximum diameter of the cross-section (**Fig. 5**). The chord length is equal to the length of the subtended line at the maximum diameter of an oval or an ellipse. The midpoint of the cross-sectional chord line is not the exact centre of the medulla at all biomechanical stations(Aira et al., 2017). If there is no significant offset at a particular cross-section normally or due to a structural defect in the clavicle's shape, then the pitch axis of the biomechanical station will lie perpendicular to its chord line. The 'influence' length of a biomechanical station is the length between the midpoints of the two adjacent stations. The influence length of each biomechanical station as a finite part of the effective length and the finite size of the biomechanical station together complete the biomechanical architectural design of the clavicle's torsion, screw twist and its pitch, medial, lateral and inferior curvatures and angle of version of a clavicle. The midpoint of each station is measured from the centroid of the sternal end articular surface. Each station will have a specified chord length for its cross-section, torsion angle, curvature and the influence length depending on how the biomechanical stations formed along the diaphysis.

Some geometrical characteristics of the clavicle are in-plane or out-of-plane movements at the sterno-costoclavicular joint. As mentioned above, contained within the substance of the clavicle, the screw axis follows the centreline, passing through the curves and twists, which may not coincide with the centre points of every biomechanical station, and is in-plane, upon which the clavicle rotates like a machine screw. This is not to be confused with the rolling motion around the pitch axis of the clavicle arising at the centroid of the sternal articular surface along a line drawn horizontally extending laterally. The pitch axis passes through the centre of the diaphyseal segment of the medial curvature but never through the lateral curvature because of the offset.

The pitch axis deflects out-of-plane. Unlike the screw axis, which is stable and fixed, the pitch axis moves with the position of the clavicle relative to the transverse, axial and coronal planes as it translates, rotates and rolls at the sternoclavicular joint. The acromial end rotates approximately 8-10 degrees caudally (*inferiorly*) and from its resting position 45-55 degrees cranially and dorsally. Thus, the clavicle makes a total arc of 55-65 degrees as it elevates and retracts with arm elevation in the coronal plane. The bending and tensile moments of the clavicle are also affected during elevation and retraction of the clavicle at the medial curvature. As the values of bending and tensile moments are not known, the out-of-plane pitch axis during rotation of the clavicle would be predictably negligible. However, unlike the fixed pitch axis of a propeller held rigidly at the hub, the clavicle is not rigidly fixed at the manubrium but has at least three degrees of freedom. Therefore, the clavicle can change its pitch and pitch axis angle to the constant longitudinal screw axis, making it a dynamic structure. The pitch actuators shift the pitch in the aeroplane propellers and turbine engine blades.

In a particular plane, the clavicle pitches around the pitch axis relative to the median plane of the body, which is characteristic of a person-specific clavicle. Therefore, there are as many pitch axii as clavicles, and bidirectional asymmetry will mostly be related to the medial curvature variations. The pitch axis is at a right angle to the chord of each biomechanical station cross-section and to the centroid at the sternal articular surface. And if it is true for every biomechanical station due to the existence of torsion and screw twist, curves and offset parameters, then the pitch axis is dynamic. The screw twist axis and pitch axis would follow the biomechanical architecture and anatomical variations of each clavicle. During rapid rotation and rolling motion of the clavicle, the azimuth angle (*assumed zero degree at the body's plane and axii, the angular distance relative to the cardinal planes*) will change with a change in the position of the shank at the sternoclavicular joint and, with it, the shaft of the clavicle.

At the nano- and microstructure level, the bone substance of the clavicle is not in a continuum, and the collagen fibres embedded in the mineral composite are arranged at varying angles to the longitudinal screw axis of the clavicle. Therefore, the torsion angle of collagen bundles at each cross-section of biomechanical stations would vary at various distances along the length of a clavicle. The collagen bundles follow a spiral path from one end of the bone to the other, depending on biomechanical forces acting on them. More importantly, the chirality of collagen is conserved genetically and ontogenetically with handedness. Therefore, the angle of torsion and, for the same reason, screw twist and screw pitch and angle of version would be unique individual characteristics.

6.1 In-built chirality in the substance of the clavicle:

Conventionally, the positive direction is clockwise when the bone is viewed along its longitudinal axis from relatively mobile free end towards the root or fixed end. The hands are mirroring image of each other. The right-hand palm cannot be superimposed on the dorsum of the left hand with thumbs in the same direction because of the chirality. Chirality (*Gk Chiral meaning hand*) refers to the right- and left-hand spiral arrangement of collagen, forming mirror image of each other, as are the right and left clavicles and the two opposing blades of a propeller. The reason right and left forearm supination and pronation occur in the opposite direction. This directional chirality is genetically determined and conserved in most human beings, with dominant righthandedness, and right-handed screw turning ability, leading to development of the screw design.

The direction of screw twist and torsion of the clavicle travels from the medial to the lateral end and from anterior to the posterior direction, passing over its superior surface. When viewed from the acromial end, it is counterclockwise on the right side and clockwise on the left and is opposite when viewed from the sternal end, as from head end of a screw. A twist is created by turning the ends of a rod or a tube in the opposite direction.

With cranial rotation around the screw axis, the twist tightens at the free mobile end relative to the fixed end under the applied torque, accumulating elastic strain energy. With the arm abducted at 90 degrees, the chirality of the humerus and the retroversion of its head align with the chirality of the ipsilateral clavicle. The screw home movement with the arm at 90 degrees of abduction is continuous along the entire length of the upper extremity. The right-handed movement (*volar surface up*) at the hand is supination, which is the rolling movement— cranial elevation, posterior retraction and dorsal axial rotation of the clavicle.

The two blades of a simple propeller meet at a central hub attached to the crankshaft of the aircraft engine, and the engine's power rotates the propeller, driving the fuselage forward, which flies smoothly because of its aerofoil shape. To generate thrust *(forward moving force)*, the blade must be at a certain angle relative to the plane of rotation, and the blade angle must vary along the length of the blade, from the shank to the tip. This necessary variation in the blade angle along its length helps the propeller to advance forward by creating a screw motion. Consequently, a point on any blade section follows a spiral path through the air. A point on a section near the blade's tip traces a larger spiral. A point on a section midway along the blade traces a smaller spiral, while a point on a section near the shank of the blade will trace the smallest spiral. For a propeller blade to trace the spiral path at each section most effectively, each airfoil element is so designed and constructed that their angles become gradually less toward the tip of the blade and greater toward the shank. This gradual change of the blade element angles is called pitch distribution, which is one of the most fundamental factors in the blade design and the one responsible for the characteristic "twist" of the propeller blade, which is not much different from the torsion in the diaphysis and version at the acromial end of the clavicle.

Equally crucial in blade design is understanding the stresses produced within the rotating propeller by the forces acting on it. A whirling weight at the end of a string pulls the weight outward by the centrifugal force— the whirling motion of the propeller results in the blade's tendency to leave the hub. The blades with pitch actuators tend to rotate towards the low blade angle in their sockets, restoring equilibrium as the wind moves rearward, pushing the fuselage forward.

Considering the forces acting on the blade, the stresses increase toward the shank; therefore, progressively stronger blade sections are required from the apex to the shank. Each blade section should have the adequate structural strength and include suitable load-bearing features to withstand the applied forces. Tapering and shaping of the blade away from its circular shank is necessary to avoid stress concentrations. The cylindrical shank provides strength, while the gradual thinning towards the apex is more about blade efficiency. For this reason, the outermost portion of the blade must be as thin as possible yet sturdy enough towards the shank to withstand the increasing stresses acting upon it. The torsion angle should increase gradually from the tip to the shank so that each blade section will follow a spiral path at the most effective angle. The forces acting on the blade have a marked effect on the design; thus, newly designed propellers have blades that can rotate in their sockets to different positions, permitting a change in blade angle and the absorption of engine power. The blades can be automatically turned in their hub sockets to the best angles for all conditions the plane might encounter in flight.

All the foregoing mechanical and functional features of an aeroplane propeller can be appreciated in the clavicle as an efficient cranking system when lifting heavy weights overhead and during projectile delivery, powered by several pectoral girdle muscles.

7.0 Scapula the fuselage of the shoulder complex:

The stability and control of the scapular movements are much more complex when the scapula is at rest, getting ready for the "setting phase", and during movements at the scapulohumeral articulation. The force generated by the force couples must be precise at all the linkages and joints engaged in elevating the arm. As the scapula is at the forefront, directly articulating with the humerus at the glenoid fossa, it must move precisely and be propelled freely by the clavicle in three dimensions around three imaginary axii. The three axii run at right angles to one another and intersect at the centre of gravity of the scapula. These axii may not lie in the same planes as the three axii of the body, because the scapula is not parallel to any of those planes. At rest, the scapula is at an azimuth angle of 30 degrees to the zero-degree coronal plane. Because it is intimately articulated with the clavicle, its axii have a conjunctive relationship with those of the clavicle and humerus as it slides over the thoracic cage. If the clavicle is an aeroplane propeller, the scapula is the 'fuselage', and the humerus is the rider at the glenoid fossa, as the cabin seat.

The scapula moving around three imaginary axii is no different from the movements of a fuselage in three planes. The rotation of the scapular blade, with the inferior angle turning laterally around the horizontal axis from front to back, is 'yaw'. The anterior and posterior tilting of the scapula away from and towards the thoracic wall around the side-to-side axis, is 'pitch'. The protraction and retraction of the scapula, gliding around the convexity of the thoracic wall, with or without swivelling, which is side-to-side tilting around the vertical axis, is equivalent to the 'roll' of a fuselage. These three-dimensional movements are co-ordinated, occurring simultaneously with the clavicle, such that the humerus is always seated optimally on the glenoid fossa to attain a full range of motion smoothly for the task in hand and reach the destination point. As the clavicle is the linkage rooted at the manubrium and in train with the scapula, its normal architecture and function provide the required stability and force to the scapula keeping the humerus in flight during its elevation. Ultimately, the central and peripheral nervous systems control the synchrony of the linkages and joints of the pectoral girdle system, including the first rib, which uniquely articulates with the first thoracic vertebra. The key components at the periphery are the accessory cranial nerve and the brachial plexus, which innervate the postcranial pectoral girdle articulations and the musculature.

8.0 Neither a strut, derrick, nor a rod, its clavicle:

The clavicle is a precision component of the pectoral girdle mechanism. It is neither a simple strut, a rod, a derrick, nor a beam of a suspension bridge spanning the axial and appendicular skeleton, nor an axle intercalated between the sternoclavicular and the acromioclavicular joints. It acts as one or the other during arm elevation, depending on the work done at the glenohumeral joint.

A strut is a rigid link intercalated within a mechanism that supports and resists compressive forces. It is a structural component that resists longitudinal compression across engineering, anatomical, aerospace, and the automotive applications. In engineering and architecture, a strut is a slender, rigid member that resists compressive forces in bridges, buildings, and aircraft. In human anatomy, a strut can refer to a ligament or a thick fibrous connective tissue band, such as the iliotibial tract, that provides support and stability to joints. In aerospace engineering, a strut is an essential component of a landing gear in an aircraft that absorb shock and supports the weight of an aircraft. In the automotive industry, in cars and heavy goods vehicles, struts are central to the suspension system, combining shock absorber and coil spring to support the vehicle's weight.

A derrick is a simple crane with at least one guyed mast and a lifting tackle suspended from a boom. Frequently, a framework is erected over an oil well to raise drilling tubes. The word originates from Derrick, the name of a celebrated hangman at Tyburn, England. In this sense, it is a device for operating gallows or a crossbeam to lower the weight of an object.

In engineering, a rod is a straight, slender, cylindrical component used in various mechanical systems. It transmits forces or motion from one point to another, provides structural support and stability to mechanisms and assemblies, and guides the motion of the moving parts, such as pistons, along a linear path. Common types of rods in engineering include connecting rods and linking rods, which connect pistons to crankshafts. In engines, hydraulic or pneumatic systems rods connect pistons to cylinders. Tie rods are used in structures such as bridges and buildings to provide support and stability. Linear motion rods guide components in linear motion systems. Fundamentally, a rod in engineering is a component that enables the transmission of forces and motion and provides support in various mechanical systems.

A fishing rod is a flexible structure designed to absorb sudden jolts when a fish struggles, reducing the risk of fracture. It stores energy in its flexible material, which is released and played on the fish when pulled and swung out, helping to fight the fish. Its flexibility provides sensitivity and detectability. It also generates speed and distance when throwing the hook farther, like a projectile, allowing for more accurate, longer casts. A flexible rod reduces the strain on the angler's arms and shoulders, making fishing more comfortable and less tiring, so it is energy-efficient and cost-effective. The composition of graphite and fibreglass offers strength, durability and flexibility to a fishing rod.

The intercalated clavicle plays a vital role as an axle, with constant velocity joints at the sterno-costoclavicular and the acromioclavicular joints, subdivided by the intraarticular discs into two compartments in each, like an automobile constant velocity axle transmitting torque to the wheels. A constant velocity joint is made up of multiple joints – three or more. The clavicle, as a constant velocity axle, is a critical component of the pectoral girdle for power transmission, carrying weight in the hand, spacing the manubrium and the scapula at an optimal distance from the median plane, away from the pelvis and maintaining alignment of the scapula for stability of the glenohumeral joint, which is suspended from the Occipitocleidal trapezius, Levator scapulae and Rhomboids. The reciprocal motion of the clavicle's ends between the sterno-costoclavicular and acromioclavicular joints provides a differential turning mechanism for accelerating a high-velocity projectile in athletics and repetitive movements without jamming.

Combining minerals with a specific helical arrangement of collagen fibres between osteons in bone provides strength, durability and the flexibility to store strain energy. Most importantly, the architecture of each bone as a link in the locomotive system assigns a specialised function relative to the adjacent link at the joint. During its evolution and development, redesigning and optimising a repurposed link in each species within its genus fits topographically within the available space, with minimum weight and maximum strength, for superior biomechanical function, generating force and carrying load with minimal energy. The well-designed clavicle meets these optimisation requirements.

The described design factors explain how the clavicle of humans acquired its current claviform shape, a structure analogous to an aeroplane propeller in many respects. To minimise weight, it has a tubular structure fitted with a trabecular network, an optimal ratio of medial and lateral curvature radii and chord lengths, and an inferior curvature forming its scimitar apex, as seen in the majority, with variations mainly concentrated at the inflexion between the medial and lateral curvatures. Analogous to the propeller, the clavicle has a broad quadrangular medial end fixed yet mobile in its shallow socket, the clavicular fossa; a diaphysis of varying thickness and torsion; with a flattened apical acromial end.

9.0 Clavicle, a hyperbolic paraboloid— a compound curve cranking system:

A mechanism is an assembly of bodies connected in such a way that the movement of one causes the required movement of another(Alexander, 1983). A simple mechanism of mobility has a four-bar crank chain. It consists of four links joined by hinges, the axii of which are parallel. The fixation of one link and the movement of the second can predict movements of the remaining links. In this regard, apart from the parallelism of the various axii, the kinematics of a normal clavicle are not paradoxical, nor are the other links within the pectoral girdle mechanism, which function synchronously and predictably.

The medial and lateral curvatures of the clavicle, arranged in series form a non-classical geometry of a [1]hyperbolic paraboloid-shaped curved lever system, creating a compound curve cranking system. Why call the clavicle's geometrical design hyperbolic paraboloid because the medial curvature forms a hyperbolic divergent conical surface, and the lateral curvature is not a true parabola with parallel walls but has shorter radius of curvature than the medial, which is a paraboloid, shaped like or comparable to a parabola. The juxtaposition of a hyperbolic and a paraboloid curve of the clavicle, when 'thrown' together in series, akin to a saucer and a bowl edge-to-edge, supports and stabilizes the shoulder complex, resisting compression, tensile and torsional forces. For its size, this design of the clavicle can generate, transmit, and multiply force, store elastic strain energy to assist and regulate the movements of the scapula, and generate powerful throwing movements at the glenohumeral joint. Power generation is made possible because of its biomechanical architecture and its ability to store energy in its substance, reinstating its resting position for the next move. Hence, the clavicle is a precision, continuous force-generating, constant velocity cranking system in repetitive movements, depending on an individual's muscle strength and endurance.

9.1 Clavicle a bio-crank:

Figure 6. An ancient carpenter's brace. The image is available in the public domain.

A crank is a lever that has long held a shared place in engineering applications for centuries. It is a mechanical component that converts rotary motion into linear motion and vice versa. A lever has a pivot point at one end and a rotating handle or wheel at the other. A crank is at a right angle to a rotating shaft, which can have circular or oscillatory motion imparted to or received from the shaft. The most common example of a cranking system analogous to the clavicle is a carpenter's brace (**Fig. 6**).

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[1] A conical surface is an unbounded surface formed from the union of infinite lines that pass through a fixed point, an apex, and a space curve. A section of a cone (quadratic curve) is a curve obtained from the cone's surface by intersecting a plane. There are three types: parabola, hyperbola, and an ellipse. A circle is a special type of ellipse. The parabola walls, when extended, are parallel; those of a hyperbola are divergent, and those of an ellipse tend to converge. The two congruent curves joint together at their apices form a special case of a conical surface. Parabola in Greek means juxtaposition. Para means alongside, and bole means throwing, and hyper means excessive or over-throwing. In geometry, the two are combined into one term: the hyperbolic-paraboloid. In classic geometry, when the two are merged back-to-back, joined at the apices, it appears to be a saddle shape. In the case of the clavicle, the two taken have different chord lengths, creating curves of various radii of curvature, merged in series like a hyperbolic-paraboloid roof structure, forming a compound curve rather than the classical geometrical saddle shape.

A square-offset handle on a brace to start an engine can be a curved lever. The centre of a curved or square lever is the point where it is gripped and turned to trace a circle *(the point of effort)*. The radius of the crank is the lever or moment arm, which is a perpendicular distance from the axis of rotation to the line of action of the force to produce torque (**Fig. 7**). For the same depth brace, the moment arm of a square brace from the axis of rotation is shorter than the radius of curvature, the lever arm, of a curved crank.

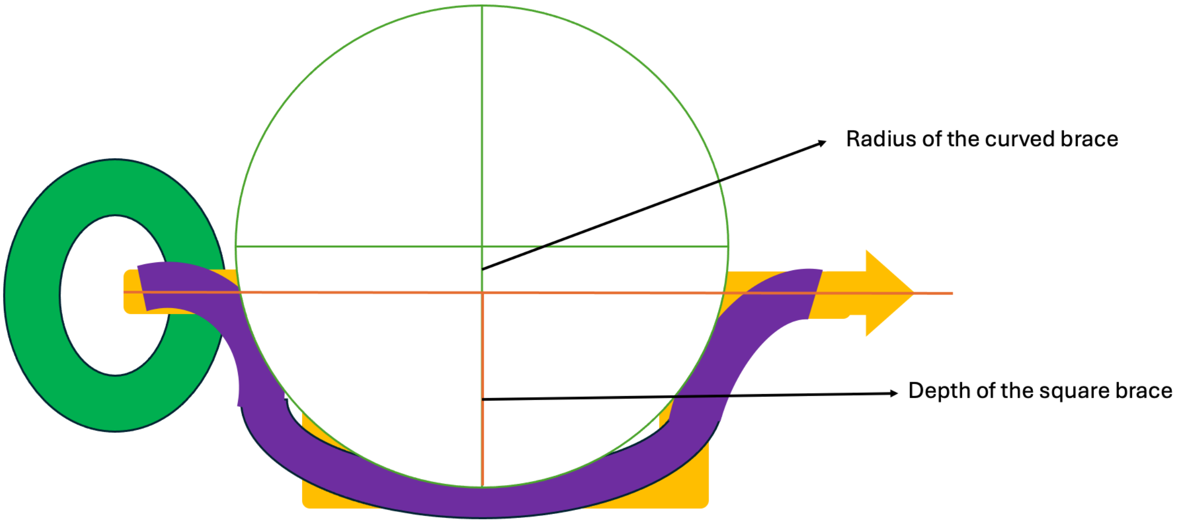


Figure 7. A square brace versus a curved brace handle as a cranking lever (created in PowerPoint by the author).

Even though the handheld cranking brace is much slower than an electric drill, it produces much greater torque and can make a deeper, wider hole. The longer the moment arm, the greater the sweep and the greater the force produced. The sweep is twice the moment arm. The sweep measures the force that can be exerted and transmitted. A curved brace with the same swing or throw as the square brace has greater sweep, occupying significantly lesser space.

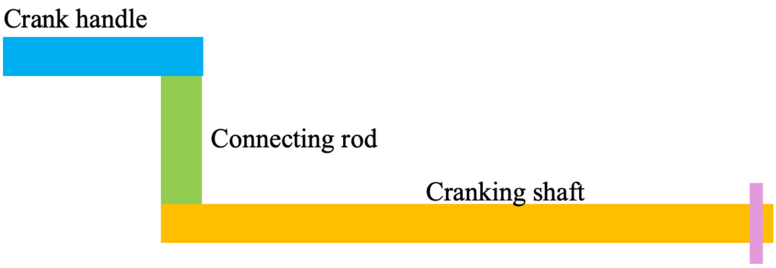


Figure 8. A traditional simple automobile cranking system to start an engine (created in PowerPoint by the author).

Levers are the simplest of all machines, in the form of a straight stick *(turning a stick on a stone to generate friction to ignite fire is an efficient cranking system)* used to shift or lift a load. A crank is a kind of lever that multiplies the force. The rotating handle that turns and moves the shaft forward in a straight line is the crank, and the connecting rod between the two is the lever arm, which constitutes a cranking system (**Figure 8**). The three components are at right angles to each other. When a lever system has more than two right angles, it forms a compound lever, increasing its applied torque. A carpenter's brace with a square crank (*handle to apply force*) is an excellent example of a compound brace. For the same moment arm length, a square crank requires much greater space than a curved crank, which has a much longer lever arm. Therefore, the curved cranking system is much more efficient and has a greater mechanical advantage. The clavicle, with its double curve, is a compound cranking system with two curves joined in series, each with a large and a small radius of curvature **(Figure 9).** Anatomically, the curves and twists of the clavicle are well optimized for superior biomechanical function, fitting within busy topography at the root of the neck.

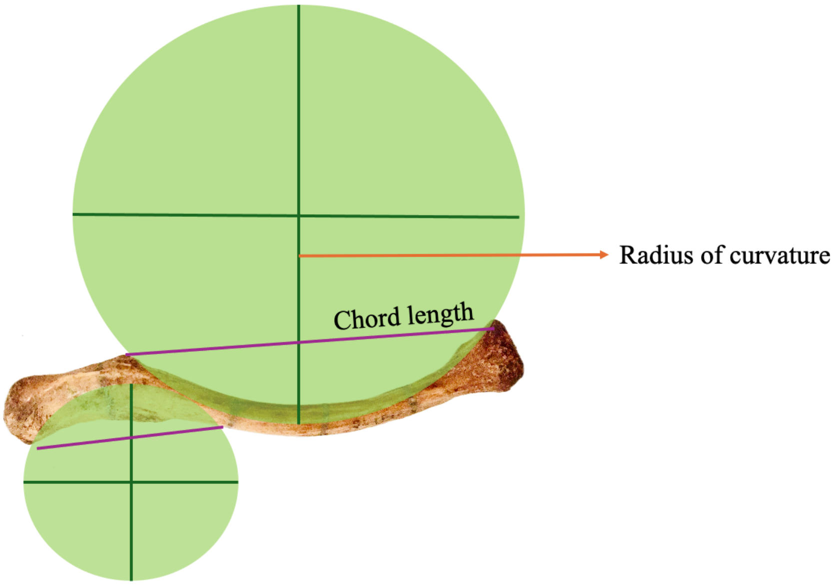


Figure 9. Respective large medial and small lateral radii of curvature, measured from the anatomic axis (*centreline*), and chord lengths of the medial and lateral curves (created in PowerPoint by the author).

An individual modifies the clavicle with great precision to achieve person-specific kinematics for performing daily tasks. The precise monolithic crankshaft design of the clavicle has developed with excellent biotechnical tolerances to meet individual demands for stability and strength, enabling power generation at the glenohumeral joint while resisting tensile, compression and torsional forces during motion.

9.2 Mechanical advantage of the clavicle:

The mechanical advantage of a crank is the ratio of the output linear force and the torque (*input turning force*) applied to the shaft, which varies throughout the crank cycle. The torque is greatest at a crank angle of less than 90 degrees. At zero degrees *(the top and the bottom of the swing are dead centres, where a flywheel is needed to oppose the system's inertia),* the force is linear and has linear acceleration. The applied force is fully converted into angular acceleration at less than 90 degrees of angle *(equivalent to going downhill)*. Mathematically, the radius is a function of the circumference. Therefore, the sweep or the circumferential path traced by the crank is functionally related to the lever arm. To achieve maximum mechanical advantage and conserve energy, the azimuth angle of the clavicle relative to the body planes, as the reference, and its motion is such that its axial rotation and rolling occur within the transverse and mid-coronal planes during arm elevation for common daily activities with minimal inertia to begin and complete a movement.

The turn of the crank multiplies the applied force depending on the length of the moment arm or the radius of curvature. Cranks are considered a type of lever because the fulcrum is at one end, and the effort is applied at the other. The radius of curvature remains constant as the crank rotates, determining the mechanical advantage and torque the crank produces. A crank with a larger radius of curvature *(shallow curve)*, like the medial curvature of the clavicle, has a greater mechanical advantage than a crank with a smaller radius of curvature *(deeper curve)*, such as the lateral curvature (**Fig. 9**).

Clavicle is a machine (*device to help make things easier*) to multiply or augment an applied force *(physical effort)* at a distance from the point *(fulcrum)* to where it is going to operate to carry out the work, creating a motion to lift or throw a load. The advantage to the user of a machine is that it conserves energy and increase efficiency. Mathematically, it is a ratio between the output and input force magnitude called mechanical advantage, which is given by_

Mechanical advantage (MA) = Output force (F_{out}) **/** *Input force* (F_{in})

The medial curvature of the clavicle is a shallow curve crank having a larger radius of curvature, hence greater mechanical advantage.

The lateral curvature of the clavicle is a deeper curve crank having a smaller radius of curvature, hence lesser mechanical advantage.

As the shallow curve has a greater mechanical advantage, it implies a straighter curve or a nearly straight shaft (*akin to a fire-igniting stick*) with an almost infinite radius of curvature, which would theoretically mean have a mechanical advantage approaching infinity. It is a matter of taking the concept to its logical extreme! However, if a shallow curve has a greater mechanical advantage due to its larger radius of curvature, then a straight shaft (*a* *rod*) clavicle could have an infinite radius of curvature, providing the maximum possible mechanical advantage. In theory, such a straight shaft would be infinitely long or have at least one large diameter in its cross-section, like the flat handle of the AO screwdriver, in the form of the flat acromial end of the clavicle. This design feature is evident in the form of oval cross-sections at the various stations along the clavicle's diaphysis **(Fig. 5)**.

A zero-degree crank is a linear straight rod whose force is purely linear having linear acceleration like an arrow. Therefore, this is not feasible in practice, as a very long straight shaft, such as a rod or a strut, needs more linear space. Secondly, it could not efficiently transmit a significant amount of rotational motion at speed to produce an adequate torque. However, a well-optimised, nearly straight shaft with a very shallow curve, such as in the femur and the radius with curvatures in two planes, has much greater mechanical advantage, making them more efficient. The reason that in some machines, there are long straight levers or linkages that amplify the applied force. Besides the biomechanical function as a force converter, the clavicle plays several other key mechanical roles. The clavicle design is not to drill a hole or thrust directly against the acromion. It helps the scapula yaw, pitch, and roll simultaneously on the curved thoracic wall and by default (*unavoidable intention for the mechanical advantage*), circumvents the structures arising from the thoracic aperture.

9.3 Mechanical advantage of double curve in series:

In the clavicle, what is the advantage of a longer shallower, curved crank joined in series to a shorter, deeper curved crank, and if the load is at the end of the shorter, deeper crank? How does this arrangement change the mechanical advantage of the entire cranking system of the clavicle?

Joining a shallow curve crank to a deeper one in series creates a composite lever system. The product of each crank's mechanical advantage determines the total mechanical advantage of the system. The shallow curve crank, corresponding to the medial curvature of the clavicle with a larger radius of curvature, provides a much greater mechanical advantage. In contrast, the deeper curve crank, with a smaller radius of curvature, provides a smaller mechanical advantage. When the load is at the deeper curve crank end, such as the lateral curvature of the clavicle:

1. The muscle force applied at the shallow curve crank is amplified due to its greater mechanical advantage.
2. The amplified force is then transmitted to the deeper curve crank, which is further modified with additional muscle force and refined by its smaller mechanical advantage. The overall mechanical advantage of the system is the product of the two:

Total mechanical advantage (MA) = MA of the shallow crank × MA of the deeper crank

Since the deeper curve crank has a smaller MA, it will not significantly increase the overall MA of the system. Still, it would provide additional MA to the proximal crank, amplifying the force. The advantage of this kind of mechanical set-up is that it can achieve a greater range of motion *(stroke)* at the load (*weight of the arm and the object in hand*) end (*deeper curve crank*), while benefiting from controlled force amplification provided by the shallow curve crank, which refines and smooths the motion.

In summary, in the clavicle, joining a medial shallow curve crank to a lateral deeper curve crank in series provides a force amplification, allowing for a more versatile mechanical system in limited anatomical space. The shallow curve crank amplifies the muscle force, and the deeper curve crank modifies it, resulting in a higher overall MA of the system.

9.4 Double curve at an offset:

How does the MA changes in the cranking system of the clavicle, with its medial and lateral curvatures in series, offset in the transverse plane and an inclination angle in the coronal plane, creating varying angles between the longitudinal screw axis, mechanical axis, and the pitch axis?

Offset crankshafts involve trade-offs. In automotive engineering, the concept of offset is motivated by efficiency and low-end torque. There is lower friction between components, smoother motion, and slightly stronger torque at low speeds. In optimally designed systems, it may help improve efficiency, mitigate vibration and reduce mechanical friction, primarily at low to medium speeds, thereby reducing energy loss(MacMillan et al., 2014). As speed and load increase, lower offsets are beneficial; at higher offsets, friction increases(Cho et al., 2003). A straight rod without an offset, produces linear motion with zero torque. With an optimal offset, the crank is at an advantageous position from the outset, resulting in rapid acceleration, reduced friction, a higher peak torque sooner after initiation of the movement, and a quicker return to the original position.

Offset directly influences the geometry of the clavicle steering the scapula **(Fig. 10).** The length shortening with deepening and reduced radius of the medial curvature and formation of the posterior-superior angular frustum, increases the turning circle of the axially rotating clavicle. Every millimetre change in the offset requires greater

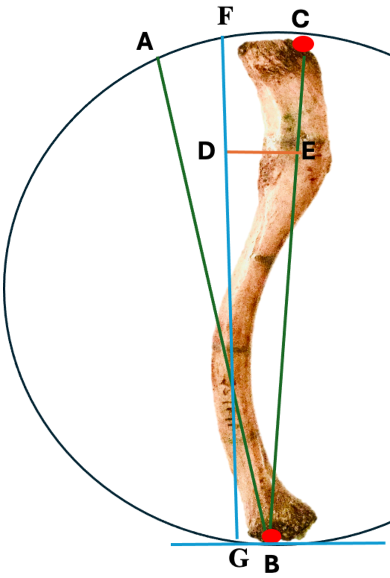


Figure 10. Angle ABC is the axial offset angle, and the line DE is the radial offset from the plumbline FG through the centre of the diaphysis; the line AB is the pitch axis, and BC is the mechanical axis between the centroids of the articular surfaces shown as red dots (created in PowerPoint by the author).

force to generate the required torque. An incorrect offset increases stress and friction between fragments within the callus during healing and later, between the frustum and the soft tissues, with the potential for early post -traumatic arthrosis, thereby affecting both comfort and performance. A greater offset in a rotating system generally increases deflection and creates more localized stress. An optimal offset in an individual improves mechanical efficiency by enabling more effective, sustained torque transmission by reducing out-of-plane loss of force in the radial direction. Offset misalignment at higher speeds causes instability, vibration and increased wear of the weight-bearing surfaces. In engineering, specifically designed offsets control vibration. An appropriate offset can mitigate certain sub-synchronous vibrations, which have destructive potential, cause fatigue and lead to unstable motion. Offset does not increase overall shaft strength, it generally increases deflection and usually increases local stresses. These offset design principles incorporated into the biomechanical architecture of the clavicle are applicable to all clavicles during normal development.

When the two cranks in series are offset, as in the clavicle, it creates a measurable angular displacement between them, with the shallow-curve crank driving the deeper curve crank. This effectively reduces the gained mechanical advantage because some of the force is lost due to the offset, which is affected adversely by the malalignment in a malunited fracture. The amount of force lost depends on the magnitude of the offset angle, between the shallow and deeper curve cranks, which in the case of the clavicle's medial and lateral curvatures varies among individuals. The force of the system can be estimated by:

MA of an angular system = MA of the system × Cosine of angular displacement

If the offset angle is 10 degrees, then the Cosine 10 is 0.9848, the MA of the angled system would be reduced by about 1.5% compared with a system without an offset. Thus, setting the cranks at an angle slightly reduces the MA, but the effect is relatively small for small angles. However, as the angle of a fracture malunion increases, the change in MA may become significant. The actual MA may vary depending on the patient-specific morphometry of clavicle's cranking system and state of other component linkages, scapula, thoracic wall shape and even vertebral column deformities, such as scoliosis and kyphosis.

The shaft diameter of the shallow curve crank is smaller than the sternal end, and the load-carrying acromial end of the deeper curve crank is flattened in one plane. Any morphometric deviation from the normal of an individual's clavicle will alter the MA of the entire in-series cranking system with an offset. The original offset is often altered following an angular malunion, thereby changing the radius of curvature, and a large callus changes the cross-section of the medial curvature.

The change in diameter due to overlapping malunion of the fracture fragments affects torque generation and the transmission from one crank to the next, as most of the fractures are at the inflection zone. The smaller diameter shaft of the shallow curve crank effectively has a smaller moment arm (*radius of curvature taken from the mid-point of the diaphyseal medulla*) compared with the larger diameter shaft *(right clavicle has more robust diaphysis)* relative to anatomical axis or the centreline **(Fig. 9)**. This diameter difference reduces the overall MA of the system because the force applied to the shallow-curve crank is transmitted through a relatively smaller radius, producing lesser torque. However, a deeper curve crank, despite a smaller radius of curvature, will amplify the torque through a larger diameter in one of the planes, acting as a multiplier will partially compensate for the loss. To estimate the MA, consider the ratio of the diameters or radii squared:

MA of the system = (MA shallow curve crank) × *(r of shallow / r of deeper)*^{2} × *MA deeper curve crank*

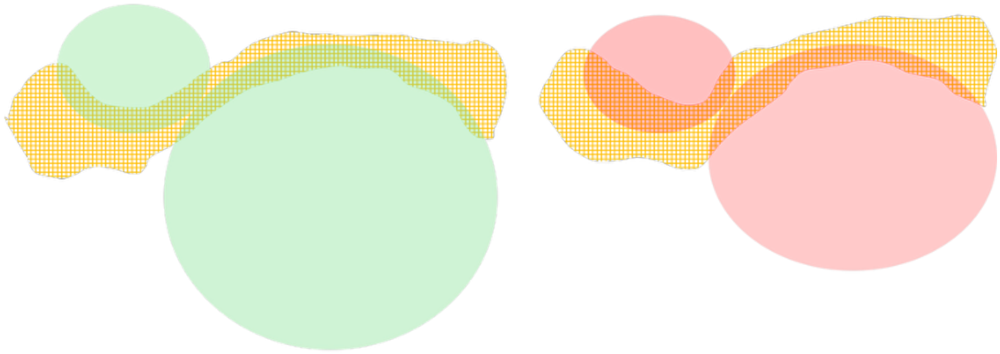
Where r is the radius.

The difference in diameter reduces the MA by the factor derived from the ratio. This is a simplified estimation equation to explain the possible effect of changes in diameter along the diaphysis in normal individual clavicles and cases of malunion. This calculation does not account for other factors, such as pre-existing range of motion (*individual kinematics*), muscle strength to generate power (*individual level kinetics*), material strength and rest of the crank geometry.

In summary, the smaller-diameter shaft of the shallow-curve crank reduces the mechanical advantage, given directional asymmetry and gender differences. However, the deeper curve crank's diameter partially compensates for this loss (*wide, flat acromial end akin to the biomimetic design of the AO screwdriver handle*).

In a clavicle with normal anatomy and attached muscles at the sternal and acromial ends, there are two leverage points to power the cranking system of the clavicle. The lateral curve, as a multiplier, also helps regain lost energy at the lateralmost end and a shorter length, bringing the pivot point or fulcrum closer to the load in hand. Thus, the two curved cranks share and amplify their contributions, assisting the scapulothoracic and glenohumeral kinematics. The increased diameter of callus in early healing stages increases the strength and the moment of inertia, preventing excessive motion between the fragments at the softer provisional callus.

In a malunion of the clavicle with increased diameter due to the overlapping fragments between the distorted curves due to malunion, has no beneficial effect because of disruption in the helical structure of the collagen bundles. The frustum formation by the posterior-superior angulation is an irregular, peaked curve that deepens the lateral curve, reducing the chord length and its radius of curvature, which further reduces the MA of the medial curve (**Fig. 11**).



Normal clavicle

Malunited clavicle

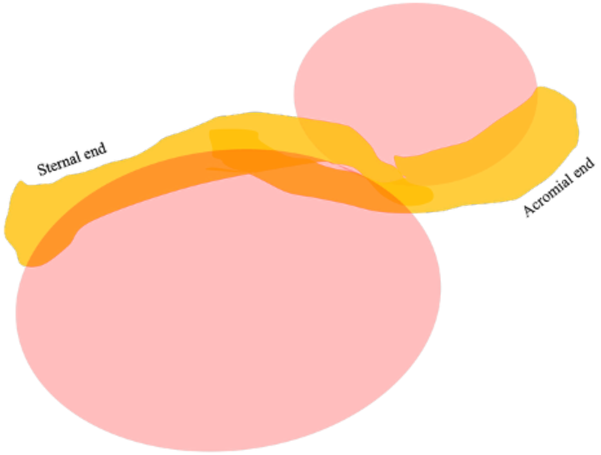


Figure 11. Altered radii of curvatures in malunited clavicle fractures. **Top**. Right image with a deep frustum causing irregular lateral curve and shortening at the inflection fourth-fifth section. **Bottom.** Telescoping shortening with loss of regular curvature of both the curves (created in PowerPoint by the author).

10.0 Why have a curved cranking system:

The curves of the clavicle occupy much less space in all the planes. Instead of being a square, the curved crank has a shorter throw or swing *(depth of the curve, the distance from the centreline to the mechanical axis of motion),* and a bigger sweep *(twice the length of the lever arm or radius of curvature, when turned through 360 degrees, compare the medial and lateral curves)*, requiring much less room to operate with greater mechanical advantage in the confined spaces (**Figs. 7 and 9**). The radius of curvature or the moment arm determines the torque and speed of rotation and roll of the clavicle. A longer moment arm (*medial curve*) provides more torque at a slower speed, and the opposite is true for the shorter moment arm (*lateral curve*) with smooth motion.

The cylindrical shape of the medial third-fifth of the diaphysis fits well, occupying lesser space around the thoracic aperture, and the rectangular spatulated cross-section of the lateral curvature takes advantage of the space lateral and superior to the first rib to rotate and roll with retraction dorsally, carrying the scapula with it. The biomechanical architecture of the clavicle is certainly an ergonomically (*what fits and works well with minimal effort*) designed, topographically befitting skeletal device in its articulated state. It is the best-fitting design given space constraints at the root of the neck to meet its biomechanical demands as a crank. Most of all, the variable sectional material distribution provides the clavicle with the required strength to excel when carrying heavy loads in all planes.

10.1 Kinematic velocities:

How does the mechanical advantage increase with changing speed of rotation and rolling of the clavicle as a crank with opposing curves in series with an offset to each other with progressively changing torsional angle and version angle, making a large end-to-end screw pitch passing between them?

The arrangement of two opposite curved cranks in the transverse plane is a highly ingenious evolutionary development. In addition, setting the screw twist at a specific torsional angle in each, with a differential screw pitch, creates a unique compound motion. A double-curved crank with a varying torsional angle along the diaphysis merging into a screw twist with a large pitch increases the mechanical advantage, allowing for more force to be applied to the curved cranking system with less effort. In addition, pre-torqued collagen enhances the response to added energy during overhead lifting and projectile delivery. The varying angle of torsion along the diaphysis introduces controlled amplification and the reduction in applied torque to rotate the clavicle facilitate efficient overhead transfer during acceleration and rapid return to the resting state for the next move.

The large screw pitch of the medial curvature results in a slower turning speed of the clavicle. Although the motion is amplified, the overall rotation is distributed over a longer distance, reducing the speed. In essence, this modification of composite cranks trades speed for increased torque and mechanical advantage, making it suitable for initially lifting heavy weights gradually. However, beyond the inflexion zone between the curves, as the screw twist changes direction, the pitch around the lateral curve becomes smaller. Therefore, the variable screw pitch between proximal medial curvature and the distal lateral curvature means that the screw twist, functioning like a differential machine screw, speeds up the motion. From the mid-chest up, it helps to heave the weight rapidly overhead and then throw it forward rapidly on reversal of the movement. All this happens by employing the stored strain energy in the pectoral girdle's osseous elements, including the muscle power. Hence, the clavicle is a vital link in the pectoral girdle that has evolved to lift and, initially, wind the arm gradually overhead, increasing the velocity of the projectile and then accelerating it.

10.2 In series but not opposing medial and lateral curvatures (synclastic curves):

Supposing, instead of the two opposing curves of the clavicle in series are on the same side of the shaft, that is, both the convexities facing ventral/anterior or posterior/dorsal, with varying segmental torsional angles, and a screw twist with differential pitch, how would that affect the mechanical advantage and the speed?

With the curves arranged on the same side of the shaft, in 180 degrees alignment, with a screw twist, angle of torsion, the mechanical advantage would still increase due to compound motion, but the effect would be less pronounced than in the opposing arrangement. The motion is more direct, with the cranks on the same side, and they would work together to amplify the forces, but the effect would be more linear. Compared with the opposing arrangement, the speed of rotation and rolling of the clavicle will increase. In addition, the angle of torsion would introduce a slight 'camming effect', allowing for faster rotation.

However, there are topographic disadvantages of the same-sided curved anatomy of the clavicle, such as the ability to fit into the root of the neck, reflected in the malunion of a clavicle with neurovascular complications.

In this configuration, the modified compound structure of the clavicle prioritizes speed over mechanical advantage. A compound carpenter's brace, where both the cranks have convexities in the same direction has never been constructed. Such a brace may be suitable for drilling smaller holes or working with softer materials, where linear speed is more important than brute force.

11.0 The function of the screw twist alongside the torsion and version:

A bullet, as a symmetric rigid body, when fired from a rifled gun *(with spiral groove cut inside the barrel)*, follows a helical path, rotating around its screw axis, while translating along a linear path. A screw axis is an imaginary geometrical line, and screw motion is a spatial displacement of a rigid body following a helical path. The helical screw motion produces simultaneous rotation and translation along the same linear path, parallel to the screw axis. In pure rotation of a smooth rod (*without a screw pitch)* the motion has zero translation and in pure translation there is zero rotation (*the pitch of the rod is infinite*). Therefore, it is the pitch of a screw that defines the properties of its rotation and translation. The linear distance (*translation*) travelled by the rigid body is equal to one pitch rotation.

The clavicle is an asymmetric rigid body; when in motion, it forms a conical bullet-shaped frame. It has a large screw pitch in its proximal three-fifths, medial curvature, and a smaller pitch in its distal two-fifths, lateral curvature, thus exhibiting varying rotational and translational capabilities at the two ends, similar to a differential screw. The laxity of the capsule and ligaments at the sterno-costoclavicular joint allows a limited translation accompanying screw motion (*simultaneous rotation and translation*) of the intercalated clavicle between the paired joints, in addition to lateral rotation of the inferior angle, and protraction of the scapula, with assistance from centrifugal force during a high velocity projectile delivery and acceleration. It is the screw twist of the clavicle that confers the angular velocity to it. In a uniformly shaped rigid body, all particles have the same angular velocity, depending on the perpendicular distance from the screw axis. Because the clavicle has non-uniform cross-sectional anatomy with varying diameters along its length, it exhibits varying velocities along its screw axis from the sternal end to its acromial end. How does this affect the rotation and translation of the intercalated clavicle is unknown.

The spiral arrangement of the collagen fibrils, with a twist laid into collagen bundles, like a rope, has right-hand and left-hand chiral property in a bone. It gives a bone characteristic direction and angle of twist as torsion, version and overall screw twist. The screw twists around the screw axis are opposite between its ends. The presence of counter-twist holds the collagen strands tightly together, providing structural stability, which is crucial for the accuracy of the projectile delivery. The stable trajectory and speed of the projectile depend on the arrangement of the collagen bundle storing the strain energy and the twist rate (*how quickly the clavicle rotates, i.e., angular velocity and acceleration*). The optimal angular velocity transmitted to the scapula and then to the humerus provides gyroscopic stability to the projectile, keeping it flying straight at the desired target and velocity. A malunited fracture convert the clavicle into a much more asymmetric body misaligning the screw axis and screw twist, producing erratic screw motion.

With the formation of a frustum and the disordered collagen arrangement at the callus deformity, the clavicle experiences insufficient rotation and translation to transmit forces and position the scapula during "setting phase" and swivelling. An irregular callus due to malunion acts as a block to the flow of forces and energy to the distal linkages and joints. Reduced torque destabilizes the projectile, causing it yaw and fall short of the target. In repetitive activity, due to poor storage of strain energy means that as stored energy declines, the clavicle's capacity to return to its baseline decreases. With each move, the bearer of a malunited clavicle experience fatigue and may incur progressive injury to the soft tissues of the pectoral girdle. Axial rotation around the mechanical axis will cause the roll of the clavicle to follow an altered motion arc around a disturbed pitch axis. As a result of the clavicle's precession (*change in the orientation of the rotational axis of a rotating rigid body*), the veering of the projectile due to the reduced torque at the clavicle is indicative of a disturbed motion cone. Even loss of a normal one degree of freedom in clavicle's cranking system can mean disturbed kinematics of scapulothoracic and the acromioclavicular synsarcoses, as well as that of the glenohumeral articulation.

12.0 A simplified mathematical analysis of the mechanical advantage and speed of a double curved device with an in-built screw twist:

The closest engineering equivalent to the clavicle mechanism for calculating mechanical advantage and speed ratio is a screw jack used to lift heavy equipment. The speed ratio of a screw is the distance the effort travels per complete turn of the handle, divided by the distance the load travels, which is the pitch. The handle of the jack is the crank, and to determine its speed ratio, divide the radius of the handle with the radius of the shaft it is turning. When the frictional forces are negligible, the speed ratio is equal to the mechanical advantage.

The ideal speed ratios (SR) of a screw and a crank are given by_

$$SRscrew = \frac{2\pi r}{pitch} \text{ and } SRcrank = \frac{Input\ radius}{output\ radius} = \frac{Input\ speed}{output\ speed}$$

[2]The jack differs in design and construction from the clavicle, having a single crank. When combining speed ratios in the case of the jack, the cranking handle acts as the lever that rotates the screw itself rather than driving it via a separate system. The crank's length is the radius of the screw's input motion. In a jack, the crank and the screw

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[2] Converting a straight rod of a car jack crank to the clavicle's design, without the offset, may provide greater mechanical advantage.

are not separate components; their speed ratios are not multiplied, but the effective radius of the screw's input motion is increased. The radius of the screw becomes the radius of the crank. If frictional forces of the system are negligible, their combined speed ratio (SR) or mechanical advantage (MA) will be_

$$Total\ SR\ or\ MA\ =\ \frac{2\pi\ radius\ of\ the\ crank}{pitch\ of\ the\ screw}$$

The clavicle is a hybrid crank-screw system. The sweep is the distance the crank travels in one full rotation, and the pitch of the screw twist is the linear distance the screw moves. The system amplifies force by combining the larger radius of curvature of the medial crank with that of the smaller lateral curvature crank and the screw twist adds finite amount of linear output movement. As the clavicle has negligible *(virtually zero, unless inline lateral movement of the clavicle's acromial end in the coronal plane, with protraction and retraction of the scapula during arm elevation is considered)* linear translation, the distance it would have travelled is traded for increased torque. As the clavicle is intercalated between two articulations with intra-articular discs, forming constant velocity joints, healthy joints will have negligible friction; the output torque will be without loss. Theoretically, the differential screw's compressive function maintains optimal distance and positioning of the scapula relative to the manubrium sterni.

Mathematically, to analyze the mechanical advantage and speed of devices such as clavicles with double curves, varying torsional angle and end-to-end screw twist of varying pitch, follow the steps as under_

Define crank's radius of curvature (r), torsional angle theta, end-to-end screw pitch (p), input force (F_{in}), and output force (F_{out}).

Calculate the mechanical advantage (MA):

$$MA\ =\ \frac{Force\ out}{Force\ in}$$

Use the principle of virtual work to relate the input and output forces.

Consider the compound motion and the effect of the torsional angle.

Calculate the speed ratio (SR), Omega as the acceleration or velocity which is *(output angular velocity divided by input angular velocity)* _

$$SR\ =\frac{\omega out}{\omega in}$$

Use the kinematic relationships between the medial and lateral curvatures and the screw pitch.

Consider the effect of the torsional angle on the motion.

Relating the radii of curvature, torsional angle and angle of version, and end-to-end screw twist pitch to the mechanical advantage and speed ratio requires knowledge of trigonometry and geometry.

It means deriving equations for mechanical advantage and speed ratio in terms of parametric analysis *(changing specific input variable affecting the output and system behaviour),* will also involve complex trigonometric and kinematic calculations.

Starting with the mechanical advantage, the principle of virtual work is applied to relate the input and output forces.

Assume a small displacement of the input crank, medial curvature of the clavicle.

Calculate the resulting displacement of the output crank, lateral curvature of the clavicle,

Using the virtual ideal work equation

F_{in} × *angular displacement of the input crank* = F_{out} × *angular displacement of the output crank*

Considering the compound motion of the medial and lateral cranks and the effect of the torsional angle, with negligible offset of Cosine10 degrees:

F_{in} = *(Medial curvature radius × angular displacement of the input crank)*

F_{out} = *(Lateral curvature radius × angular displacement of the output crank) × (angle Cos theta) × (2π × radius) / pitch of the screw twist*

Angular displacement for medial and the lateral curvatures is same at each rotation.

MA =F_{out} */* F_{in} *= {(Lateral curvature radius × angle Cos*θ*) / (Medial curvature radius)}* × [(2π × *Medial curvature radius) / Pitch of the screw twist)*]

$$MA = \frac{(Lateral\ curvature\ radius\ \ Cos\theta)}{Medial\ curvature\ radius}\ \frac{2\pi\ Medial\ curvature\ radius}{Pitch}$$

$$MA = Lateral\ curvature\ radius \times Cos\theta \times \frac{2\pi}{Pitch}$$

The MA is significantly related to the curvature of radius and the pitch of the screw twist. The mechanical advantage of the crank with multiple curves and a screw twist is multiplied by combining simple machines, compounding the mechanical advantage. The screw twist between the medial and the lateral curvatures has a differential screw pitch.

The speed ratio of the clavicle is the combination of the speed ratios of its medial and lateral cranks and the screw twist. The calculations become rather complicated when the varying diameter of the clavicle, the differential screw pitch, the torsional angle, and version are taken into considerations. Simply combining the ratios yields the product of speed ratios of the cranks and screw twist, which indicates how much the output lateral curvature crank turns compared to the input medial curvature crank, and how much the screw twist at the output lateral shaft turns compared to the screw twist at the input medial shaft. Thus, the clavicle as a compact single integrated unit, forms a jointless monolithic kinetic chain or the gear train within the pectoral girdle mechanism.

To calculate the combined speed ratio (SR), the input and output angular velocities are related to the kinematics of the clavicle.

Calculate the speed ratio of a screw twist by dividing the circumference of the screw by its pitch. The speed ratio of a curved crank component depends on its chord length and the radius of its curvature.

Assuming an input angular velocity

Calculate the resulting output angular velocity by taking into account screw pitch and torsional angle.

Output angular velocity = (*input angular velocity* × *Medial curvature radius)* **/** (*Lateral curvature radius* × *angle Cos theta)* × *(screw pitch / 2* × *π)*

Speed Ratio = output angular velocity **/** *input angular velocity*

Speed Ratio = (lateral curvature radius × *angle Cos theta) / (Medial curvature radius)* × *(2* × *pi* × *Medial curvature radius / screw pitch)*

$$SR = \frac{Lateral\ curvature\ radius \times Cos\theta}{Medial\ curvatutre\ radius}\ \frac{2\pi\ Medial\ curvature\ radius}{Screw\ pitch}$$

$$SR = Lateral\ curvature\ radius \times Cos\theta \times \frac{2\pi}{Screw\ pitch}$$

Thus, both the mechanical advantage and the speed ratio of the clavicle are related to the parameters of the radius of curvature, torsional angle, offset and screw twist pitch. Note that the laterally concentrated inferior curvature is excluded from the formula for reasons of simplicity.

In engineering, to improve upon a task or activity, for greater MA and speed change parameters, such as the size of the curves, torsional angle of the shaft and screw twist pitch, by forming a set of orthogonally arranged and opposing double curve cranking systems. Theoretically, consider such an application for preventing rotator cuff injury and subacromial impingement or, to say, how a malunited clavicle fracture can adversely influence the delivery of a projectile in sports and the health of the rotator cuff in manual workers.

Theoretically, in an individual to optimize the composite cranking system formed by the clavicle for a specific task, the following parameters would need to be adjusted.

For greater mechanical advantage (more force and less speed):

1. Increase the crank's radius of curvature
2. Increase torsional angle
3. Increase screw pitch
4. Use a larger crank ratio *(output crank radius of curvature* **/** *input crank radius of curvature)*

For greater speed (less force and more speed):

1. Decrease the crank's radius of curvature
2. Decrease the torsion angle
3. Decrease the screw pitch
4. Use a smaller crank ratio *(output crank radius of curvature / input crank radius of curvature)*

To lift heavy weights, a greater force is required. Therefore, to prioritize mechanical advantage, a crank with a larger radius of curvature (more force, higher MA), a larger torsional angle, and a larger screw pitch are needed. For speed, a smaller screw pitch and a smaller torsional angle are needed.

Biologically, these parameters change because biomechanical forces adjust the crank ratio to optimize for specific tasks over time, adapting the clavicle's anatomy to sedentary desk jobs, manual labour, leisure and athletic activities.

Similarly, the length of a curved crank can affect the mechanical advantage, hence the need for the restoration to the patient-specific clavicle length.

A longer, curved crank will increase the moment arm *(the distance from the pivot point to the point where force is applied)* and amplify the force, resulting in a higher mechanical advantage for lifting a given weight. For example, this can occur with lengthening of the clavicle after a fracture or following an intramedullary fixation of a mid-diaphyseal fracture. However, such considerations are limited by anatomical constraints and orientation.

1. An additional, larger curve crank may increase the weight and size of the bone, making it more difficult to control and manoeuvre. It will introduce more friction and wear of adjacent joints and affect the pivot point where the motion occurs.

2. A shorter curve crank may reduce the mechanical advantage, making the clavicle more compact and easier to handle, offering better stability and control, and preventing rapid joint wear. However, in addition to shortening of the clavicle following a fracture, there is a frustum formation, altered torsion and version angles, and pitch and screw twist deformity, all which change the segmental anatomy of the entire diaphysis. In addition, scapular dyskinesia and impingement. These changes can be detrimental, reducing the overall mechanical advantage.

In engineering, the optimal length of a crank depends on a specific application, required material, and the desired balance between mechanical advantage and usability of a system. Generally, a curved crank with a length of 1.5 to 3.0 times the radius of curvature is a good starting point for achieving a suitable mechanical advantage without compromising usability. In clavicles, the ratio is < 2.0, presuming that the radius of curvature of the curve is measured along the centreline and the diameter of the circumscribed circle lies along the centreline in the transverse plane. The chord length is less than the diameter *(twice the radius of curvature)* but longer than the radius of curvature (**Fig. 9**).

13.0 Length ratio of medial and lateral curvatures of the clavicle:

The ratio between the lengths of the doubly curved cranks in a composite cranking system can significantly affect the mechanical advantage and overall performance. Commonly, a ratio of 1:2 to 1:3 between the lengths of two cranks, where the shorter crank with a smaller radius of curvature is at the loading end, and the longer crank with the larger radius of curvature is at the input end, as seen in the case of the clavicle. This ratio provides greater mechanical advantage through composite motion, improving balance between force amplification and speed, and enhancing control and stability during projectile delivery. A shorter crank at the loading end (acromial end) with a smaller radius of curvature increases the force applied to lift the weight but reduces the speed of lifting or throwing a projectile. A longer curved crank at the input end with a longer radius of curvature (*longer moment arm*) reduces the force required to initiate the motion, increasing the speed of the curved crank, thereby making the lifting of a weight and throwing of an object much easier.

The optimal ratio varies depending on the specific application and requirements, and the ratio of the crank lengths is adjusted to optimize the composite curved cranking system for a particular task and user performance. Therefore, if there is an alteration in the already adapted preinjury ratio of the medial and lateral curvatures of the clavicle, then due to the malunion, one can expect changes in the MA and speed of projectile delivery.

13.1 The necessity of adding a laterally concentrated inferior curve:

Adding a third gentle curve in a system, such as a laterally concentrated inferior scimitar curve in the clavicle, orthogonal to the plane of the other two curved cranks, introduces additional level of complexity to the composite multifactorial motion. It increases the mechanical advantage by adding another level of force amplification through subtle changes in direction, thereby increasing the effective momentum. It also affects the speed and velocity. An inferior curve introduces a camming effect that reduces drag in the tissues, supports elevation and retraction during rolling motion and can potentially increase the system's speed. However, the orthogonal orientation creates a subtle "wobbling" motion, affecting acceleration, deceleration and targeting during pitching, impacting the overall motion. The combination of three curves produces a unique, intricate motion, still dominated by the two major curves, the large screw pitch and torsional angle.

The addition of the inferior curve, with a gentle screw twist, increases strength and weight-carrying capacity. The longitudinal, inferiorly directed curve decreases bending stiffness in the inflexion zone under heavy loads, whereas the torsional stiffness would increase due to the screw twist, making it more resistant to torsional forces due to the wider stress distribution. In a malunited clavicle with frustum formation and higher degree of torsion and version angles, screw twist creates areas of high stress concentration, potentially leading to fatigue cracks and sudden failure. Bone strength and stiffness at the fracture site return only following optimal bone material distribution with reformation of a patient-specific shape.

The exact effects of the composite design depend on the fusion of specific parameters, such as the radius of curvature, length and orientation of the third inferior curvature, with those of the other two curvatures. The addition of the third curve enhances the versatility and adaptability of the composite cranking system of the clavicle, enabling more precise control and optimization for specific tasks and load-carrying.

14.0 Hyperbolic paraboloid structure of the clavicle:

14.1 Geometry of Hyperbolic paraboloid:

The saddle shape is the usual term for a curved hyperbolic paraboloid surface. The hyperbolic paraboloid is a continuum of convex and concave surfaces merging into one another. A hyperbolic paraboloid structure combines hyperbolic and parabolic geometries in varying orientations without joint lines of discontinuity. In architecture, its perimeter constitutes straight lines that skew, but, when projected on a horizontal plane, would generate a square(Melaragno, 1991).

A hyperbolic paraboloid structure comprises back-to-back, double-curved surfaces, shaped on a single plane or two planes by bending the corners of a square in opposite directions. When the edges of the surface are curved in two planes, it forms a saddle-shaped structure. Primarily, the clavicle has two principal opposing curvatures joined end-to-end on a transverse plane, which renders hyperbolic paraboloid structure to it. The hyperbolic medial curvature is in one direction, and the parabolic lateral curvature is in the other (**Fig. 12**). The superior and inferior curvatures vary in distribution in the coronal plane, making its anatomy an advanced compound three-dimensional hyperbolic paraboloid structure in two planes. The inferior curvature frequently begins at the junction of the medial and the lateral curvatures. The multiple curvatures projected in two planes, combined with

Figure 12. The hyperbolic paraboloid geometric form of the saddle and the clavicle (created in PowerPoint by the author).

axial torsion embedded in them, give the clavicle a very complex geometry, daunting to create a monolithic integrated mathematical and biomechanical model.

The most salient structural property of a hyperbolic paraboloid is that it has a minimal surface area for given boundaries in minimal space, and its double curvature is stiffer than a single curvature, which is often applied to design bridges and very tall cooling towers for nuclear thermal plants. The surface curvature of hyperbolic paraboloid structures provides exceptional stiffness through the opposing inherent tension and compression (**Fig. 13**).

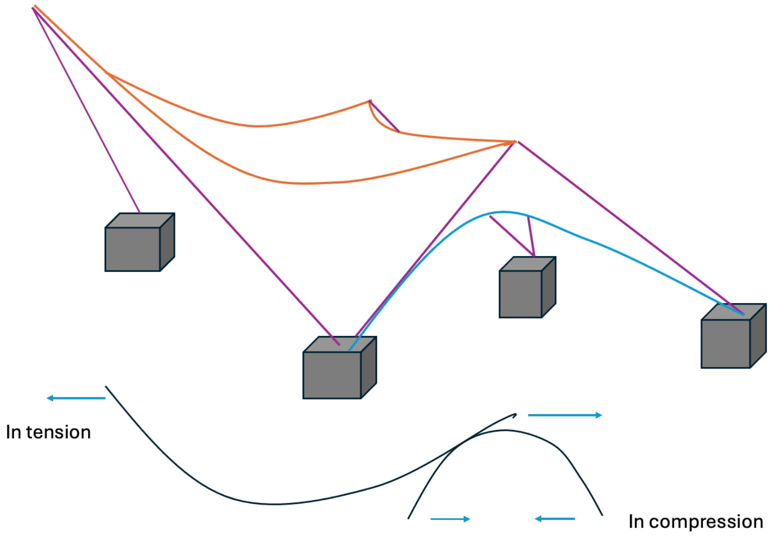

Figure 13. Architectural configuration of a hyperbola paraboloid structure (created in PowerPoint by the author).

The Russian architect and engineer Vladimir Shukhov first exploited this structural advantage of the hyperbolic paraboloid geometry(English, 2005). The opposing curves of hyperbolic paraboloid geometry of the clavicle act conjunctively under tension and compression to prevent the concentration of stress lines. Naturally, this prevents the development of stress fractures and the propagation of the cracks. A rugby ball cut open longitudinally cannot be laid flat, even more difficult is a soccer ball. In the same way, hyperbolic paraboloid structures cannot be flattened without distorting their shape. Hence, technically speaking, even the two major fragments of a fractured clavicle cannot be flattened easily without breaking it further. Failure to restore its hyperbolic paraboloid anatomy will certainly jeopardize all its functions.

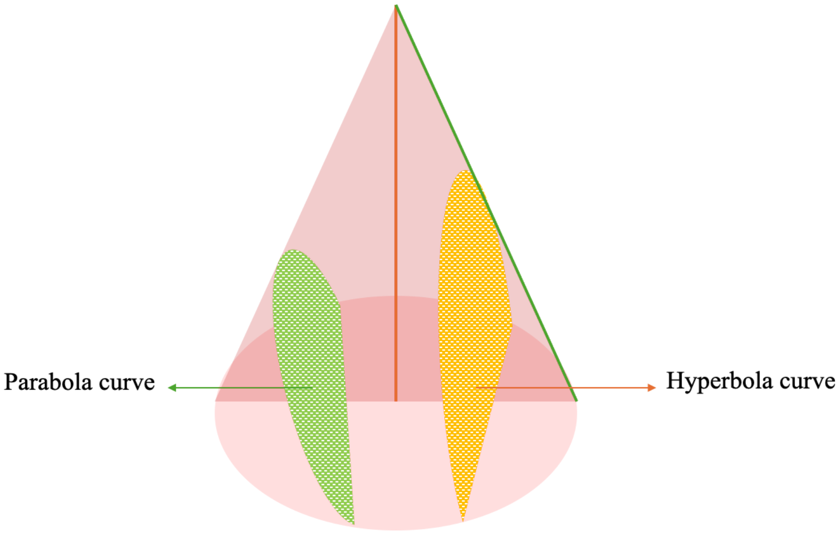

Figure 14. Geometric shape of parabola and hyperbola (created in PowerPoint by the author).

Hyperbolic paraboloids are special geometric curves shaped like arches. Both are a section of a cone(Avis et al., 1983; Hilbert & Cohn-Vossen, 1990) (**Fig. 14**). The directrix is a reference line used to define a shape. It is situated on the convex side of a conic section and is used to define and calculate its eccentricity. A parabolic section is parallel to the surface of the cone, making similar angle with the base of the cone. Any point on a parabola is equidistant from a fixed point, the focus, and a fixed line, the directrix(Hilbert & Cohn-Vossen, 1990). The two distances are always equal when a line is drawn from the focus point to a point on the curve; therefore, in a parabola, the ratio is one. A hyperbola section is parallel to the axis of the cone, and when cut the resultant curve makes a larger angle with the base than the side of the cone. In a hyperbola curve, the distance of any point, from a fixed point, the focus, and to a fixed point on the directrix is always greater. Hence, in the case of hyperbola, the ratio is greater than one. An ellipse has two focal points, and its eccentricity is less than 0.5. The ratio determines the eccentricity of the curve. A circle has no focal point and is non-eccentric; hence, its eccentricity is zero. So, eccentricity proves the "non-circular" behaviour of parabola and hyperbola. The bigger the eccentricity, the less curved it is. The eccentricity of a straight line is equal to infinity. Applying this to the malunion of the clavicle, the loss of its hyperbolic paraboloid architecture proportionately alters the eccentricity of the curves, kinematics and the mechanical advantage.

A parabola is a type of quadratic curve in mathematics. A second-degree polynomial equation, like $y = ax^2 + bx + c$, defines the parabola. A hyperbola is a two-dimensional curve in a plane that takes the form of two branches that are mirror images of one another that together form a shape like a bow (https://www.math.net/hyperbola). Hyperbola paraboloid is a three-dimensional surface like a saddle. Its quadratic surface can be defined mathematically by an equation of the form: $z = (x^2 / a^2) - (y^2 / b^2)$, where a and b are constant. The basic hyperbola paraboloid equation is given by $z = ax^2 + by^2$, where a and b having opposite signs are $x^2 + y^2$ and $x^2 - y^2$, depending on the direction of x and y and the value of the z.

$z = ax + by + ax - by = 2a + by + 2x - by = 2a + 2b = 4ab$

Further mathematics of the parabolas and hyperbolas and their application to the clavicle's biomechanical architecture is beyond the scope of this study.

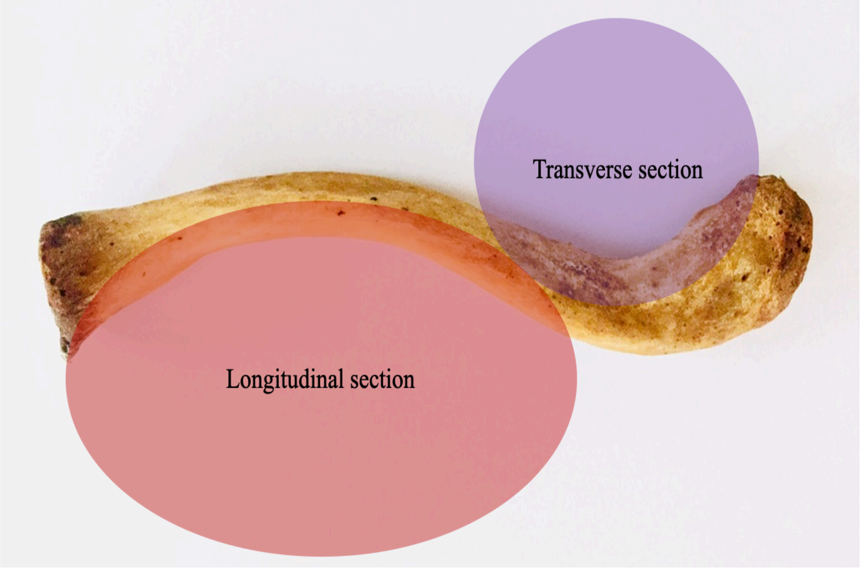

Figure 15. Illustration showing hyperbolic paraboloid curves of the clavicle (created in PowerPoint by the author).

Unlike a U-shaped parabola, a hyperbola is a shallow curve with a large radius of curvature. Such a hyperbola has an eccentricity close to 2, whereas a parabola is a deeper curve with a smaller radius of curvature and has an eccentricity close to 1. A longitudinal section of a rugby ball shows two hyperbolas on either side of its longitudinal axis. If cut transversely, perpendicular to the longitudinal axis, the cut section shows parabolic curves on either side of the transverse axis. Laying hyperbolic and parabolic surface lines against the medial and the lateral curves, they respectively approximate the shape of the curvatures of the clavicle (**Fig. 15**). When the hyperbolic and parabolic lines continue with each other, they approximate the centreline of the clavicle and, if twisted around a screw axis, will develop an offset. Hence, the general shape of the clavicle resembles a hyperbolic paraboloid structure, with a screw twist and an offset.

The hyperbolic paraboloid curves share tensile and compressive stresses under load. The opposite double curvature of the clavicle is prototypic biological invention over millions of years. It has an extrinsic cortical shell and a trabecular network that provide intrinsic structural strength and stability. This hyperbolic paraboloid compound crank acts as a force multiplier and a modifier. Its varying configurations, with progressive diaphyseal torsion angle, screw twist, and angle of version, are unmatched in the entire skeletal system in design and precision of functions. The invention of a well-formed hyperbolic paraboloid saddle matches the hyperbolic back of a horse and parabolic contour of human buttocks to seat a rider comfortably. The easily visible parabolic heel and hyperbolic longitudinal medial arch of the foot carry greatly varying body weights against gravity. A well-contoured trunk of the human body reflects the hyperbolic paraboloid curves (*hourglass shape*) in both the coronal and sagittal planes, and hyperbolic paraboloid thoracolumbar vertebral column in sagittal plane against gravity meet the desirable strength and stability of the locomotive skeletal system and body posture at rest and in motion efficiently.

The combination of a hyperbola and a parabola in series produces a surface curve that is both strong and flexible in compression and in tension. The concavity of the one resist tension, and the convexity of the other resists compression, stabilizing the entire compound curved structure. These dynamic biomechanical characteristics built into the articulating vertebrae are lost following the spinal fusion in scoliosis. The neutral zone of forces flowing between the two curves is where they catenate *(point of linking together like a chain)*. A push of one curve creates tension in the adjacent curve in series, and pulling the latter curve apart creates compression in the former. This dynamic mechanism of reciprocal tension and compression introduces the idea that clavicle acts as a unique device, effectively functioning like a strut, a derrick, cantilever, and an intercalated constant velocity axle between the sternoclavicular and the acromioclavicular articulations, during various activities under load. Two or more curves remain in equilibrium until the externally applied forces exceed this balance to break down the hyperbolic paraboloid mechanism of the structure.

Double-curved structures rotated about their axis can be either synclastic or anticlastic. Synclastic structures have similar surface curvatures in the same direction. Hyperbolic paraboloids and all hyperboloids are anticlastic because the curves are in opposite directions and have different curvatures in each direction. Thus, the clavicle is an anticlastic structure. Unlike a cylinder made of two curves of the same diameter, which can be unrolled to lie flat, the combination of hyperbola and parabola curves cannot be flattened without tearing them apart, as they collapse suddenly. The crack propagation in these curves is never in a straight line; hence, they end up being fragmented. The tubular and trabecular hyperbolic paraboloid clavicle is lightweight, graceful, delicate looking, yet strong in shape. This result from the balanced push and pull between the curves. It magnificently carries the weight of the upper extremity by transferring to the manubrium, and via the first rib to the vertebral column and ultimately down to the ground by pure compressive forces, borne by its curvatures pushing and pulling against each other when the curves get squeezed simultaneously. The compression of the lateral curvature is resisted by the medial curvature, following Newton’s third law. Thus, the strength of the clavicle is rooted in its geometry in addition to its material properties.

14.2 Clavicle – A hyperbolic paraboloid tube:

A hyperbolic paraboloid-shaped tube exhibits mechanical properties very similar to a ‘saddle-shaped’ structure, apart from some differences due to its tubular geometry. A double curve with peaks in the opposite direction is a stronger configuration than the curves on the same side of the axis and has a greater mechanical advantage. The opposing peaks of the hyperbolic paraboloid tubular shape create a more even weight distribution on either side of its mechanical and anatomic axii, reducing the likelihood of concentration of compression and tensile forces at any single point, decreasing the risk of material failure. At the same time, it offers excellent bending and torsional strength to counteract rotational stresses. The hyperbolic paraboloid shape, being stiffer *(resistance to change in shape)* than a straight tube, makes it less prone to deformation under load. Apart from the advantages of this shape, the strength of the structure depends on its dimensions, material properties, material distribution, and loading conditions. It was an excellent evolutionary choice for the clavicle to be a hyperbolic paraboloid cortico-cancellous tube, with varying cross-sections along its diaphysis and cortical thickness, conferring high strength, stiffness, and resistance to torsion and bending.

The screw twist in the hyperbolic paraboloid tube further increases its stiffness by distributing the applied torsional forces *(stresses)* uniformly around its circumference, thereby increasing its weight-carrying capacity marginally better. The twisted tubular bone responds to Wolf’s law, in all the three planes, laying additional bone material at places of higher stresses. Though the screw twist increases the torsional stiffness of the hyperbolic paraboloid tube, the varying pitch decreases the fatigue resistance *(a material property dependent on the number of cycles)* of the tube due to the areas of high stress concentration, leading to a crack invitation *(stress fracture)* and its propagation over time. On the other hand, the gradually varying pitch allows a gradual transmission of torsional forces and varying speeds between the opposing curves, reducing the likelihood of sudden localized stress risers and fracture.

Therefore, depending on the loading conditions, the clavicle is not free from the likelihood of a stress fracture at the inflexion site, where the screw twist changes direction. The occurrence of stress fracture at the transition zone of the hyperbolic paraboloid tube would also increase due to the decreased bending stiffness at the laterally concentrated inferior curvature of the tubular clavicle. Optimization of the twist pitch minimizes stress concentrations, and reinforcement with additional material provides higher stiffness at the critical areas of the structure. Engineers consider using a high-strength, fatigue-resistant material and reinforcement to mitigate potential drawbacks. In contrast, in a tubular cortical bone, the thickness of the cortex varies by laying down a thicker cortex at areas of higher stress.

15.0 Importance and parameters for reconstructing the hyperbolic paraboloid clavicle:

The hyperbolic curve has a longer radius of curvature, a longer chord and subtends a shorter line between the vertex and the centre of the chord. The parabola has a smaller curvature radius, smaller chord length, and subtends a relatively longer line between the vertex and the centre of the chord.

For maximum mechanical advantage in a linear hyperbolic paraboloid lever system, theoretically, the optimal ratio of_

Hyperbolic chord length / Parabolic chord length = 2:1 or greater.

And the lines subtending between vertices and centre of chords –

Hyperbolic line length / Parabolic line length = 1:2 or smaller.

In the case of the clavicle, the medial chord is longer than the lateral chord. It does not matter a great deal if the medial two-thirds are marginally flattened by an intramedullary implant. The ratio ensures an optimal balance between force multiplication and structural stability, maximizing the mechanical advantage of the linear hyperbolic paraboloid lever system.

In a differential screw, the smaller pitch thread should be at the leading end to draw the two blocks together into compression. The smaller pitch thread has a higher thread density *(threads per inch or cm)* and a smaller lead angle. This results in a greater mechanical advantage, allowing for more force to be applied to the screw, compressing the blocks firmly. The smaller pitch thread also provides a slow rate of travel, which is beneficial for applications that require precise control and high force. The recovery of this parameter in the intercalated clavicle with a differential pitch between its medial and lateral curvatures is vital to keep the manubrium and the acromion pulled together in compression, opposing the centrifugal force for a controlled projectile delivery.

A hyperbolic paraboloid structure has a point zero, where the two curvatures meet. The equilibrium of tensile and compressive forces at the point zero prevents the formation of a stress line and discourages the initiation and propagation of cracks. However, changes in the direction of the screw twist and the varying pitch about the point zero are also the sites of higher stress concentration. Therefore, once a crack line develops on the surface of a hyperbolic paraboloid shape, it never spreads symmetrically along the initial fracture line. The structure and substance fall apart unpredictably in different directions, producing small and large fragments of varying shapes due to the loss of equilibrium of intrinsic forces in the stable hyperbolic paraboloid geometry. The force equilibrium property of the hyperbolic paraboloid geometry makes the clavicle robust, but when fails, it often results in fragmented fractures.

Figure 16. Kitchen water pump.

The tubular hyperbolic paraboloid clavicle has lower stiffness in the radial direction (*along the radius, bending in elevation and retraction*), often causing posterior-superior angulation with transverse or short spiral fractures, and higher resistance to tangential forces (*perpendicular to radius, posterior axial rotation*) rarely causing long spiral torsional fractures. It provides a higher strength-to-weight ratio due to the hollow core and operates in environments with combined high radial and tangential forces, during abduction, forward flexion, and circumduction. The radial force keeps the arm turning into the cocking pose, and variable turning speed, due to the tangential force, controls correct positioning, providing the angular velocity to accelerate the projectile delivery. The longer the radius (*length of the humerus acting as the radius of the cocking arm*) higher the tangential force and angular acceleration. The hyperbolic paraboloid handle of a traditional kitchen water pump, not much different in design to the clavicle, offers potential advantages: it is aesthetically distinctive in appearance, ergonomical, occupies minimal space and amplifies the force applied to the piston rod, making it easier to pump (**Fig. 16**). Its triple curve resembles the two curves of the clavicle continuing with the curved acromion.

In summary, an opposing hyperbolic paraboloid design of the clavicle offers several advantages. 1. Increased stability due to unique curvatures that offer greater resistance to buckling and torsion. 2. Enhanced, even load distribution reduces stress concentrations and increases structural integrity, preventing potential failure points. 3. The free parabolic end (*acromial end*) of a hyperbolic paraboloid (*clavicle*), acting as a cantilever strut, is ideal for hanging weights (*upper extremity*) because it has a shorter radius of curvature and a higher second moment of inertia in the anterior-posterior plane, due to its rectangular cross-section, making it stronger and more stable for pushing load. 4. The paraboloid curve is also more resistant to deformation and bending, ensuring that the weights lifted in front of the body are securely supported. 5. The hyperbolic end (*medial curvature*), with its shallower depth and longer radius of curvature, is better suited for attachment to a fixed point (*sterno-costoclavicular joint*) for the cantilever function. 6. Increased design flexibility during future evolution of the structure, in terms of repurposing, of design and re-engineering optimisation of the structure's performance.

Thus, the topographical configuration of the clavicle as a cranking lever system with the paraboloid free end maximises the structure's strength, stability, and load-carrying capacity. Therefore, patient-specific and patient-appropriate surgical planning to select type of implant and site of its placement requires computer-based bone-implant modelling in each fracture type to support detailed stress analysis and fatigue testing(Gandhi, 2022a, 2022b). By carefully considering these factors, one can harness the benefits of the clavicle's unique hyperbolic paraboloid tubular shape, with intrinsic strength of the trabecular plates and columns during bone remodelling. Minimizing post-fracture malunion can limit the long term adverse biomechanical functions of the clavicle.

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