Complex distal humerus trauma
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CHAPTER 1

Evolution of the Distal Humerus

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Introduction
The quality of elbow function after fracture of the distal humerus is related to the degree to which normal anatomic relationships are restored.\textsuperscript{1-4} Through time, the human elbow has evolved into a complex non-weight bearing articulation, giving the distal humerus an intricate osseous anatomy.\textsuperscript{5} The ulnohumeral articulation allows the hand to move from and to the body, where the radio-ulnar articulation facilitates hand position.\textsuperscript{6}

The same basic elbow design is shared amongst all vertebrates.\textsuperscript{7} In most vertebrates, the elbow is primarily used for locomotion. However, the elbow is used in different ways depending on the locomotor demands placed upon the system. Understanding these demands enables us to appreciate the differences in distal humerus morphology between species.

This chapter will discuss the evolutionary changes to the elbow in general and more specifically the distal humerus. A general perspective of vertebrate evolution will be given after which the distal humeri of 6 species that use their elbow in different manners will be compared. Finally, general considerations regarding the comparative morphology of the distal humerus will be given.

Evolution
Bone is only found in vertebrates.\textsuperscript{8} The origin and early evolution of vertebrates took place in marine water, somewhere around 544 million years ago (Ma). Fossils have left a detailed record of the structure of lobed fins: pectoral appendages that internally possess bones homologous to those of early Tetrapod limbs. (fig. 1) Tetrapods ('four-footed') are the common ancestor, shared by amphibians, reptiles, bird and mammals. Ancathostega, an early Devonian, showed transitional features from fish to Tetrapod and could be described as a “food-footed fish”(fig. 2A and 2B). The first tetrapods quickly displayed changes in the appendicular skeleton correlated with locomotion on land and the exploitation of the terrestrial environment.\textsuperscript{9-11} The pelycosaur is a late Paleozoic reptile that later gave rise to therapsids.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fins_to_limbs.png}
\caption{Fins to limbs. From left to right: Polypterus, Sauripterus (Tetrapodomorph) and Limnoscelis (Thetrapod). (From Anderson, J.S.)}
\end{figure}
The distal humerus of the pelycosaur shows a bulbous capitellum and the humero-ulnar articulation is formed but has a concave ventral surface and a flat dorsal surface.\textsuperscript{12-14}(fig. 3A) Three-hundred and forty Ma the amniotes (reptiles) evolved from the tetrapods: the first fully terrestrial vertebrates. Therapsids, mammal-like reptiles, appeared in the late Permian (300 Ma). Their stance was quadrupedal and their limb posture was less sprawled than reptiles. The femur and especially the humerus show torsion of their distal ends which rotates the digits in line with the direction of travel.\textsuperscript{13}

Cynodons (256 Ma), the common ancestor of all mammals, had limbs directly beneath the body, not sprawled, thereby contributing to the ease and efficiency of active terrestrial locomotion.\textsuperscript{15-20} On the distal humerus of the cynodont, the radial condyle (capitellum) and ulnar condyle are separated by a shallow groove. (fig. 3B) The distal humerus of the theria (live bearing mammals) had several modifications. The trochlea is more apparent, deeper and separated from the capitellum.\textsuperscript{13} (fig. 3C) Around 125 Ma the theria evolved into monotremes (egg laying mammals), metatheria (marsupials) and eutheria (placentals).\textsuperscript{21}
FIGURE 3

A. Distal Humerus of a pelyocaur. (From Jenkins, F.A.)

B. Distal humerus of a cytodont. (From Jenkins, F.A.)

C. Distal humerus of a bear. (From Jenkins, F.A.)
Comparative Morphology of Eutheria

Locomotion through a fluid medium:
Aquatic: Dolphin (*Lagenorhynchus acutus*)
The dolphin is a species of the Delphinidae, in the order of cetacean. Cetaceans (whales, dolphins, and porpoises) descended from terrestrial mammals. Their forelimbs have been radically modified during the limb-back-to-flipper transition. (fig. 4)
Like many other fully aquatic animals, cetaceans employ a lift based propulsion system using an oscillating hydrofoil to generate thrust. Their smooth, streamlined fusiform body is propelled by high aspect ratio flukes. Flippers are of prime importance in total hydrodynamics controlling stability, minimizing drag, and effecting forces in roll, pitch, and yaw directions. The morphology and skeletal design both favor maneuverability over speed – adaptations suited to prey and feeding techniques.

In the transition to an aquatic lifestyle, cetaceans have lost most forelimb structural complexity and evolved into a stiff forelimb distal to the shoulder. They display a mostly immobile flipper that is rigid, reinforced by dense connective tissue. If the flippers were malleable and deformed under hydrodynamic pressure, this would increase drag and decrease the speed of corkscrewing.

The elbow joint is immobilized as the radius and ulna are firmly attached to the distal end of the humerus by articular cartilage. The lower end is broad and flattened and its inferior surface is divided into two nearly equal flat surfaces placed side by side (one external, the other internal) and meeting at a very obtuse angle. The wrist is mostly immobilized by closely opposed carpal elements that lack the ability to glide relative to another.

Corresponding with the loss of elbow joint mobility, cetaceans are unique in displaying atrophied muscles in the triceps complex. A shortening and flattening of the humerus, radius, and ulna is also observed. Flipper movement is generated at the glenohumeral joint primarily by means of the deltoid and subscapularis muscles. The musculature of the in the brachial region have become vestigial or absent, given the lack of mobility of the forelimb at the elbow joint and antebrachial muscles display drastically reduced origins and insertions.

Areal: Bat (*Pteropus giganteus*)
Bats (order Chiroptera) have gone beyond the gliding and parachuting abilities of several lineages of flying squirrels, flying lemurs and Australian gliders and developed active flight. As a consequence of this achievement, bats underwent one of the greatest adaptations in the history of mammalian evolution. (fig. 5) Bat powered flight is made possible by several key morphological innovations, one of the most crucial being the elongation of the forelimb digits to support the broad, two-layered wing membrane, stretched between the side of the body and the collapsible support system formed by the arm, hand and finger bones.
Many of the joints of the bat forelimb are specialized to restrict movement in the plane of the outstretched wing. This allows a reduction of the joint stabilizing
musculature and a decrease of insertion area of the remaining muscles that control flexion and extension.\textsuperscript{42}

The large, strong humerus is suspended from the scapula\textsuperscript{41} and has a slight sigmoid curve.\textsuperscript{32} The distal articular surfaces are rotated anteriorly and both lateral and medial epicondyles are widely displaced from the long axis of the shaft.\textsuperscript{43, 44} The medial condyle is large, the lateral side small.\textsuperscript{45}

The humeral capitellum is non-spherical with its articular surface limited laterally and medially by ridges and grooves and its articular surface is mostly aligned with the shaft. The groove separating the capitellum from the trochlea is deep and rather V-shaped.\textsuperscript{46} The presence of a prominent spinous process from the medial condyle is consistent throughout the chiroptera.\textsuperscript{44}

The extensive, rigid articulation between the trochlea and the radius only allows motion in the anteroposterior plane and is associated with relatively fast, direct flight.\textsuperscript{47-49} The radius occupies the greater part of the joint and is greatly enlarged, sometimes being twice as long as the humerus.\textsuperscript{45} The radius cannot rotate and the wrist can only flex and extend. The ulna is reduced: only the upper third being present and that is ankylosed with the radius. There is a detached sesamoid ossicle on the olecranon.\textsuperscript{32} These modifications make the wing gain strength and rigidity in order to withstand air pressures associated with flight.\textsuperscript{49, 50}

**Locomotion through a solid medium:**
**Fossorial: Mole (Talpa europaea)**

Moles are the majority of the members of the mammal family Talpidae, in the order Soricomorpha. Fossil evidence shows that the Talpidae radiated into subterranean habitats as early as Eocene times.\textsuperscript{51, 52} (fig. 6)

Ridges are a common sign of the presence of moles and are made as they travel just beneath the surface by forcing their way through the soil.\textsuperscript{53} Their burrows are used for nesting, food storage, sanitation\textsuperscript{54} and retreat.\textsuperscript{55-57} The closed environment provides a relatively constant microclimate, protection from predators or competitors, and access to food.\textsuperscript{58-60}

The manner of its subterranean locomotion necessitates very powerful forelimbs and a pectoral girdle to excavate the burrow.\textsuperscript{61, 62} The moles almost swim through the earth, their burrowing process called a ‘lateral thrust method of digging’.\textsuperscript{63, 64} Their front limbs are armed with broad spade-like claws.\textsuperscript{62} When the claws are moved aside, the mole straightens its forelimbs forward, extending the shoulder and elbow, while rotating the shoulder as to fixate the humerus in parasagittal position.\textsuperscript{64-67}

In no other group of mammals has the humerus undergone as remarkable a rotation and transformation as in talpids.\textsuperscript{62, 65} Associated changes are related to the development of areas of muscle attachment.\textsuperscript{68} The humerus has undergone considerable medial rotation. Its lateral border faces antero-medial and its medial border postero-lateral, while, as a result of extension and abduction, its proximal extremity is directed postero-medial and its distal extremity antero-lateral.\textsuperscript{69}
The distal humerus has four oversized processes. The lateral epicondyle consists of a sharp spinous process, a smooth, oval shaped capitellum and the radial fossa. The medial epicondyle is marked by a spinous process proximally and the trochlea is shaped like a slightly bent cylinder. Adjacent to the medial epicondyle on the ventral surface are the supracondylar foramen, which transmits the median nerve, and a slight coronoid fossa with on the dorsal surface the deep olecranon fossa.

**Locomotion on a substrate:**

*Arboreal: Gibbon (Hylobates lar lar)*

The bimanual arm swinging locomotion of the gibbons (Hylobatidae) is a highly specialized mode of locomotion that involves energy-saving mechanisms using gravity. 70-74 Besides brachiation, gibbons frequently walk along branches using bipedal locomotion and climb vertically. 75 Analytical studies of body proportions in gibbons using an oscillating model showed that the concept of a pendulum motion of the free arm in gibbons is important for acceleration of the body. 72, 73 (fig. 7) Elbow flexion of the support arm during brachiation is important to accelerate body progression. 72, 76 Increased arm length results in improved periodicity, greater efficiency and higher velocity. The shoulders are very mobile, mostly as a result of freedom of movement of the scapula. 77 Increased stability of the elbow joint is achieved by making use of the crachioradialis muscle as a shunt, contracting automatically if its fibers are suddenly extended and so cushioning the shock which prevents potential dislocation of the elbow. 78

The humerus of brachiators has prominent muscular processes and the upper limb bones are very slender as well as elongated. A supratrochlear foramen in the humerus appears rarely in hylbatids. 80 The articular surface is perpendicular to the shaft with a relative low biepicondylar width. 81

The elbow joint has several features associated with full extension: small olecranon process of the ulna, deep olecranon fossa and posterior extension of the distal articular surface of the humerus. The lateral keel of the trochlea is much less well-defined and the medial slope of the lower humeral surface is lacking. The capitellum is rounded, and occupies more of the articular surface than the trochlea.

Pronators and supinators are strongly developed in brachiators, correlated with a strongly developed medial epicondyle to the humerus which makes it possible to rotate 180 degrees. 83 However, the lateral epicondylar ridge is poorly developed. 84

*Terrestrial, quadrupedal: Lion (Felis leo)*

Cats are part of the order of the carnivora. Efficiency as a predator necessitates the ability to make a wide variety of movements. Carnivores have not specialized in the performance of one particular type of movement to the detriment of others: some are swift runners, but most can also climb or dig to some extent and many are good swimmers. 85-86 (fig. 8)
In felines, elbow and knee are oppositely oriented. When the forefoot contacts the ground the humerus is vertical and the elbow and wrist slightly flexed. The paw thus comes down well in advance of the elbow. Retraction of the humerus with extension of the elbow and wrist then follows. In the recovery stroke, the elbow is first flexed and the humerus protracted; as the latter nears the vertical position, elbow and wrist extend again to set the foot down for the next step.¹⁶¹

This gait is associated with digitigrade foot pressure: elevated metacarpals to an acute angle, leaving only the phalanges in contact with the substrate.⁸⁹ In cursorial species there is a tendency for action to be limited to movement in the sagittal plane: the head of the humerus is more cylindrical and the articulating grooves between the humerus and ulna are deeper.⁸⁸, ⁹⁰ Some carnivores retain supinatory ability, allowing them to manipulate prey and other items with their forepaws.⁸⁵-⁸⁷, ⁹¹

The articular surface of the distal humerus is displaced 90 degrees anteriorly and is slightly dorsally to the axis of the shaft. The concave trochlea continues directly into the capitolium, without a defined lateral margin of the trochlea.⁹², ⁹³ The olecranon fossa is deep compared to other species since the olecranon is enlarged for the attachment of a powerful triceps, necessary for fast quadrupedal movement. The supracondylar foramen is a narrow perforation from the ventral to the dorsal aspect of the humerus near the caudal side of the distal extremity. Through it pass the median nerve and the brachial artery.⁹⁴

Terrestrial, bipedal: Human (Homo Sapiens)
Most paleoanthropologists agree that bipedalism is the key adaptation of the hominin clade.⁹⁵ Some of the most long-standing questions in paleoanthropology concern how and why human bipedalism evolved. Some theories include monkey-like arboreal or terrestrial quadrupedalism, gibbon- or orangutan-like (or other forms of) climbing and suspension, and knuckle-walking. (fig. 9) The functional characteristics of the shoulder and arm, elbow, wrist, and hand shared by African apes and humans, including their fossil relatives, most strongly supports the knuckle-walking hypothesis, which reconstructs the ancestor as being adapted to knuckle-walking and arboreal climbing.⁹⁶ The elbow is typically extended during knucklewalking,⁹⁷ which suggests that stability in extended postures may be particularly important to resist torque. Some early hominin humeri have features related to strong elbow extension, such as extension of the distal margin of the capitellum onto the posterior aspect of the humerus.⁹⁸ Details of the forelimb remains of Ardihipithecus, including a well-developed lateral trochlear ridge on the distal humerus,⁹⁹, are consistent with the knuckle-walking hypothesis.

Flexion at the elbow underlies man’s ability to carry food to his mouth. The distal end of the humerus bulges anteriorly at an angle of 30 to 45 degrees to the shaft (or: its most anterior point of the articular surface lies 11.7 mm in front of the anterior border of the shaft).¹⁰⁰-¹⁰⁵ In the same way the trochlear notch of the ulna projects anteriorly and superiorly at an angle of 45 degrees to the ulnar shaft. This anterior projection of the articular surfaces and their inclination promotes
The anterior translation evolved during the transition from quadruped to biped as the need for stability was supplanted by the need for flexion. A straight distal humerus offers more stability in extension, whereas an anteriorly translated distal humerus offers more stability in flexion.\textsuperscript{106, 107}

The trochlea is pulley-shaped with a central groove and is bound by two convex limps accommodating the trochlear notch of the ulna. The capitellum is a hemisphere placed anteriorly and distally on the distal humerus, laterally from the trochlea, articulating with the radial head. Immediately above the articular surfaces, two concavities are present: anteriorly, the coronoid fossa which receives the coronoid process during flexion; and posteriorly the olecranon fossa which receives the olecranon process of the ulna during extension. The compact portions of the distal humerus lie on either side of these fossae, forming two divergent pillars, one ending on the medial epicondyle, the other on the lateral epicondyle; in this fork-like construction, the capitulo-trochlear articulation complex lies supported.\textsuperscript{106}

The humero-ulna articular combination (the true elbow joint) has a range of motion of 145 degrees actively and up to 160 degrees passively.\textsuperscript{6} Women and children can increase this by 5-10 degrees depending on the laxity of the ligaments, allowing hyper extension.\textsuperscript{106} The range of motion of rotation (pronation and supination) is around 175 degrees. Rotation is a function of the radio-ulnar joints, superior and inferior. The muscles for of the upper limb are adapted for climbing: maximum efficient flexion occurs when reaching up while strongest extension is achieved when the arm is pointing downwards.\textsuperscript{106}

**General considerations on distal humerus comparative morphology**

Evolution is the process of continuously changing life on earth, sustaining the most practical adaptations. The evolutionary development and diversification of the mammalian humero-ulnar joint principally reflects changes in forelimb posture and excursion.\textsuperscript{13}

Bones, cartilage, tendons, ligaments and muscles of all vertebrates have a gracefully efficient physical order. The existence of a hierarchy of structural and kinematic harmony is not accidental but the result of unique and complex phylogenetic and ontogenetic histories in which genes and mechanical forces provide critical control.\textsuperscript{108} The development of joint surfaces and bone geometry near joints can be viewed as an interdependent causal relationship between form and function. The structural changes of the distal humerus articulation reflect a functional shift in load bearing, joint stability and forearms rotation that is connected with differences in forearm use.\textsuperscript{109}

Capitellum shape is correlated with movement of the radius on the humerus, and a more spherical shape is generally indicative of multi axial movement, whereas a trochleated capitellum is correlated to varying degrees with fast flexion/extension of the ulna that requires lateral bracing. A distally flattened (as opposed to rounded) capitellum with well-defined borders is characteristic of more terrestrial vs. arboreal species.\textsuperscript{110-115}
The deeper trochlea of terrestrial mammals\textsuperscript{10, 114-116} has extended surface area for ulnar articulation and medial restriction of that articulation.\textsuperscript{117} A more derived mammalian condition where the trochlea takes over more direct loads at the elbow, and the capitellum is reduced, plays an important role in movement associated with radial rotation.\textsuperscript{115}

Deep or perforated coronoid and/or olecranon fossae are generally attributed to more extreme degrees of forearm flexion and extension, respectively.\textsuperscript{113} There is a significant correlation between anterior translation of the articular surface of the distal humerus and elbow flexion.\textsuperscript{100} The entepicondylar foramen, which transmits the median nerve\textsuperscript{64} is considered to be a primitive therian trait that has been lost in several mammalian taxa.\textsuperscript{114, 115, 118, 119}

Most of the variation in the width of the distal humerus is accounted for by the medial and lateral epicondyles. These structures serve as areas of origin for the wrist and digital flexors (medially) and extensors (laterally).\textsuperscript{120-124} Differences in mediolateral widths of the trochlea and capitellum suggest how much body weight is distributed on one side of the humerus relative to the other.\textsuperscript{113, 114}
FIGURE 4: Distal humerus of *Lagenorhynchus acutus*

A. Anterior view  
B. Posterior view  
C. Lateral view  
D. Medial view

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FIGURE 5: Distal humerus and olecranon sesamoid of *Petropus giganteus*

A. Anterior view  
B. Posterior view  
C. Lateral view  
D. Medial view  
E. Articular surface

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FIGURE 6: Distal humerus of *Talpa europaea*

A. Anterior view with complete arm
B. Anterior view
C. Posterior view
D. Medial view
E. Lateral view

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FIGURE 7: Distal humerus of *Hylobates lar lar*

A. Anterior view
B. Posterior view
C. Lateral view
D. Medial view
E. Articular surface

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FIGURE 8: Distal humerus *Felis Leo*

A. Anterior view  
B. Posterior view  
C. Lateral view  
D. Medial view  
E. Articular surface

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FIGURE 9: Distal humerus Homo Sapiens

A. Anterior view
B. Posterior view
C. Lateral view
D. Medial view
E. Articular surface

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References
44. Walton DW, Walton GM. Comparative osteology of the pelvic and pectoral girdles of the phylllostomatidae (Chiroptera; Mammalia). Dallas: Southern Methodist University Press; 1968.
57. Scheffer TH. Excavation of a runway of the pocket gopher (Geomys bursarius). Trans Kans Acad Sci 1940;43.

28
64. Reed CA. Locomotion and appendicular anatomy in three soricoid insectivores. American Midland naturalist 1951;45:513-671.
116. Szalay FS, Sargis EJ. Model-based analysis of postcranial osteology of marsupials from the Palaeocene of Itaborai (Brazil) and the phylogenetics and biogeography of Metatheria. Geodiversitas 2001;23:139-302.