The Morphological Basis of the Arm-to-Wing Transition

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Human-powered flight has fascinated scientists, artists, and physicians for centuries. This history includes Abbas Ibn Firnas, a Spanish inventor who attempted the first well-documented human flight; Leonardo da Vinci and his flying machines; the Turkish inventor Hezarfen Ahmed Celebi; and the modern aeronautical pioneer Otto Lilienthal. These historic figures held in common their attempts to construct wings from man-made materials, and though their human-powered attempts at flight never came to fruition, the ideas and creative elements contained within their flying machines were essential to modern aeronautics. Since the time of these early pioneers, flight has continued to captivate humans, and recently, in a departure from creating wings from artificial elements, there has been discussion of using reconstructive surgery to fabricate human wings from human arms. This article is a descriptive study of how one might attempt such a reconstruction and in doing so calls upon essential evidence in the evolution of flight, an understanding of which is paramount to constructing human wings from arms. This includes a brief analysis and exploration of the anatomy of the 150-million-year-old fossil *Archaeopteryx lithographica*, with particular emphasis on the skeletal organization of this primitive bird's wing and wrist. Additionally, certain elements of the reconstruction must be drawn from an analysis of modern birds including a description of the specialized shoulder of the European starling, *Sturnus vulgaris*. With this anatomic description in tow, basic calculations regarding wing loading and allometry suggest that human wings would likely be nonfunctional. However, with the proper reconstructive balance between primitive (*Archaeopteryx*) and modern (*Sturnus*), and in attempting to integrate a careful analysis of bird anatomy with modern surgical techniques, the newly constructed human wings could function as *cosmetic* features simulating, for example, the nonfunctional wings of flightless birds. *(J Hand Surg 2008;33A:277–280. Copyright © 2008 by the American Society for Surgery of the Hand.)*

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In AD 875, Abbas Ibn Firnas, a Spanish inventor who had formally studied chemistry, physics, and astronomy, attempted the first well-documented human flight.[1] After he had completed the final construction of his human flying machine, he invited prominent members of the community to witness his flight and then he leapt from a nearby building (Fig. 1). Though some reports have Firnas gliding some distance, the landing was rough and he sustained multiple injuries, including a debilitating back injury that approximately 10 years later would claim his life. This began the long and storied history of humans attempting flight with fabricated wings, a history that includes Leonardo da Vinci and his flying machines, as well as the 17th century Turkish inventor Hezarfen Ahmed Celebi, who attempted, and apparently succeeded in, a short-distance human-powered flight from the Galata Tower in Istanbul. Since these early attempts at flight, the captivating form of the wing and its exquisite locomotor function has continued to capture the attention of humans. In both the popular press and scientific circles, this interest has taken a departure from the premise of attempting to fabricate wings from non-human materials and has instead focused on using reconstructive surgical techniques to construct human wings from human arms.[2]

The evolution of wings specialized for flight and the adaptive radiation of modern birds resulting from such specialization has spanned more than 200 million years and includes the derivation of anatomic characteristics unique to birds, including feathers for lift and insulation, a highly derived shoulder (triosseal canal for passage of the supracoracoideus tendon), and apparati of the thorax

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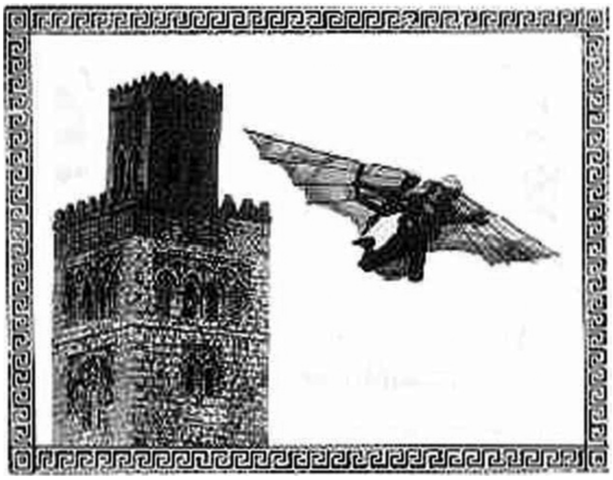

FIGURE 1: Artist's rendition of Abbas Ibn Firnas' AD 875 attempt at human-powered flight (artist and date unknown).

distinctly associated with flight (derived supracoracoideus muscle and unusual arrangement of the pectoralis).[3–6] In order to create a bird wing out of a human arm, each of these characteristics will need to be addressed in turn.

It is important to maintain an evolutionary perspective in answering this question and to carefully consider stages in the evolution of flight in which the forelimb was more primitive and less derived than modern birds while still achieving the characteristic look and shape of a modern bird wing. For example, *Archaeopteryx lithographica*, from the Solenhofen Limestone Formation in Germany, is one such specimen that lived approximately 150 million years ago (Fig. 2). It is likely that this bird and other Mesozoic birds (eg, *Confuciousornis sanctus* and others from China) were at least capable of some degree of powered flight, albeit rudimentary.[7] In briefly parting from an attempt to construct a wing out of an arm for functional purposes and instead opting to construct a wing for cosmetic purposes alone—such as to simulate the wings of an angel—it is more realistic to conceive of the reconstructed forelimb resembling the wing of *Archaeopteryx lithographica* rather than the wing of a highly derived modern bird such as a pigeon. *Archaeopteryx* was clearly a bird in its wing structure, which included feathers that were the appropriate size and shape, but also lacked complexity in the wrist and shoulder, features that would be nearly impossible to surgically reconstruct with any detail.

Cosmetic wings could be fabricated from a human arm using advanced reconstructive techniques by first fixing the distal row of carpal bones to the metacarpals to form the carpometacarpus. The small finger and ring finger should be fused, while also fusing the ring and index finger. The carpometacarpus together with the proximal row of carpals and the phalanges are collectively referred to as the manus.[8] Particular attention should be paid to not disturbing the thumb, which should remain free and functional thereby retaining the characteristic "thumb" of the bird, the alula

FIGURE 2: *Archaeopteryx lithographica*. Pictured here is the 150-million-year-old "Berlin Specimen" of *Archaeopteryx lithographica*, 1 of 8 known specimens. Thought to be an intermediate form in the evolution of birds from theropod dinosaurs, *Archaeopteryx* clearly has structures that resemble bird (eg, feathers, derived wing structure) while retaining the less derived osteology of theropod dinosaurs. (Photo by O. Louis Mazzatenta.)

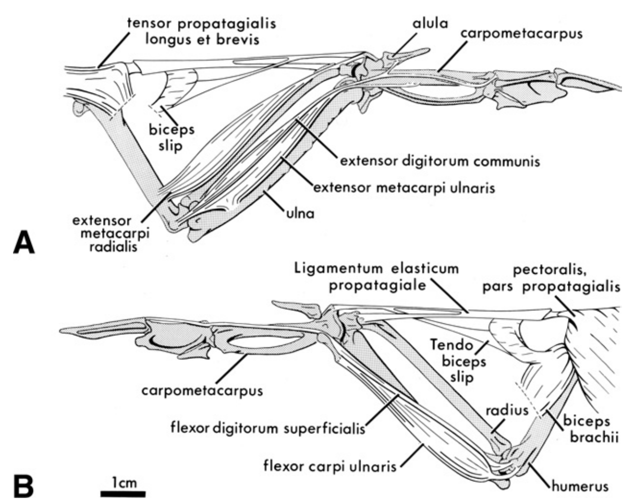

FIGURE 3: Right forelimb of a pigeon shown from both **A** dorsal and **B** ventral perspectives. The muscles in this illustration are those that span 2 joints and therefore aid in the automatic flexion-extension mechanism of the avian wrist. Structures of note are the alula (homologous to the thumb in humans) as well as other directly homologous structures (eg, extensor metacarpi ulnaris/radialis, flexor carpi ulnaris, flexor digitorum superficialis). (Adapted from Vazquez RJ. The automating skeletal and muscular mechanisms of the avian wing [aves]. Zoomorphology 1995;114:59, with permission.)

(Fig. 3). The manus should be fixed on the radial side of the carpometacarpal joint to prevent radial deviation while still allowing for full ulnar deviation. The resting position should be about 30° ulnar deviation. The elbow should be

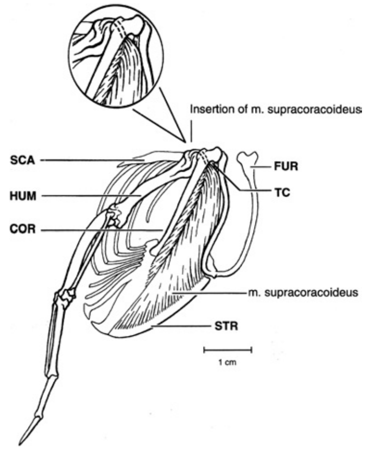

FIGURE 4: Anterolateral view of the right shoulder in the European starling *(Sturnus vulgaris)* demonstrating the "reverse-pulley" organization that is a hallmark of flying birds. The pectoralis muscle has been removed to expose the ventral supracoracoideus muscle. The muscle takes its origin from the sternal keel, and its tendon of insertion traverses through the triosseal canal (composed of the furcula, scapula, and coracoid) to its dorsal insertion on the humerus. The organization of this muscle allows for humeral rotation and elevation with muscle contraction. SCA, scapula; HUM, humerus; COR, coracoid; TC, triosseal canal; FUR, furcula; STR, sternum. (Adapted from Poore SO, Sanchez-Haiman A, Goslow GE. Wing upstroke and the evolution of flapping flight. Nature 1997;387:799, with permission.)

reconstructed primarily by limiting extension beyond about 110° maximum. *Bony* fixation should not be used in the elbow because active flexion and extension are necessary to achieve the classic folded wing posture of birds or the slightly extended wing posture of angels. Rather than using a bony device or even redirected ligaments to tether the joint, limitation of full extension beyond 110° degrees should be achieved by constructing a propatagium out of existing muscle and skin. The propatagium in birds consists of the propatagialis muscle complex, which is covered by skin and feathers to form the web of tissue that spans the elbow joint (see the ligamentum elasticum propatagiale in Fig. 3). This important leading edge structure could be reconstructed in humans by redirecting the biceps muscle along with its tendon of insertion to a more distal location on the radius (becoming the propatagialis muscle *de facto*) with adequate skin coverage being achieved using tissue expansion techniques.

The shoulder in modern birds is highly derived with a unique arrangement of the coracoid, scapula, and furcula (wishbone) to form the triosseal canal, an osseus canal that permits passage of the tendon of the supracoracoideus muscle to its dorsal insertion on the deltopectoral crest of the humerus (Fig. 4). This muscle is used for high-velocity rotation of the humerus about its long-axis during the upstroke, thereby placing the wing in the proper position for the ensuing downstroke.[6,9] If wings were being constructed in an attempt to attain powered flight in humans, reconstructing the shoulder to this avian configuration would be absolutely necessary. However, for nonfunctional cosmetic wings, further modification of the shoulder or the thorax is not necessary.

The final issue, and the one that is probably the most difficult to achieve, is the question of feathers. Feathers are highly derived structures, unique to the lineage, including birds, and their evolution likely followed a trajectory consisting of multiple steps involving downy feathers first, contour feathers second, and ultimately flight feathers.[3,10] One plausible option would be to somehow modify feathers from preexisting hair or latent hair-follicles. Unfortunately, however, whereas feathers and hair are both epidermal in origin, the papilla giving rise to the follicle for a hair starts out deep in the dermis, whereas a feather follicle begins surrounding an outpocketing of dermis from the surface of the epidermis. The specifics of the biochemistry of the keratins of each are different, too.[11] Thus, in order to cover the "cosmetic wings" of humans, some new innovation for the feather-like structures would need to be employed.

The question of weather it is realistic to reconstruct *functional* wings from human arms is also interesting to consider, and this is best answered by looking at a sample of research on the functional aspects of bird flight. Starting distally: There are several mechanisms with respect to the wrist that are essential to bird flight including finely controlled supination and pronation and tenodesis of the carpometacarpus with flexion and extension of the elbow.[12] The shoulder is also complex in its organization for flight including the triosseal canal for passage of the tendon of the supracoracoideus muscle, important for high-velocity rotation of the humerus during upstroke and thus repositioning the wing for downstroke, an action essential for powered flight in birds.[6] The supracoracoideus muscle (homologous to the infraspinatous/supraspinatous in mammals) also has a unique organization, being located deep to pectoralis major but inserting on the dorsal aspect of the humerus (Fig. 4).[13] It is a hallmark of modern birds. The pectoralis also has a unique organization, consisting of 2 dominant heads, the thoracobrachialis and the sternobrachialis, and is specialized for flight in its organization of motor units, fiber types, and architecture.[14,15] It would be difficult to achieve in humans the unique pulley-like organization of the supracoracoideus as well as the specific partitioning of the pectoralis because of both a lack of anterior thorax modification and the proper configuration of the triosseal canal. The final issue is that of wing loading, which is defined as the ratio of body mass to wing surface area (wing area/body weight). This parameter is critical in determining a bird's ability to fly, with the heaviest wing loading above which flight cannot be sustained being approximately 4.0 g/cm^2. Therefore, for a 170-lb human to achieve any type of flight, he or she would need wings with approximately 20 square feet of surface area. Because the goal is to construct wings using nothing but the arms, it is impossible from the outset to

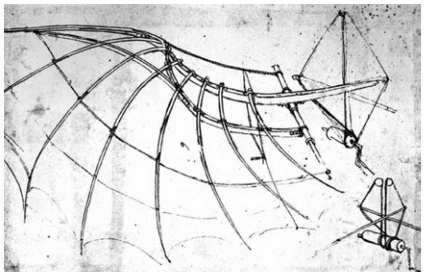

FIGURE 5: Illustrated wing structure by Leonardo da Vinci. From *Codex Atlanticus* dated to between 1486 and 1490. This particular wing illustration, based on da Vinci's earlier study *Codex on the Flight of Birds,* was an important step in the design of a human-powered flying machine.

envision reconstructing arms large enough relative to body size to provide lift for flight.[16,17] Given that mother nature had more than 200 million years to hone the forelimb of reptiles into a functional wing, it is highly unlikely that a reconstructive hand surgeon would be able to form the forelimb into a functional flying appendage over the course of 1, or even a series, of operations.

This is not to say, however, if we were able to modify the forelimb into a wing, either through reconstructive surgery or by other means (wings fabricated from man-made materials), that they would have no use. In microgravity climates, for example, issues of wing loading and lift are much less important, and in this environment wings might prove to be a reliable source of locomotion and navigation.[18] On Earth, however, it is only realistic to envision wings as a cosmetic feature, not a functional one. That raises the bigger question of what we can do and what we should not do.

Humans have been fascinated with flight throughout time. It is a subject that has captured the imagination and tickled the minds of artists, scientists, and physicians throughout history. Icarus experimented with flight and failed. Leonardo da Vinci in *The Codex on the Flight of Birds* attempted to use bird flight as his guide to the requirements of man's flying machine, and his experiments never came to fruition (Fig. 5). The physician Frank Hartman was also fascinated by flight, and his early studies on the locomotor mechanism of birds are widely cited as defining the allometric boundaries of flighted forms.[19] Finally, there is the German scientist Maxheinz Sy (1936) who demonstrated in a simple experiment that when 1 variable—the supracoracoideus—was removed from the flight apparatus of the pigeon, 200 million years of evolution came crashing down.[20]

Despite advances in surgical technique that could theoretically lead to the ability to construct wings from arms, it is evident that humans should remain human, staying on the ground pondering and studying the intricacies of flight while letting birds be birds and angels be angels.

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