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Reinforcements in avian wing bones: Experiments, analysis, and modeling

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ABSTRACT

Almost all species of modern birds are capable of flight; the mechanical competency of their wings and the rigidity of their skeletal system evolved to enable this outstanding feat. One of the most interesting examples of structural adaptation in birds is the internal structure of their wing bones. In flying birds, bones need to be sufficiently strong and stiff to withstand forces during takeoff, flight, and landing, with a minimum of weight. The cross-sectional morphology and presence of reinforcing structures (struts and ridges) found within bird wing bones vary from species to species, depending on how the wings are utilized. It is shown that both morphology and internal features increases the resistance to flexure and torsion with a minimum weight penalty. Prototypes of reinforcing struts fabricated by 3D printing were tested in diametral compression and torsion to validate the concept. In compression, the ovalization decreased through the insertion of struts, while they had no effect on torsional resistance. An elastic model of a circular ring reinforced by horizontal and vertical struts is developed to explain the compressive stiffening response of the ring caused by differently oriented struts.

1. Introduction

1.1. Bird wing skeletons and wing motion

Birds and flying mammals (bats) have lightweight skeletons, which coupled with a high lift to weight ratio, make flight possible. Birds range in mass from several grams (hummingbird) to more than 100 kg (ostrich), with overall range of birds weighing between 10 g and 10 kg (Silva et al., 1997). For bald eagles, the skeleton amounts to only 7% of the body mass, $\sim{}^{1}/_{3}$ of what the feathers represent (Brodkorb, 1955). For flight, other adaptations have evolved such as having a smaller number of bones compared to terrestrial vertebrates, and the fusion of some bones (Proctor and Lynch, 1993; Wolfson, 1955). Birds also have a complex pulmonary system; many have pneumatic bones (particularly the proximal limb bones - the humerus and femur) that are directly connected to the respiratory system, thereby increasing buoyancy (Proctor and Lynch, 1993; Gill, 2007; O'Connor and Claessens, 2005). Flying birds have more hollow bones (not marrow filled) than flightless birds (e.g. ostrich, penguin) (Proctor and Lynch, 1993). Diving birds and hummingbirds have few hollow bones. The diving birds need to have a higher density skeleton to propel themselves through water, and for hummingbirds, the weight savings involved with hollow bones is minimal (Proctor and Lynch, 1993). Bird bones are characterized by a much thinner sheath of cortical bone, compared to terrestrial animals (Currey and Alexander, 1985). The mean bending strength and flexural modulus were found to be significantly higher for marrow-filled than pneumatic bones, but these calculations do not incorporate the differences in moment of inertia due to the internal structure (Cubo and Casinos, 2000). The ratio of internal to external radius is larger in pneumatic bones (~0.80) than in marrow filled bones (~0.65), which results in a mass advantage of pneumatic over marrow filled bones, estimated to be between 8% and 13% by Pauwell (Pauwells, 1980) and Currey and Alexander (Currey and Alexander, 1985).

The bird wing skeleton consists of the humerus ('upper arm'), which is attached to the main flight muscles in the breast, the ulna and radius (radio-ulna or 'forearm'), carpometacarpus ('wrist' and 'hand') and the phalanges ('fingers'). These are shown in Fig. 1 for a turkey vulture (*Cathartes aura*) wing (Novitskaya et al., 2014). Turkey vultures comprise the largest group of New World vultures and are large, soaring birds with an average wingspan of ~ 1.7 m, weigh between 1–2 kg, and feed exclusively on carrion. During flight, the ulna (the main load-bearing element of the radio-ulna) is roughly perpendicular to the humerus, which itself is shorter and thicker, since it needs to withstand larger forces (Proctor and Lynch, 1993).

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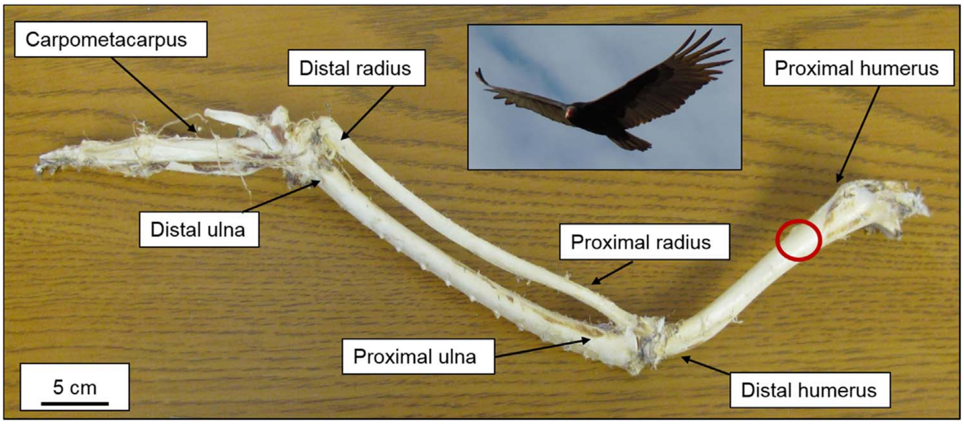

Fig. 1. Photograph of the bones in the left wing of a turkey vulture, pointing out the humerus (attached to the body), radius, ulna and carpometacarpus. Adapted from (Novitskaya et al., 2014). The red circle indicates the area of maximum bending and torsion moments during flight (Pennycuick, 2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Wing motion can be classified as flapping/soaring (flapping wings and soaring, e.g. vultures, eagles), flapping/gliding (flapping wings and gliding, e.g. seagulls, pelicans), flapping (with periodic gliding, e.g. ravens, crows) and flightless (e.g. emus, ostriches and rheas) (Pennycuick, 2008; Bruderer et al., 2010). Microstructural analysis was recently performed on the cross-sections of humeri and ulnae for several flying and non-flying bird species (Novitskaya et al., 2014). It was found that thickness of the bone walls was not uniform for all flying birds due to presence of external pressure and stress distribution in them during the flight. Additionally, it was concluded that bones from flapping/soaring and flapping/gliding birds had ovalized sections, while bones from flapping and non-flying birds have more circular cross-sections.

1.2. Bird bone adaptations

An interesting example of structural adaptation in nature is the internal structure of avian wing bones, which consists of reinforcing structures (struts and ridges, see Fig. 2) (Proctor and Lynch, 1993; Pennycuick, 2008). The bones need to be sufficiently strong and stiff to withstand forces during takeoff, flight, and landing. Wing bones have to resist both bending and torsion loads; they are rarely loaded in pure tension or compression. Due to the high metabolic cost of creating bone, it is believed that the reinforcing structures in bird wing bones grow in response to specific stresses experienced by flying birds, and therefore should be optimal for their purpose. As with mammalian bone, there is a periosteal and endosteal sheath surrounding the cortical bone and a medullary core that is filled with less dense trabecular bone, as shown in the schematic illustration in Fig. 2b. Examples of struts commonly found in many avian bones are shown in Fig. 2a,c from a condor femur and turkey vulture humerus, respectively, for illustrative purposes. The struts are isolated rods that span across the interior diameter of the bone. The struts cannot be classified as trabecular bone because the density of the array is too low. They appear to be at locations “in need,” working against extensive bending forces and preventing the localized buckling of bone walls. They are mainly found on the ventral side of the wing bones of flying birds (Novitskaya et al., 2014; Pennycuick, 2008). Interestingly, the ulnae of the vulture and gull (soaring and gliding birds) have the struts, while ulnae of the raven and duck (flapping and non-flying birds) lack those (Novitskaya et al., 2014). The ridges are rod-like in appearance that lay flat against the interior wall (Fig. 2d). The orientation of the ridges likely develops at about $\pm 45^\circ$ to horizontal axis to help carry large tensile stresses developed during torsion along those directions. Maximum tensile and compressive stresses are generated at $\pm 45^\circ$ to the longitudinal axis. Ridges aligned in these directions will decrease tensile stresses that occur in torsional loading and reverse torsional loading. Since failure in bone is produced by tensile stresses, the configuration of ridges along such directions is most effective (Fig. 2e).

Table 1 lists some of the physical and mechanical properties of humeri and ulnae for different birds, compared to bovine femur bone. The bird bones have higher porosity and lower density, compared to the bovine bone. Additionally, among the birds, the domestic duck has the highest porosity and lowest mineral content, indicating that having high wing bone strength is not essential for a non-flying birds. The present values for the density of the humerus are lower than the mean density found in perching birds (Dumont, 2010), which suggests that a reduction in mineral content for larger soaring and gliding birds is a beneficial development for weight savings and increasing toughness.

The current study will describe in details the influence of struts on the mechanical performance of bird wing bones, while the impact of ridges will be summarized in another publication. Particularly, we analyze the internal structure of wing bones from a turkey vulture and a California condor (*Gymnogyps californianus*) to assess the contribution of reinforcing struts to bending (ovalization) and torsion resistance. Additionally, bone prototypes with reinforcing structures (struts) were fabricated by 3D printing and mechanical testing was performed to investigate ovalization and torsional behaviors. Finally, an elastic model of a circular ring reinforced by horizontal and vertical struts was developed to explain the stiffening of the ring caused by the differently oriented struts.

2. Mechanics background

2.1. Bending and torsion analysis of thin walled sections

Fig. 3a shows the main torsion and bending axes and their respective moment arms for wing bones during activity. During lift, the dominant bending and torsion moment are balanced by a downward pull of the pectoralis muscle. From Fig. 3a one can see that the humerus is subjected to significant torsion. The “radio-ulna unit” can only rotate in the plane of the wing, and is subjected to a bending moment from the outer part of the wing. This is transmitted through the joint as a twisting moment on the humerus (Pennycuick, 1967). The bending and torsional moments carried by the humerus are transferred to the proximal end of the radio-ulna through the elbow joint. The points of application of the forces are marked in the feathers and are approximately 25% of their length. This is, of course, an approximation that integrates the distributed load on the feather due to the aerodynamic force. The bending moment and torsion axes for a specific feather with respect to the humerus are shown in Fig. 3a. The bending moment arm with respect to the proximal end of the humerus is $\overline{OB}$ and torsion arm is $\overline{OA}$. The bending moment is $M = F \times \overline{OB}$ and the torque is $T = F \times \overline{OA}$. The humerus has evolved to resist bending and torsion, and is has adapted to resist torsion at both microscopic and macrostructural levels (de Margerie et al., 2006).

For simplicity, the wing bones of flying birds can be considered as a hollow cylinder with thin walls. If placed in bending, the relationship