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The Anatomy That Makes Birds Fly or Stay Grounded

Jhuma Debbarma[1], J B Rajesh[2*], Bensia Debbarma[1], Jashima Debbarma[3], Jagan Mohanarao Gali[4], Abhishek Paul[5], Zosangpuii[6]

1PG Scholar, Department of Veterinary Anatomy and Histology,
2Associate Professor, Department of Veterinary Medicine,
3PhD Scholar, Department of Veterinary Medicine,
College of Veterinary Sciences and Animal Husbandry, Central Agricultural University (Imphal), Selesih, Aizawl, Mizoram: 796015
4Associate Professor, Department of Fish Genetics and Reproduction,
College of Fisheries, Central Agricultural University (Imphal), Lembucherra, West Tripura, Tripura: 799210
5Assistant Professor, Livestock Production Management,
College of Veterinary Sciences and Animal Husbandry, Central Agricultural University (Imphal), Selesih, Aizawl, Mizoram: 796015
6Subject Matter Specialist, Livestock Production,
Krishi Vigyan Kendra, Central Agricultural University (Imphal), Selesih, Aizawl, Mizoram: 796015
***Corresponding Author:** leovet@gmail.com
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Abstract:

Flight has strongly shaped avian anatomy, producing marked differences between flying and flightless birds. Flying species exhibit lightweight pneumatic bones, a prominent sternal keel, powerful pectoral muscles, fused wing elements, and an efficient air-sac respiratory system that supports powered flight. In contrast, flightless birds possess denser bones, reduced or absent keels, diminished flight musculature, and strengthened hind limbs adapted for running or swimming. Variations in glandular and reproductive structures further reflect ecological and evolutionary influences. These differences highlight functional adaptations associated with aerial versus terrestrial or aquatic lifestyles.

Keywords: Anatomy, Birds, Bone, Feather, Flying

Introduction:

Birds (*Aves*) represent one of the most diverse vertebrate groups, unified by feathers yet divided by their ability to fly. Birds are further classified as Flying birds and non-flying birds. Flying birds often referred to as Carinatae (*e.g.*, Peregrine falcons, eagles, swallows, pigeons), exhibit specialized anatomical features that enable powered flight (Pandey *et al.*, 2025). In contrast, non-flying birds, collectively referred to as Ratitae (*e.g.*, ostriches, emus, kiwis) and other secondarily flightless species (*e.g.*, penguins, cormorants), display markedly different anatomical traits. The divergence between flying and non-flying birds is not limited to skeletal and muscular systems. It extends to respiratory efficiency, glandular structures, and reproductive anatomy (Dudley, 2002).

Skeletal Differences:

1. Bone Structure and Pneumaticity:

Flying birds possess lightweight, pneumatic bones containing air spaces connected to the respiratory system, reducing body mass without compromising strength. Long bones such as the humerus and femur commonly show extensive pneumatization (Dyke and Kaiser, 2010). In contrast, non-flying birds have denser, marrow-filled bones that provide increased strength and stability for terrestrial locomotion or diving. Penguins, for example, exhibit solid bones that reduce buoyancy during swimming (Habib and Ruff, 2008).

2. Sternum and Keel:

The sternum in flying birds bears a prominent carina (keel), which provides attachment for powerful flight muscles, particularly the pectoralis major and supracoracoideus (Low-merri *et al*., 2025). In flightless birds, especially ratites, exhibit a reduced or absent sternal keel, producing a flattened sternum with limited surface area for attachment of the primary flight muscles, the m. pectoralis and m. supracoracoideus. The consequent reduction of these muscles diminishes flight capability and shifts locomotor function toward the hind limbs, reflecting adaptation to terrestrial or cursorial movement rather than aerial flight (Low-merri *et al*., 2021).

3. Limb Bone Structure:

In flying birds, the forelimbs are elongated and transformed into wings with extensive fusion of skeletal elements, including the carpometacarpus and tibiotarsus, which increase rigidity and stability during flight strokes. In contrast, flightless birds exhibit reduced or vestigial wing bones with limited functional capacity, while the hind limbs are robust, elongated, and strengthened to support terrestrial running or aquatic propulsion, as observed in ratites and penguins (Dyke and Kaiser, 2010).

Muscular differences:

1. Pectoral Muscles:

In flying birds, the pectoralis major and supracoracoideus muscles dominate anatomy, providing the downstroke and upstroke power necessary for flight. These muscles may account for a large proportion of total body mass in strong flyers. Flightless birds have markedly smaller flight muscles, with muscle mass reallocated to leg muscles for terrestrial locomotion (Deetjen *et al*., 2024).

2. Respiratory System and Flight Mechanics:

Birds possess a highly efficient respiratory system featuring air sacs and unidirectional airflow. Recent research demonstrates that specialized air sac structures, such as the subpectoral diverticulum (SPD), interact with flight muscles to improve flight mechanics, particularly in soaring birds, illustrating an anatomical link between respiratory organs and flight performance. Flightless species retain the basic avian respiratory design but do not exhibit the same specialized adaptations linked to flight mechanics (Schachner *et al*., 2024).

Glandular Differences:

1. Uropygial (Preen) Gland:

A bilobed holocrine gland located at the dorsal base of the tail that produces oily secretions used in feather maintenance, waterproofing, and flexibility. Present in many flying birds, especially those requiring extensive feather care for flight and waterproofing. Absent or reduced in several flightless taxa, including some ratites (*e.g*., ostrich, emu, cassowary), indicating that absence is associated more with ecological and integumentary adaptations rather than flight capability alone (Karaavci *et al*., 2024)

2. Harderian Gland:

An orbital gland situated near the eye, composed of secretory acini and ducts that secrete fluids involved in eye lubrication and immune protection. Present in both flying and non-flying birds with similar basic histological structure (multilobular, columnar secretory cells), though morphological differences correlate with species-specific habits and ecology rather than flight ability per se (Beheiry *et al*., 2020).

Reproductive Differences:

1. Gonadal Structures and Ovary Number:

- **Flying birds:** Most female birds possess only one functional ovary (the left) and a single oviduct, an adaptation thought to reduce weight for flight and conserve energy.
- **Flightless birds:** Although many flightless birds also have a single ovary, exceptions exist. For example, kiwi (*Apteryx* spp.) retains two functional ovaries, indicating that loss of flight does not strictly dictate inherited reproductive asymmetry (Guioli *et al*., 2014).

2. Copulatory Organs:

In most flying birds, males lack an external intromittent organ and instead transfer sperm *via* brief contact between the male and female cloacas in a mechanism known as the "cloacal kiss," which is the typical mode of copulation in approximately 97% of avian species. In contrast, a minority (~3%) of birds retain a functional intromittent phallus, an erectile structure that can be inserted into the female's reproductive tract; this is characteristic of certain large flightless birds such as ostrich (*Struthio camelus*) and emu (*Dromaius novaehollandiae*) as well as other basal lineages like tinamous and waterfowl. The avian phallus represents a retained ancestral feature found primarily in Paleognathae and some Galloanseriformes, whereas most flighted neognaths have lost this organ evolutionarily (Patricia, 2022).

Conclusion:

Flying and non-flying birds show clear anatomical divergence related to locomotor demands. Volant birds are specialized for flight through lightweight skeletons, strong flight muscles, and advanced respiratory mechanisms, whereas flightless birds demonstrate regression of flight structures and

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enhancement of hind limb function. Overall, these modifications illustrate the close relationship between anatomy, function, and evolutionary adaptation in birds.

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