Aerodynamic efficiency and wing morphology in high-performance racing pigeons (*Columba livia*)

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Abstract. Aerodynamic efficiency in racing pigeons is a multifactorial trait shaped by the interaction between wing morphology, biomechanical function, and environmental modulation. This mini-review synthesizes current understanding of how key morphological parameters, wing loading and aspect ratio, govern flight performance in high-performance racing pigeons. Low to moderate wing loading is associated with improved lift efficiency, reduced sink rates, and enhanced endurance, while higher wing loading may confer advantages in short-term speed and stability under turbulent conditions. Aspect ratio further refines aerodynamic performance by modulating induced drag; higher values favor long-distance cruising efficiency, whereas lower values enhance maneuverability and rapid acceleration. The energetic trade-off between flapping and gliding flight is central to sustained performance, with pigeons optimizing flight strategy according to environmental conditions such as wind direction, air density, and thermal availability. In addition to morphological traits, physiological adaptations—including enhanced aerobic muscle capacity, mitochondrial density, and coordinated neuromuscular control—enable prolonged flight performance. The integration of these structural and functional components results in an optimized aerodynamic system that supports both endurance and navigational precision. This review highlights the importance of considering flight performance as an emergent property of combined morphological and physiological optimization rather than isolated traits.
Key Words: racing pigeons, aerodynamic efficiency, wing loading, aspect ratio, flight biomechanics, gliding flight, flapping flight, avian morphology, energy expenditure, endurance flight.

Introduction. Aerodynamic efficiency in racing pigeons represents a complex integration of morphological, physiological, and environmental variables that collectively determine flight performance (Ionescu & Oroian 2015; Ionescu et al 2015; Deng et al 2023). Selective breeding has intensified traits associated with endurance, speed, and navigational reliability, making racing pigeons a valuable model for studying applied avian flight mechanics (Rackowski 2022). Central to this efficiency are structural parameters such as wing loading and aspect ratio, alongside functional dynamics involving the balance between flapping and gliding flight. These parameters influence lift generation, drag minimization, and energy expenditure over long distances (Shen et al 2025; Wu et al 2025).

We have been breeding racing pigeons (Figure 1) as well as show pigeons for a long time (Figure 2), but we have always been passionate about aerodynamic efficiency and wing morphology in high-performance racing pigeons. The aim of this mini-review is to synthesize and critically examine the relationships between wing morphology (particularly wing loading and aspect ratio), flight energetics, and aerodynamic efficiency in high-performance racing pigeons. It seeks to integrate morphological, physiological, and environmental perspectives to clarify how selective breeding and natural functional constraints jointly shape optimized flight performance in this avian model.

Figure 1. "Racing pigeons represent an old passion that has returned at the right time, as family commitments will always exist and life can pass by without being fully enjoyed" (Adi Popescu – original pictures).

Figure 2. Romanian rollers of Galați from the loft of Adi Popescu (first author), who has been breeding this breed for 40 years; original pictures.

Wing loading and its functional implications. Wing loading, defined as the ratio of body mass to total wing area, is a primary determinant of aerodynamic performance in birds. In racing pigeons, relatively low wing loading is advantageous for sustained flight as it reduces the minimum speed required to maintain lift and enhances gliding capacity. Lower wing loading allows birds to remain airborne with less energetic effort, particularly during long-distance races where energy conservation is critical (Shen et al 2025; Wu et al 2025).

Conversely, higher wing loading can facilitate increased flight speed due to greater momentum and reduced sensitivity to turbulence, but this comes at the cost of increased metabolic demand. High-performance racing pigeons exhibit an optimized wing loading that balances these competing demands, allowing for both efficient cruising and the ability to maintain speed under varying environmental conditions (Shen et al 2025; Wu et al 2025).

Aspect ratio and wing shape optimization. Aspect ratio, calculated as wingspan squared divided by wing area, reflects the elongation of the wing and directly influences aerodynamic efficiency. Wings with higher aspect ratios generate less induced drag, making them more efficient for sustained, long-distance flight. In racing pigeons, the aspect ratio is typically moderate to high, representing a compromise between energy-efficient soaring and maneuverability (Shen et al 2024; Zhang et al 2024).

Shorter, broader wings with lower aspect ratios enhance agility and rapid acceleration but are less suited for prolonged flight due to increased drag. Racing pigeons require a wing morphology that supports both endurance and control, particularly when navigating complex terrains and varying wind conditions. This intermediate wing design is a hallmark of species adapted for both flapping-dominated flight and intermittent gliding (Shen et al 2024; Zhang et al 2024).

Energetics of flapping versus gliding flight. The energetic cost of flight is a central constraint in avian performance (Oroian et al 2025ab). Flapping flight, while necessary for thrust and lift generation, is metabolically expensive due to continuous muscular activity. Gliding, in contrast, allows birds to conserve energy by exploiting aerodynamic lift without active wingbeats. Racing pigeons primarily rely on flapping flight but incorporate short gliding phases when environmental conditions permit (Çelik 2023; Erdem et al 2024; Shen et al 2024; Zhang et al 2024).

The efficiency of this mixed flight strategy is influenced by wing loading and aspect ratio. Birds with lower wing loading and higher aspect ratios exhibit reduced sink rates and improved glide angles, enabling longer gliding intervals. This reduces overall energy expenditure and enhances endurance, particularly in long-distance competitions where cumulative energy savings are significant (Shen et al 2024; Zhang et al 2024; Oroian et al 2025a).

Biomechanical and physiological integration. Aerodynamic efficiency is not determined by morphology alone but is closely linked to underlying physiological adaptations. The pectoralis major muscle, responsible for generating the downstroke, is highly developed in racing pigeons and is adapted to sustain prolonged aerobic activity. Efficient flight requires synchronization between muscle output and wing kinematics, ensuring optimal force generation throughout the wingbeat cycle (Godin 2025).

Structural features such as feather arrangement, wing flexibility, and joint articulation contribute to aerodynamic performance by modulating airflow and reducing drag. These biomechanical properties are supported by metabolic adaptations, including high mitochondrial density and enhanced oxidative capacity, which allow pigeons to sustain prolonged flapping without rapid fatigue (Ionescu & Oroian 2019; Deng et al 2022; Li et al 2022).

Environmental interactions and flight modulation. Flight performance in racing pigeons is highly dependent on environmental conditions such as wind speed, air density, and thermal currents. Birds continuously adjust their flight behavior in response to these variables, modifying wingbeat frequency, glide duration, and flight altitude to optimize efficiency.

In headwind conditions, pigeons increase flapping intensity to maintain forward motion, resulting in higher energy expenditure. In contrast, tailwinds and updrafts facilitate extended gliding phases, reducing metabolic cost. Wing morphology plays a critical role in determining how effectively pigeons can exploit these conditions, with optimized wing loading and aspect ratio enhancing adaptability and performance across diverse flight environments.

Quantitative relationships between key aerodynamic parameters. The interplay between wing loading, aspect ratio, and flight energetics can be summarized through their functional relationships (Table 1).

Table 1

The interplay between wing loading, aspect ratio, and flight energetics

Parameter	*Definition*	*Aerodynamic effect*	*Performance outcome*
Wing loading	Body mass / wing area	Influences lift requirement and sink rate	Lower values improve endurance and gliding
Aspect ratio	Wingspan² / wing area	Determines induced drag	Higher values enhance efficiency in cruising
Glide ratio	Distance traveled per unit altitude lost	Reflects aerodynamic efficiency	Higher ratios reduce energy expenditure
Flapping cost	Energy expenditure during active flight	Depends on muscle output and wing mechanics	Lower cost improves long-distance performance.

These parameters interact dynamically, and optimal performance in racing pigeons is achieved through a finely tuned balance that maximizes aerodynamic efficiency while maintaining sufficient power and control for sustained flight.

Bio-inspired flight: pigeon locomotion as a model for advances in bionic engineering and robotics. Research into the flight mechanics and behavioural ecology of Pigeon has become increasingly significant for the advancement of bionics and the development of next-generation robotic systems (Zhang et al 2023; Zhang et al 2024; Pu et al 2025). Pigeons exhibit highly efficient flapping flight, remarkable manoeuvrability, and robust navigation capabilities across complex and unpredictable environments, making them an excellent biological model for bio-inspired engineering. Their flight involves sophisticated integration of aerodynamics, musculoskeletal dynamics, and real-time sensory feedback, enabling stable control under varying wind conditions and during rapid directional changes. Of particular interest is their sensorimotor coordination, which combines visual processing, vestibular input, and proprioception to maintain equilibrium and trajectory precision.

In robotics and unmanned aerial vehicle (UAV) design (Zan et al 2023), these biological principles inform the development of flapping-wing micro air vehicles (MAVs) and adaptive control algorithms that emulate avian flight efficiency and agility (Fang et al 2023). Insights derived from pigeon flight have contributed to improvements in lightweight structural design, energy-efficient propulsion mechanisms, and autonomous navigation systems capable of operating in cluttered or GPS-denied environments. Furthermore, studying their homing behaviour has influenced advancements in bio-inspired path planning and distributed intelligence in swarm robotics. Overall, the systematic analysis of pigeon flight serves as a critical bridge between biological understanding and technological innovation, enabling the creation of more resilient, adaptive, and efficient robotic platforms (Figure 2).

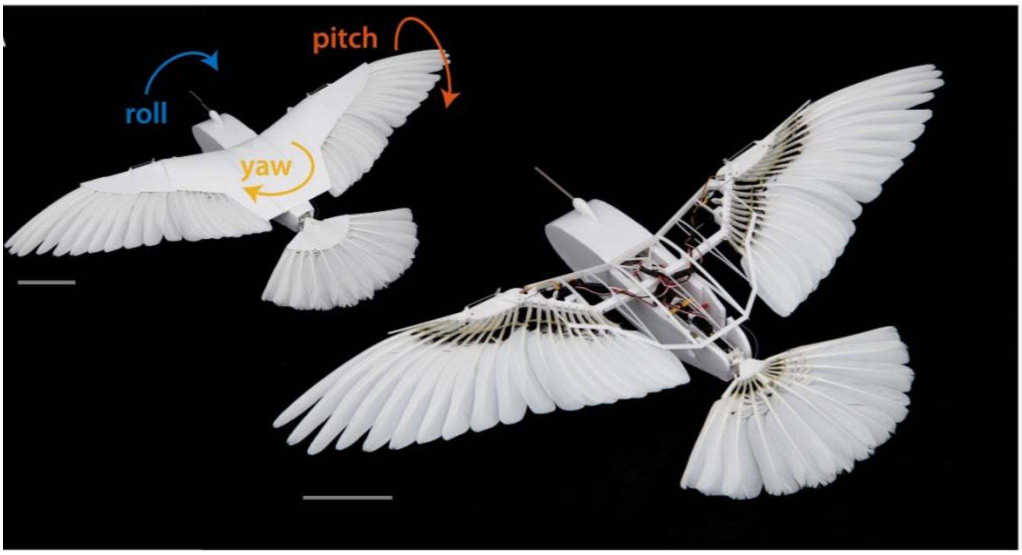

Figure 2. PigeonBot II morphs its wing and tail reflexively to fly rudderless autonomously. Biomimetic skeleton and connective elastic ligaments underactuate the wing's 40 remiges with four servomotors (two wrists and two second digits) and the tail's 12 feathers with five servomotors (movie S3). Scale bars, 100 mm (Chang et al 2024).

Conclusions. Aerodynamic efficiency in racing pigeons (*Columba livia*) emerges from the integrated interaction between wing morphology, physiological capacity, and environmental dynamics. Wing loading and aspect ratio function as primary structural determinants of flight performance, jointly influencing lift generation, drag reduction, and stability. Rather than acting independently, these parameters operate within a balanced configuration—typically moderate wing loading combined with relatively high aspect ratio—that enables both sustained endurance and sufficient maneuverability under variable flight conditions.

Flight energetics are optimized through the strategic alternation between flapping and gliding, reducing cumulative metabolic expenditure during long-distance travel. This behavioural strategy is closely supported by physiological adaptations, including enhanced aerobic muscle performance, mitochondrial efficiency, and precise neuromuscular coordination, which collectively sustain prolonged flight activity. Consequently, performance should be interpreted as the result of coordinated structural–functional integration rather than the effect of isolated traits.

Beyond biological performance, these aerodynamic principles extend to applied domains such as bio-inspired engineering. The flight mechanics of racing pigeons provide a robust model for the design of flapping-wing aerial systems, where efficiency, control, and adaptability are critical. The coupling of morphology, kinematics, and environmental responsiveness observed in pigeons offers valuable insights for the development of advanced micro air vehicles and autonomous flight technologies operating in complex conditions.

Conflict of interest. The authors declare that there is no conflict of interest.

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