SI Appendix

Flight Performance Analysis. Most functional analyses of flight performance of flying animals have centered on birds, taking advantage of aerodynamic equations used in aircraft design. The most common method for approximate performance estimation is an aircraft-like model (1), which uses familiar parameters such as lift and drag coefficients, wing area, wing aspect ratio, and span efficiency. In this method, the power required to maintain steady level flight is calculated as the product of aerodynamic drag and flight airspeed. The total drag is calculated as the sum of two components: the so-called induced drag, which is the penalty that must be paid for the production of aerodynamic lift, and a component (sometimes called zero-lift drag) assumed independent of lift, comprising pressure drag and surface skin friction. This simple method has a limitation: it predicts infinite induced drag and power at zero airspeed and therefore cannot be used without modification for performance estimation in hovering or near-hovering flight. A second model, known as momentum streamtube theory, was originally proposed for straight wings by Ludwig Prandtl (2) and developed further by helicopter designers (3) and adapted to animal flight (4, 5). It avoids the zero-speed problem by making the assumption that a cylindrical tube of air having a cross-section area (A) with diameter approximately equal to the wingspan (b), or rotor diameter, initially approaching the wing or rotor at flight speed (V), is deflected downward through an angle (ø), which can vary from 90º in hovering at zero speed to a small angle in cruising and high-speed flight. The flight power is equated to the change in kinetic energy flow in the streamtube from far upstream to far downstream, which is required to balance lift and aerodynamic drag. In comparison with the aircraft method, the streamtube model has its own drawbacks: unfamiliarity to most animal flight researchers, and greater numerical complexity in application. However, it is important to note that the two methods produce essentially identical results in powered flight at speeds that are usually >5 to 10 m/s.

We have tabulated the aerodynamic data of 13 species of thermal soaring birds and motor glider for performance analysis (Table 1). The level flight power and steady glide performance relate only to equilibrium flight during which speed, aerodynamic forces, propulsive power (if any), and flight path angle remain steady. There are important flight modes, however, in which these quantities continuously change. They include takeoffs, landings, and other non-steady maneuvers. A computer program named ANFLTSIM has been developed (4) to simulate these modes. It uses the same theoretical methods for computing aerodynamic forces as already described, but integrates the equations of motion in small time steps to reconstruct flight path histories. Flights are under the control of a "pilot" who can vary power, lift coefficient, and other parameters such as "dive brakes" (e.g., high-drag appendages) and pitch damping to tone down so-called "phugoid" pitch oscillations that sometimes occur. Wind speed (headwinds or tailwinds) can also be specified. The following flight simulations are examples of ANFLTSIM flights.

Power Available and Power Required. The continuous available power has been estimated from many measurements of metabolic rates for birds and other vertebrates, where the basal metabolic rate is about 20 W/kg of body weight (6, 7). The conversion efficiency from metabolic energy to mechanical power was assumed to be 20% (7). A power curve (Fig. 2*A*) shows that the maximum continuous power available to *Argentavis* was 170 W, but the minimum power required for steady level flight was 600 W, or about 3.5 times the estimated power available. *Argentavis*, like most large soaring birds, appears to have been too large to sustain powered flight. Fig. 2*B* shows the gliding capability of *Argentavis*. Each curve has been marked with a circle at the speed for maximum lift/drag ratio. In each case these curves show the flight speed at which the glide slope is minimum in still air (i.e. no upward thermal activity). For most birds, including *Argentavis*, the minimum glide slope is close to 3°, which indicates excellent gliding capability. The exception is the small Black Kite, which has a minimum slope close to 3.5°, or about 20 to 25 percent lower. The glide polar curves show that there is a regular progression of gliding performance of landbirds as size increases. The sharp downturn on each glide polar indicates a stall.

Thermal Soaring. The twelve extant birds listed in Table 1 are carnivorous or scavenging birds that depend for their livelihood on their remarkable ability to soar and turn with outstretched wings for long periods while searching for prey on the ground (8). Birds can gain altitude by gliding in thermals, if the rate at which the air is rising is greater than the rate at which they are sinking relative to the air (Fig. 3*A*). In Fig. 3*B*, a bird turning in a small circle is able to climb faster than a bird flying in a wider circle because there is less lift round the outside of the thermal. To fly in circles the wings must be banked, and increasing the angle of bank can tighten the turn. Of course, increasing the angle of bank reduces wing surface area exposed to uplift, so tight turns could be more inefficient than wide turns. The most efficient circling radius is proportional to the wing loading and the strength of thermal uplift. A bird gliding at speed v in circles of radius r has an acceleration v^2/r toward the center of circles. If its mass is M, it needs a centripetal force of Mv^2/r to give this acceleration. We have calculated the optimal turning radius of *Argentavis* in thermals at 30 m (using its estimated weight 686 N) while flying in a level circle at speed 15 m/s. It would require a centripetal force $F(N) = 70 \times 15^2/30$ or 525 N, directed toward the center of the circle to keep it in equilibrium. Note that it is 76.5% of the bird's weight. In order to simultaneously maintain a vertical lift force equal to its weight, it must bank at an angle of about 37.4º (tan 37.4º = 0.765). Note also that the bird's mass has disappeared from the calculation, so big birds can turn as sharply as small ones, if compared at equal speeds. The wing loading of *Argentavis* is not high, which permits fairly low soaring speeds. In Fig. 3*C*, turning radius is plotted against the sinking speed for three soaring birds: White-backed Vulture (8), California Condor, and *Argentavis* (see Table 1). The trend in these curves is such that the optimal turning radius is achieved by flying as close as possible to stalling speed, but at some cost in sinking speed. Again, there is not much difference between *Argentavis* and the smaller condor. These two curves have been calculated for only single values of g-loading and bank angle (1.2 g and 33.6°).

Takeoff and Landing. Because *Argentavis* was so large and heavy, its most crucial maneuvers in flight would be takeoff and landing. We have used ANFLTSIM to calculate the metabolic power (P) needed to takeoff, liftoff distance, and speed. It appears that a light headwind (about 5 m/s) would be helpful to add extra power. Various takeoff and landing strategies probably employed by *Argentavis* are shown in Fig. 4. Fig. 4*A* shows the gliding takeoff of *Argentavis* launching from a height of 20 m with a launch speed at 2 m/s, and then pulling up at a maximum continuous power. The lower curve shows takeoff from a perch without headwind, the upper one with a headwind. As airspeed increases, lift becomes greater than weight and the path flattens rapidly to near level after dropping about 20 m with no head wind. Note the sensitivity of headwind of 5 m/s blowing toward the bird that greatly reduces altitude loss and the minimum speed in the pitchup. In these simulations, a rapid pitchup was initiated with the wing acting as a horizontal high-drag sloping parachute, which retains some lift. In both cases the lift coefficient was set at 1.0, just below maximum lift. Since the airspeed required to generate sufficient lift to support a bird with this wing loading (about 85 N/m^2) is estimated to be around 12 m/s, the initial flight path steepens rapidly for lack of lift. In both cases the minimum speed reaches 5.9 and 5.0 m/s respectively. Because a maximum landing speed of around 5 m/s is considered marginally safe, the presence of some wind seems essential.

Figure 4*B* shows four simulated takeoff runs on a 10º sloping surface along which the gravity component of force is equivalent to an additional 600 W of propulsive power at a running speed of 5 m/s. Curve 1 shows a takeoff attempt with no flapping wing power and no wind. Liftoff was barely possible at about 50 m run, but the climb remains below horizontal. Curve 2 is similar but with maximum aerobic power (170 W). Addition of power makes little difference, since 170 W remains well below the power required for level flight. Curves 3 and 4 correspond respectively to curves 1 and 2, but show the important effect of a steady 5 m/s headwind. The climb is now slightly above horizontal, and once airborne *Argentavis* could take advantage of thermals with updrafts of 1 m/s or more. Conditions for each takeoff run are given in the table below:

Run #	Power, W	Headwind speed, m/s	Liftoff x, m	Liftoff speed, m/s	Equilibrium climb speed, m/s	Equilibrium climb angle, degrees
1	0	0	43.3	10.8	10.8	5.4
2	170	0	32.5	10.4	10.5	6.5
3	0	5	11.4	5.8	5.8	10.2
4	170	5	7.8	5.4	5.6	12.3

Fig. 4*C* illustrates one safe landing strategy of *Argentavis*. Landing could also be made at the end of a long flat glide. Landing could have been hazardous to *Argentavis* (upper curve) at a touchdown speed above the safe landing speed of 5 m/sec. *Argentavis* could exploit a moderate headwind of 5 m/s, which would make landing safe. The touchdown speed is about 1.5 m/s (lower curve), which might considerably lower than the safe landing speed. The combination of high lift and high pitchup initially produces a slight climb with rapid deceleration, and then a descent to minimum airspeed well below the level flight stalling speed.

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