

Figure S1 | Vertical actuator disk area calculation. **A**, The 3D positions of Bird 2's right wing outline over one full stroke are shown in red. These points are projected onto the horizontal plane (light red) so that the swept area could be calculated. **B**, The area enclosed by the projected points (black perimeter) was calculated using an alpha hull (custom MATLAB script). The normal vector of this projected actuator disk area pointed in the same direction as the measured vertical force.

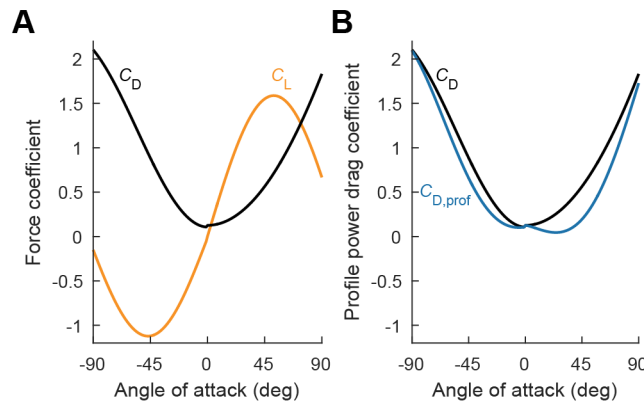


Figure S2 | Translational lift and drag polar used to determine profile drag coefficient. **A**, The translational lift, C_L , and drag, C_D , force coefficients for each angle of attack were adapted from previously published wing spinner measurements on prepared *Calypste anna* wings (Kruij, et al., 2014). **B**, The profile drag coefficient, $C_{D,prof}$, was calculated by subtracting the induced drag, calculated based on the measured lift in (A), from C_D for every angle of attack (Eqn A3).

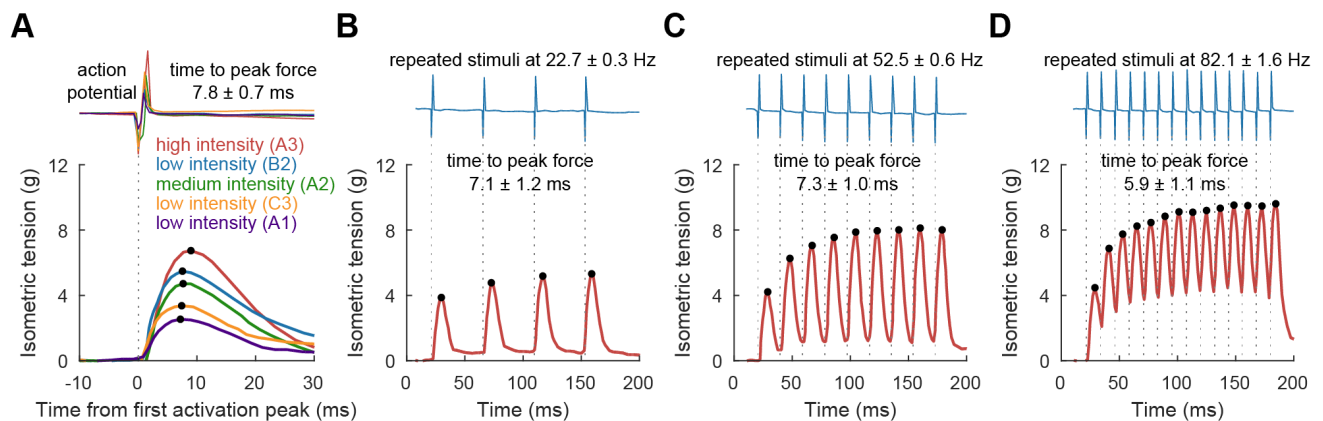


Figure S3 | Peak force in Anna's pectoralis is achieved in less than 8 ms after stimulus. **A**, Isometric tension traces from the pectoralis of Anna's hummingbirds due to a single stimulus (adapted from Fig. 2 of Hagiwara *et al.* (Hagiwara, et al., 1968)). Letters and numbers after description correspond to the subpanel in the original figure. Simultaneous traces of isometric tension (red) and repeated stimuli (blue) at 22.7 Hz (**B**), 52.5 Hz (**C**), and 82.1 Hz (**D**) show that the peak force is reached in 7.1, 7.3 and 5.9 ms respectively. Traces adapted from Fig. 3 A-C of Hagiwara *et al.* (Hagiwara, et al., 1968).

Table S1 | Mass, morphology parameters and wingbeat statistics for all six birds (mean \pm s.d.).

| | Bird # 1 | Bird # 2 | Bird # 3 | Bird # 4 | Bird # 5 | Bird # 6 | Total |
|-------------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| | <i>n</i> = 5 flights | <i>n</i> = 5 flights | <i>n</i> = 4 flights | <i>n</i> = 4 flights | <i>n</i> = 5 flights | <i>n</i> = 5 flights | <i>N</i> = 6 individuals |
| Mass (g) | 5.4 \pm 0.2 | 5.1 \pm 0.1 | 4.7 \pm 0.1 | 5.0 \pm 0.1 | 4.7 \pm 0.1 | 4.4 \pm 0.1 | 4.9 \pm 0.4 |
| | <i>n</i> = 5 wingbeats | <i>n</i> = 5 wingbeats | <i>n</i> = 5 wingbeats | <i>n</i> = 5 wingbeats | <i>n</i> = 5 wingbeats | <i>n</i> = 5 wingbeats | <i>N</i> = 6 individuals |
| Wing radius (mm) | 51.4 \pm 0.3 | 47.5 \pm 0.3 | 52.2 \pm 0.2 | 52.0 \pm 0.3 | 50.5 \pm 0.4 | 54.7 \pm 0.1 | 51.4 \pm 2.4 |
| Single-wing area (mm ²) | 568 \pm 45 | 527 \pm 8 | 561 \pm 27 | 587 \pm 22 | 530 \pm 42 | 615 \pm 35 | 565 \pm 34 |
| Average chord length (mm) | 12.3 \pm 0.8 | 12.6 \pm 0.2 | 11.7 \pm 0.5 | 11.9 \pm 0.1 | 11.5 \pm 0.8 | 12.0 \pm 0.6 | 12.0 \pm 0.4 |
| Aspect ratio | 4.2 \pm 0.3 | 3.8 \pm 0.1 | 4.5 \pm 0.2 | 4.4 \pm 0.1 | 4.4 \pm 0.3 | 4.6 \pm 0.2 | 4.3 \pm 0.3 |
| \hat{r}_2 | 0.53 \pm 0.01 | 0.54 \pm 0.01 | 0.51 \pm 0.01 | 0.50 \pm 0.01 | 0.52 \pm 0.01 | 0.50 \pm 0.01 | 0.52 \pm 0.02 |
| \hat{r}_3 | 0.57 \pm 0.01 | 0.58 \pm 0.01 | 0.56 \pm 0.01 | 0.55 \pm 0.01 | 0.56 \pm 0.01 | 0.55 \pm 0.01 | 0.56 \pm 0.01 |
| | <i>n</i> = 568 wingbeats | <i>n</i> = 743 wingbeats | <i>n</i> = 644 wingbeats | <i>n</i> = 585 wingbeats | <i>n</i> = 789 wingbeats | <i>n</i> = 765 wingbeats | <i>N</i> = 6 individuals |
| Flapping frequency (Hz) | 39 \pm 1 | 40 \pm 1 | 42 \pm 1 | 43 \pm 1 | 41 \pm 1 | 40 \pm 1 | 41 \pm 2 |
| Downstroke time (%) | 46 \pm 1 | 46 \pm 1 | 46 \pm 1 | 47 \pm 1 | 48 \pm 1 | 46 \pm 1 | 47 \pm 1 |
| Weight support (%) | 97 \pm 6 | 95 \pm 5 | 100 \pm 5 | 98 \pm 5 | 100 \pm 7 | 104 \pm 5 | 99 \pm 3 |
| Upstroke weight support (%) | 28 \pm 1 | 28 \pm 2 | 29 \pm 2 | 28 \pm 2 | 27 \pm 2 | 27 \pm 2 | 28 \pm 1 |



Movie 1 | Wingbeat-resolved *in vivo* aerodynamic weight support of a hummingbird. The high-speed video shows an Anna's hummingbird hovering in the setup. The simultaneously recorded vertical aerodynamic force is shown with a green vertical arrow, bodyweight is indicated with a black vertical arrow.



Movie 2 | Automatic wingbeat transition detection from high-speed video. A demonstration of how the wingbeat transitions were automatically obtained. A white dot tracks the area centroid of the bird outline. The wingbeat transition is defined as the moment when the area centroid changes horizontal direction (red being downstroke and blue upstroke).

In vivo weight support recording of a hummingbird flying freely into the setup

How the hummingbird wingbeat is tuned for efficient hovering

Rivers Ingersoll
David Lentink
Stanford University



Movie 3 | *In vivo* weight support recording of a hummingbird flying freely into setup. An unidentified Anna's hummingbird freely flies into and hovers in a rugged outdoor version of the setup, attracted by a feeder, we simultaneously recorded the vertical aerodynamic force shown with a green vertical arrow.