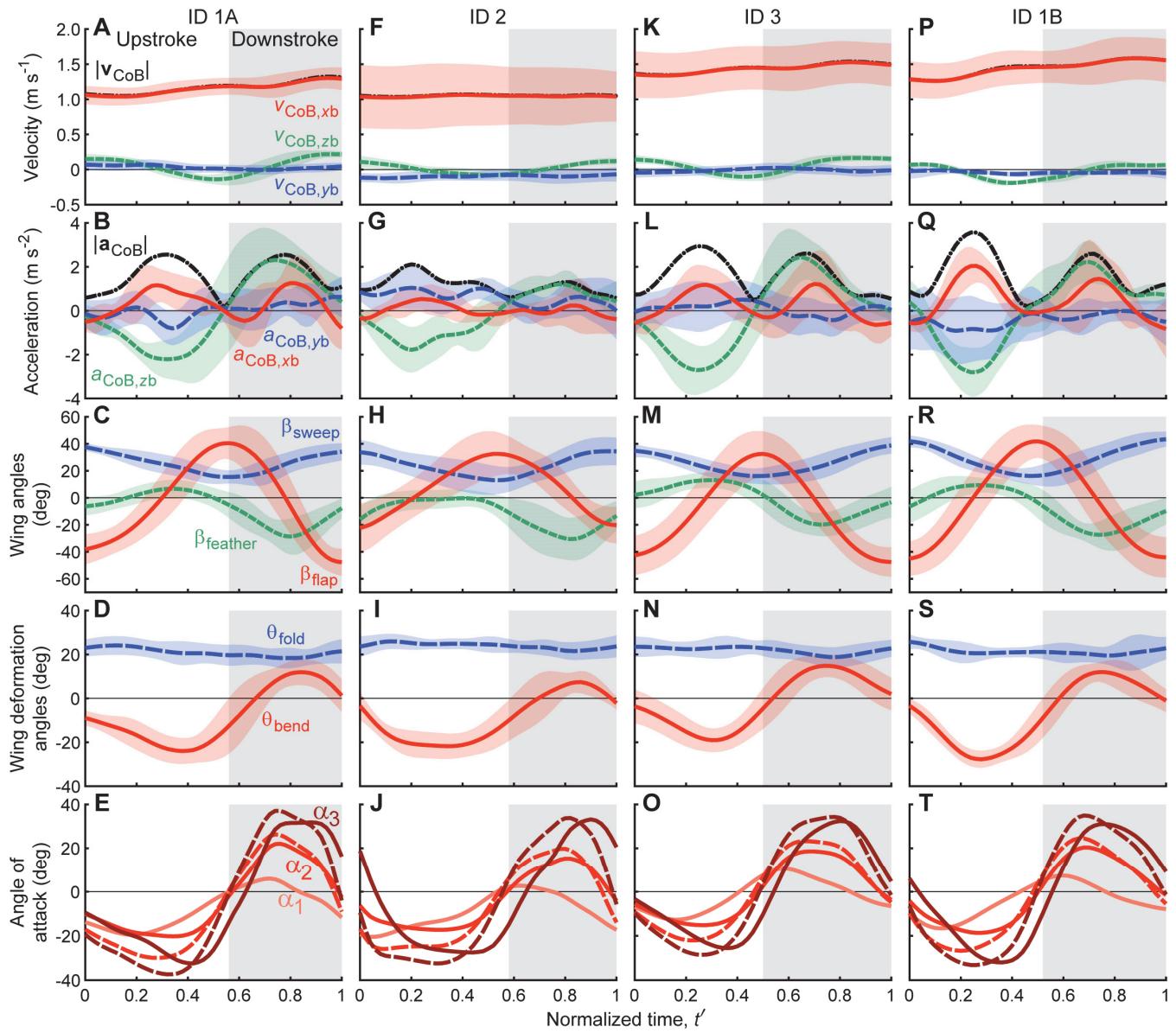


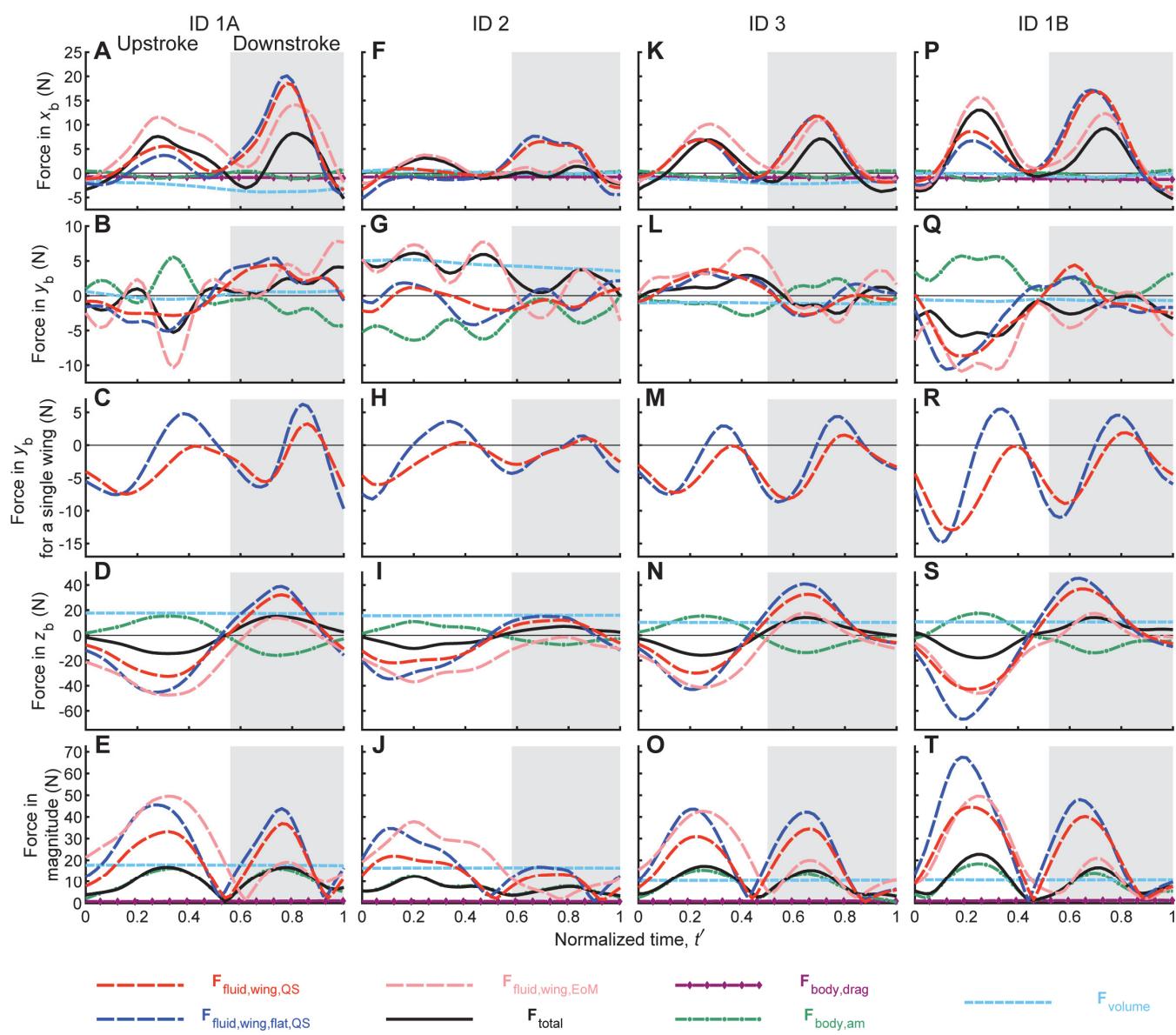
**Fig. S1. Quasi-steady force calculation method.**

- (A) Side-view photo and the 3D body model of penguin ID 1A.
- (B) Right wing of individual 1 measured with a 3D scanner.
- (C) The 3D model of the wing without sweepback. In the original scanned data (left), the cross-sectional profiles are almost symmetric. For simplification, its cross-sectional profiles were modified into completely symmetric (right).
- (D) Representative cross-sectional shapes of the original scanned wing (top) and symmetric wing (bottom). Spanwise positions from the wingbase of the sections are 32% (a-a' and d-d'), 55% (b-b' and e-e') and 87% (c-c' and f-f').
- (E) Wing elements and outline. The blue points represent the intersection of the borderlines and the outline.
- (F) Schematic side view of the water tunnel. The test section was closed except for a 30 mm diameter hole on the top for the supporting rod of the wing model. The wing was always submerged under the water surface.

**Fig. S2. Body and wing kinematics of each penguin in a normalized wingbeat cycle.**

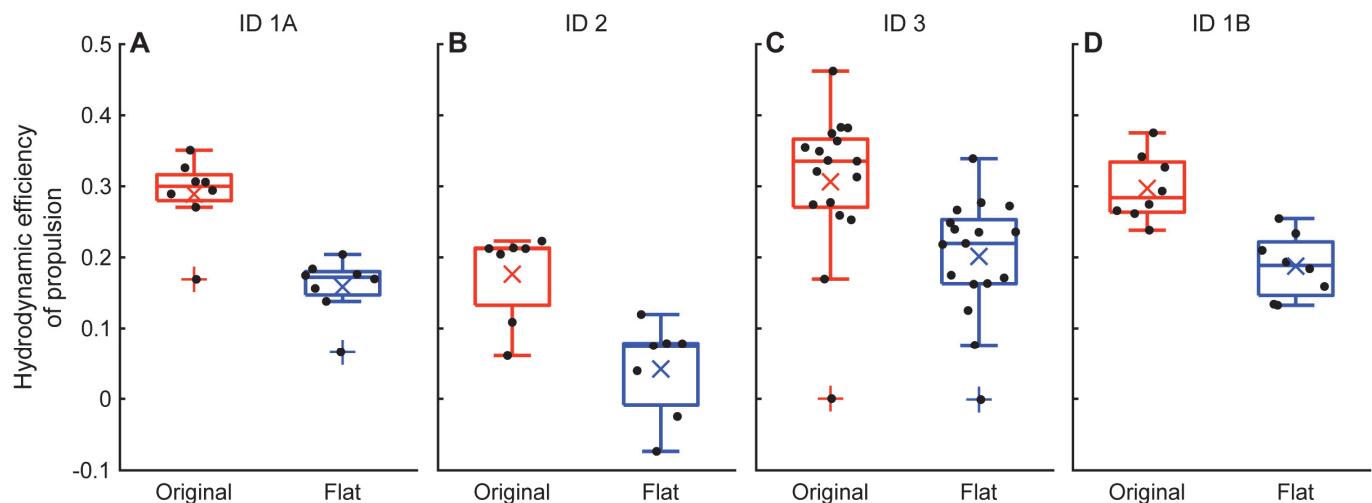
Ensemble-averaged kinematic parameters of four penguin IDs (A-E, ID 1A; F-J, ID 2; K-O, ID 3; P-T, ID 1B) in a normalized wingbeat cycle. The white and grey backgrounds represent the upstroke and downstroke, respectively.

(A,F,K,P) Velocity in the body coordinate system. (B,G,L,Q) Acceleration in the body coordinate system. (C,H,M,R) Wing angles. (D,I,N,S) Wing deformation angles. (E,J,O,T) Angle of attack of the original wing (solid lines) and the flat wing (dashed lines) at each spanwise position. Here,  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_3$  are the angles of attack at positions  $P_{R,1}$ ,  $P_{R,2}$ , and  $P_{R,3}$ , respectively. Each shaded band represents s.d.; however, in E, J, O, and T, only the averages are shown for ease of viewing.



**Fig. S3. Force generation of each penguin in a normalized wingbeat cycle.**

Ensemble-averaged parameters of four penguin IDs (A-E, ID 1A; F-J, ID 2; K-O, ID 3; P-T, ID 1B) in a normalized wingbeat cycle. The white and grey backgrounds represent the upstroke and downstroke, respectively. (A,F,K,P) The  $x_b$  component of the force calculated from the body acceleration,  $\mathbf{F}_{\text{total}}$  (black solid line), the force generated by the original wing,  $\mathbf{F}_{\text{fluid,wing,QS}}$  (red dashed line), the force generated by the flat wing,  $\mathbf{F}_{\text{fluid,wing,flat,QS}}$  (blue dashed line), the force generated by the wing calculated by equation of motion,  $\mathbf{F}_{\text{fluid,wing,EoM}}$  (pink dashed line), the body drag force,  $\mathbf{F}_{\text{body,drag}}$  (purple dash-diamond line), the body added-mass force,  $\mathbf{F}_{\text{body,am}}$  (green dash-dot line), and the volume force,  $\mathbf{F}_{\text{volume}}$  (light-blue dotted line). (B,G,L,Q) The  $y_b$  component. (C,H,M,R) Force in  $y_b$  for a single wing. In these panels, the sign of the data from the right wing was reversed, and the data were averaged together with the data from the left wing. (D,I,N,S) The  $z_b$  component. (E,J,O,T) The magnitude of the forces.



**Fig. S4. Hydrodynamic efficiency of propulsion of each penguin.**

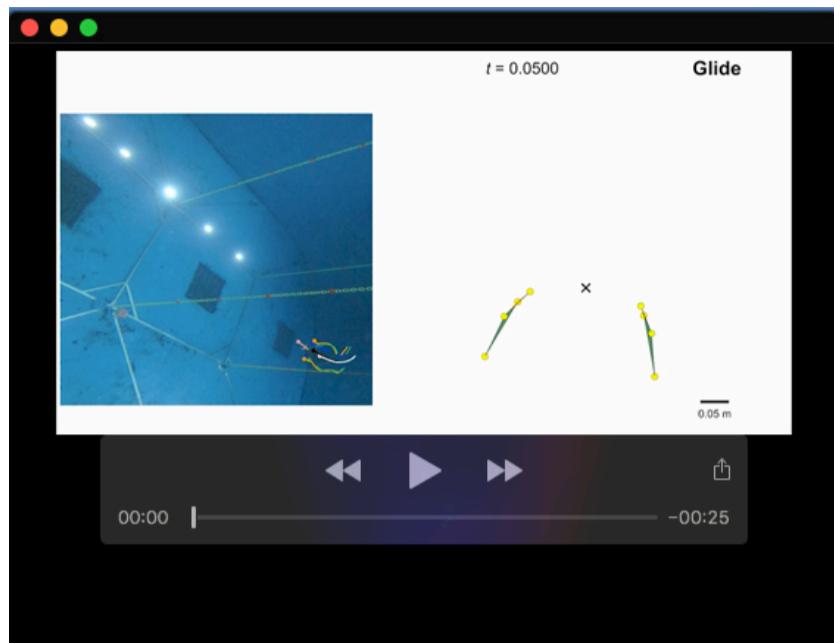
Box plots and swarm plots of the hydrodynamic efficiency of propulsion of the original wing (red) and the flat wing (blue) of four penguin IDs. A mean value appears as an x sign. An outlier appears as a + sign, which is a value more than 1.5 times the interquartile range away from the box.

**Table S1. Wing model profiles along the spanwise axis.**

Spanwise position from the wingbase (%)	Original 3-D scanned model without sweepback					Symmetrical model with a sweepback of 35 deg		
	Max. thickness (%)	Chordwise position at the max. thickness (%)	Max. camber height (%)	Torsion (deg)	Max. thickness (%)	Chordwise position at the max. thickness (%)	Max. camber height (%)	Torsion (deg)
	(%)				(%)			
10	35.6	34.1	4.3	8.4	17.3	25.5	0	0
20	24.0	28.3	2.2	5.2	20.1	27.1	0	0
30	18.6	29.9	0.8	0.9	18.6	25.5	0	0
40	15.9	26.1	0.5	-3.0	16.9	25.8	0	0
50	17.8	30.3	0.5	-5.8	17.1	30.2	0	0
60	15.1	36.8	0.2	-7.0	14.9	32.5	0	0
70	15.2	30.5	0.4	-7.0	13.8	30.8	0	0
80	15.6	32.5	-0.7	-7.2	13.5	32.9	0	0
90	16.5	28.2	-1.6	-4.2	13.8	30.9	0	0
Mean	19.4	30.8	0.7	-2.2	16.2	29.1	0	0
SD	6.3	3.1	1.6	5.4	2.2	2.9	0	0

**Table S2. Measured kinematic parameters for the forward wingbeats**

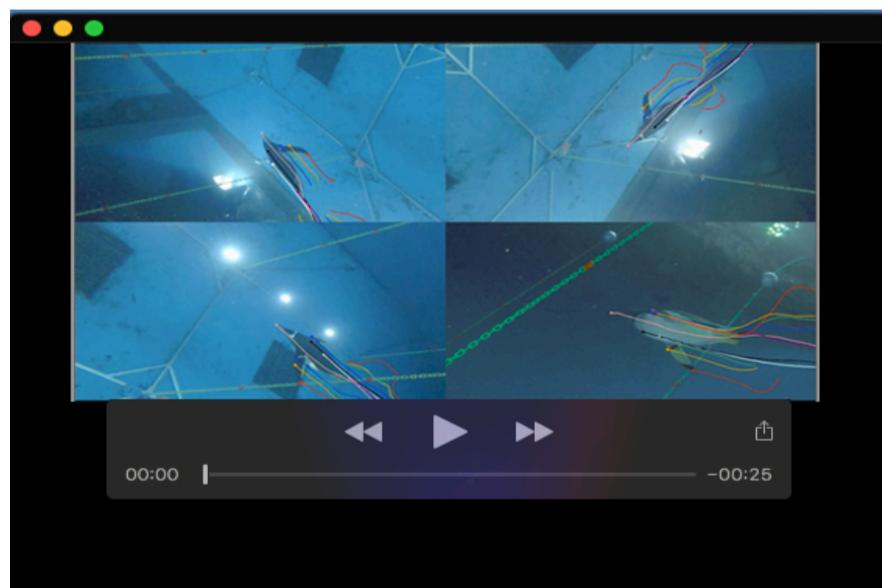
[Click here to download Table S2](#)



**Movie 1. Example of an obtained sequence and wing motion.**

Sequence ID 4 (see Table S2). This sequence contains wingbeat IDs 4 ( $t= 0.6500$  to  $1.1667$ ) and 5 ( $t= 1.3500$  to  $1.9000$ ).

The left panel shows the actual camera view (camera 4, see Fig. 1A) and the trajectories of each marker. The right panel shows wing motion relative to the body, viewed from the front of the penguin. The x mark represents the centre of body.



**Movie 2. Example of an analysed wingbeat viewed from multiple directions.**

Wingbeat ID 5 (see Table S2) viewed from Camera 1 (upper left), Camera 2 (upper right), Camera 4 (lower left), and Camera 10 (lower right) (see Fig. 1A) during  $t'= -0.21$  to  $1.21$ . Each camera view was cropped from the original footage to focus on the penguin.