Allometric wing growth links parental care to pterosaur giantism

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Methods for Allometric Analysis

All measurements were logarithmically transformed and then subjected to allometric analysis using a multivariate approach of principal components analysis (PCA) following Yang et al. [1].

For each species, a covariance matrix of the log-transformed measurements was subjected to PCA to extract the first principal component (PC1) as an internally defined size variable; this accounted for every skeletal variable involved and allowed calculation of the allometric coefficient for each skeletal variable [2,3]. Missing data were imputed using the iterative PCA method [4], also known as the EM-PCA algorithm [5]; this is suitable for small datasets and provides better estimates than other imputation techniques when variables are highly correlated [6]. To test the null hypothesis of isometry (allometric coefficient = 0), a bootstrap method [7] was applied on account of the small sample size and unknown distribution of the allometric coefficient; bootstrapping with 1000 iterations generated a one-tailed 95% confidence interval for the allometric coefficient. We rejected the null hypothesis if the 95% confidence interval lay entirely above or below 1, i.e., positive or negative allometry, respectively; otherwise, isometry was assumed.

These were calculated in R v. 3.5.1 using the "missMDA" [8] and "boot" [9] packages, using code provided below.

```
############### PCA allometric analysis with missing data ##############
rm(list=ls())
library(missMDA)
library(boot)
# Copy and paste the log-transformed measurements into a csv file using the name PCAdata.csv (each
skeletal variable as a column; missing values marked as NA), and then load the dataset into R
originaldata<-read.csv("PCAdata.csv",header=TRUE)
originaldata
# estimate number of components for imputation
nc <- estim_ncpPCA(originaldata, ncp.min=0, ncp.max=5)
nc$ncp
# imputation to generate a complete dataset
imputation <- imputePCA(originaldata, ncp=nc$ncp)
# show the complete dataset
completedata<-imputation$completeObs
completedata
# proportion of variance explained by PC1
```

```r
pca<-prcomp(completedata)
summary(pca)$importance[2,"PC1"]
# define a function to calculate the allometric coefficient for each skeletal variable
bootdata = function(data,indices){
   a<-data[indices,]
   b<-prcomp(a)
   c(abs(b$rotation[,1])/(ncol(completedata)^(-0.5)))
}
#bootstrap with 1000 iterations
bootresult<-boot(completedata,bootdata,R=1000)
# allometric coefficient for each skeletal variable
bootresult$t0
# one-tailed 95% confidence interval for each allometric coefficient
for(i in 1:ncol(completedata))
{if(bootresult$t0[i]>1)
{print(names(bootresult$t0[i]))
   print(quantile(bootresult$t[,i],c(0.05,1)))}
   else
   {print(names(bootresult$t0[i]))
      print(quantile(bootresult$t[,i],c(0.00,0.95)))}}
```

Table S1. Growth allometry of skull, neck and tail length.

		Skull	Neck	Tail
Rhamphorhynchus	Allometric coefficient	1.06	1.06	1.03
	One-tailed 95% CI	>1.02	>1.01	>0.99
	Allometry	+	+	=
Pterodactylus	Allometric coefficient	1.14	1.25	
	One-tailed 95% CI	>1.06	>1.18	
	Allometry	+	+	
Sinopterus	Allometric coefficient	1.07		
	One-tailed 95% CI	>0.91		
	Allometry	=		

Table S2. Ontogenetic changes in wing planforms using taxon-specific postures.

	Wingspan (m)	Wing area (m^2)	Wing aspect ratio
Anurognathids	0.3	0.01	8.71
	1	0.11	9.50
	2	0.42	9.51
	3	0.96	9.35
	4	1.75	9.14
	5	2.78	9.00
	6	4.08	8.83
	7	5.64	8.70
Rhamphorhynchus	0.3	0.01	11.45
	1	0.08	11.78
	2	0.34	11.82
	3	0.76	11.78
	4	1.38	11.62
	5	2.17	11.49
	6	3.12	11.52
	7	4.31	11.36
Pterodactylus	0.3	0.01	9.30
	1	0.12	8.25
	2	0.52	7.72
	3	1.20	7.50
	4	2.20	7.26
	5	3.57	7.00
	6	5.20	6.92
	7	7.27	6.74
Sinopterus	0.3	0.01	14.75
	1	0.08	12.99
	2	0.35	11.52
	3	0.84	10.77
	4	1.58	10.15
	5	2.56	9.75
	6	3.79	9.51
	7	4.79	10.23
Pteranodon	0.3	0.01	10.40
	1	0.07	13.36
	2	0.27	14.70
	3	0.58	15.63
	4	0.99	16.15
	5	1.54	16.23
	6	2.14	16.84
	7	2.94	16.67

Table S3. Ontogenetic changes in wing planforms using the neutral posture.

	Wingspan (m)	Wing area (m^2)	Wing aspect ratio
Anurognathids	0.3	0.01	8.26
	1	0.12	8.66
	2	0.46	8.67
	3	1.04	8.64
	4	1.89	8.49
	5	3.02	8.29
	6	4.37	8.23
	7	6.07	8.08
Rhamphorhynchus	0.3	0.01	11.78
	1	0.08	12.56
	2	0.32	12.37
	3	0.74	12.22
	4	1.29	12.36
	5	2.03	12.30
	6	2.95	12.20
	7	4.08	12.00
Pterodactylus	0.3	0.01	9.52
	1	0.12	8.55
	2	0.50	8.07
	3	1.17	7.69
	4	2.16	7.42
	5	3.50	7.15
	6	5.04	7.14
	7	7.02	6.98
Sinopterus	0.3	0.01	14.48
	1	0.07	13.39
	2	0.33	11.95
	3	0.81	11.15
	4	1.50	10.70
	5	2.35	10.63
	6	3.81	9.45
	7	4.72	10.38
Pteranodon	0.3	0.01	9.80
	1	0.08	12.59
	2	0.29	13.98
	3	0.60	14.92
	4	1.05	15.22
	5	1.59	15.69
	6	2.26	15.90
	7	3.09	15.87

Table S4. Ontogenetic changes in aerodynamics using taxon-specific postures.

	Wing span (m)	Based on body mass estimations by Witton (2008)					Based on body mass estimations by Henderson (2010)				
		Body mass (kg)	Wing loading (N/m^2)	COT^{-1} (kg m/J)	V_z (m/s)	Glide ratio	Body mass (kg)	Wing loading (N/m^2)	COT^{-1} (kg m/J)	V_z (m/s)	Glide ratio
Anurognathids	0.3	0.02	22.03	0.45	0.61	9.93	0.01	10.52	0.24	0.42	10.03
	1	0.68	63.49	2.97	0.88	12.81	0.30	27.97	1.51	0.56	13.90
	2	4.77	111.10	8.60	1.09	14.44	2.00	46.72	4.29	0.66	16.37
	3	14.87	151.54	15.92	1.23	15.38	6.09	62.02	7.61	0.73	17.43
	4	33.35	186.99	24.23	1.34	15.89	13.39	75.07	11.34	0.78	18.05
	5	62.40	220.46	33.50	1.43	16.22	24.68	87.19	15.45	0.82	18.50
	6	104.09	250.49	43.54	1.51	16.48	40.67	97.87	19.85	0.86	18.83
	7	160.45	279.31	54.35	1.58	16.69	62.04	108.00	24.55	0.89	19.10
Rhamphorhynchus	0.3	0.02	28.95	0.47	0.66	9.73	0.01	13.82	0.25	0.45	9.96
	1	0.68	78.70	3.08	0.94	12.44	0.30	34.67	1.57	0.59	13.66
	2	4.77	138.10	8.90	1.16	13.93	2.00	58.08	4.46	0.70	15.98
	3	14.87	191.05	16.48	1.33	14.76	6.09	78.19	8.17	0.78	17.36
	4	33.35	237.58	25.44	1.45	15.37	13.39	95.38	12.23	0.84	18.05
	5	62.40	281.45	35.60	1.56	15.83	24.68	111.31	16.70	0.88	18.53
	6	104.09	326.84	46.92	1.66	16.16	40.67	127.69	21.61	0.93	18.90
	7	160.45	365.00	58.73	1.74	16.41	62.04	141.14	26.74	0.97	19.20
Pterodactylus	0.3	0.02	24.43	0.47	0.63	9.87	0.01	14.65	0.30	0.49	10.03
	1	0.52	42.01	2.33	0.73	13.44	0.32	25.50	1.53	0.55	13.97
	2	3.04	57.53	5.74	0.79	15.73	1.86	35.16	3.80	0.60	16.44
	3	8.55	69.85	9.46	0.83	16.70	5.24	42.86	6.26	0.63	17.46
	4	17.80	79.25	13.42	0.86	17.33	10.95	48.77	8.90	0.66	18.11
	5	31.44	86.32	17.54	0.88	17.77	19.39	53.24	11.63	0.67	18.53
	6	50.06	94.41	21.93	0.91	18.13	30.93	58.34	14.57	0.70	18.89
	7	74.16	100.09	26.38	0.93	18.39	45.89	61.94	17.52	0.71	19.14
Sinopterus	0.3	0.02	38.73	0.52	0.73	9.42	0.01	23.23	0.34	0.56	9.73
	1	0.52	66.11	2.52	0.83	12.75	0.32	40.13	1.67	0.63	13.46
	2	3.04	85.87	6.21	0.89	15.14	1.86	52.48	4.17	0.67	16.16
	3	8.55	100.38	10.54	0.92	16.69	5.24	61.60	7.02	0.70	17.71
	4	17.80	110.77	14.87	0.95	17.45	10.95	68.17	9.90	0.71	18.47
	5	31.44	120.30	19.42	0.97	18.00	19.39	74.20	12.93	0.73	19.01
	6	50.06	129.67	24.20	0.99	18.42	30.93	80.13	16.12	0.75	19.42
	7	74.16	151.89	30.03	1.04	18.77	45.89	94.00	20.05	0.79	19.85
Pteranodon	0.3	0.02	27.31	0.48	0.65	9.78	0.01	16.38	0.31	0.50	9.99
	1	0.52	68.02	2.53	0.84	12.69	0.32	41.28	1.68	0.63	13.42
	2	3.04	109.54	6.49	0.96	14.52	1.86	66.95	4.38	0.73	15.63
	3	8.55	145.62	11.26	1.06	15.60	5.24	89.36	7.65	0.79	16.95
	4	17.80	176.27	16.59	1.12	16.41	10.95	108.48	11.33	0.84	17.94
	5	31.44	200.21	22.32	1.17	17.13	19.39	123.49	15.29	0.87	18.78
	6	50.06	229.71	28.60	1.22	17.59	30.93	141.94	19.48	0.91	19.21
	7	74.16	247.53	35.00	1.25	18.16	45.89	153.19	23.59	0.93	19.64

Table S5. Pair-wise permutation test on estimated flight efficiency (COT^{-1}) using the taxon-specific posture model.

Estimations based on Witton (2008)	*Pteranodon*	*Sinopterus*	*Pterodactylus*	*Rhamphorhynchus*
Anurognathids	Z = 2.1217, p-value = 0.01562	Z = 2.0982, p-value = 0.01562	Z = 2.1106, p-value = 0.01562	Z = -1.9859, p-value = 0.007812
Rhamphorhynchus	Z = 2.1001, p-value = 0.01562	Z = 2.0834, p-value = 0.01562	Z = 2.096, p-value = 0.007812	
Pterodactylus	Z = -2.0845, p-value = 0.007812	Z = -2.1832, p-value = 0.007812		
Sinopterus	Z = -1.9993, p-value = 0.02344			
Estimations based on Henderson (2010)	*Pteranodon*	*Sinopterus*	*Pterodactylus*	*Rhamphorhynchus*
Anurognathids	Z = 1.053, p-value = 0.3984	Z = 1.9268, p-value = 0.04688	Z = 2.0325, p-value = 0.03125	Z = -2.1203, p-value = 0.007812
Rhamphorhynchus	Z = 1.9147, p-value = 0.04688	Z = 1.9941, p-value = 0.03125	Z = 2.0548, p-value = 0.02344	
Pterodactylus	Z = -2.1127, p-value = 0.007812	Z = -2.1967, p-value = 0.007812		
Sinopterus	Z = -2.039, p-value = 0.02344			

Table S6. Pair-wise permutation test on estimated glide ratio using the taxon-specific posture model.

Estimations based on Witton (2008)	*Pteranodon*	*Sinopterus*	*Pterodactylus*	*Rhamphorhynchus*
Anurognathids	Z = -1.892, p-value = 0.0625	Z = -2.1873, p-value = 0.03125	Z = -2.5547, p-value = 0.01562	Z = 2.6867, p-value = 0.007812
Rhamphorhynchus	Z = -2.421, p-value = 0.007812	Z = -2.3972, p-value = 0.02344	Z = -2.6303, p-value = 0.007812	
Pterodactylus	Z = -2.4837, p-value = 0.007812	Z = 0.62833, p-value = 0.5547		
Sinopterus	Z = 2.2094, p-value = 0.02344			
Estimations based on Henderson (2010)	*Pteranodon*	*Sinopterus*	*Pterodactylus*	*Rhamphorhynchus*
Anurognathids	Z = 0.51774, p-value = 0.6172	Z = -1.2219, p-value = 0.2422	Z = -2.5469, p-value = 0.007812	Z = 1.1527, p-value = 0.3438
Rhamphorhynchus	Z = 0.096766, p-value = 0.9297	Z = -1.8816, p-value = 0.07031	Z = -1.617, p-value = 0.08594	
Pterodactylus	Z = -0.79078, p-value = 0.4766	Z = -0.96563, p-value = 0.3672		
Sinopterus	Z = 1.9445, p-value = 0.0625			

Table S7. Ontogenetic changes in aerodynamics using the neutral posture.

	Wing span (m)	Based on body mass estimations by Witton (2008)					Based on body mass estimations by Henderson (2010)				
		Body mass (kg)	Wing loading (N/m^2)	COT^{-1} (kg m/J)	V_z (m/s)	Glide ratio	Body mass (kg)	Wing loading (N/m^2)	COT^{-1} (kg m/J)	V_z (m/s)	Glide ratio
Anurognathids	0.3	0.02	20.90	0.45	0.60	9.95	0.01	9.98	0.23	0.42	10.03
	1	0.68	57.87	2.92	0.85	12.95	0.30	25.49	1.48	0.55	13.97
	2	4.77	101.29	8.48	1.06	14.63	2.00	42.60	4.20	0.64	16.43
	3	14.87	140.13	15.63	1.20	15.48	6.09	57.35	7.43	0.71	17.39
	4	33.35	173.55	23.73	1.31	15.93	13.39	69.67	11.08	0.76	18.00
	5	62.40	202.92	32.70	1.39	16.26	24.68	80.25	15.06	0.80	18.42
	6	104.09	233.56	42.67	1.48	16.51	40.67	91.25	19.42	0.84	18.76
	7	160.45	259.41	53.21	1.55	16.72	62.04	100.31	23.99	0.88	19.01
Rhamphorhynchus	0.3	0.02	29.78	0.48	0.66	9.70	0.01	14.22	0.25	0.45	9.94
	1	0.68	83.92	3.11	0.96	12.31	0.30	36.97	1.60	0.61	13.57
	2	4.77	144.64	8.96	1.18	13.81	2.00	60.83	4.50	0.72	15.88
	3	14.87	198.05	16.58	1.34	14.65	6.09	81.06	8.22	0.79	17.27
	4	33.35	252.78	25.69	1.48	15.17	13.39	101.48	12.47	0.86	18.01
	5	62.40	301.27	35.98	1.60	15.60	24.68	119.15	17.07	0.91	18.49
	6	104.09	346.01	47.32	1.69	15.96	40.67	135.18	22.01	0.95	18.87
	7	160.45	385.53	59.58	1.77	16.30	62.04	149.08	27.21	0.98	19.18
Pterodactylus	0.3	0.02	24.99	0.47	0.64	9.85	0.01	14.98	0.31	0.49	10.02
	1	0.52	43.55	2.34	0.73	13.40	0.32	26.43	1.54	0.56	13.95
	2	3.04	60.18	5.82	0.80	15.75	1.86	36.78	3.85	0.61	16.48
	3	8.55	71.69	9.53	0.83	16.72	5.24	43.99	6.32	0.63	17.50
	4	17.80	80.97	13.51	0.86	17.35	10.95	49.83	8.96	0.66	18.14
	5	31.44	88.26	17.66	0.89	17.80	19.39	54.44	11.71	0.68	18.58
	6	50.06	97.46	22.16	0.92	18.18	30.93	60.22	14.72	0.70	18.97
	7	74.16	103.63	26.67	0.94	18.45	45.89	64.13	17.73	0.72	19.23
Sinopterus	0.3	0.02	38.02	0.51	0.72	9.44	0.01	22.80	0.33	0.55	9.75
	1	0.52	68.18	2.53	0.84	12.69	0.32	41.38	1.68	0.64	13.41
	2	3.04	89.06	6.25	0.90	15.06	1.86	54.43	4.20	0.68	16.09
	3	8.55	103.85	10.60	0.93	16.60	5.24	63.73	7.10	0.70	17.70
	4	17.80	116.78	15.11	0.96	17.43	10.95	71.87	10.07	0.73	18.48
	5	31.44	131.21	19.95	0.99	17.98	19.39	80.93	13.31	0.75	19.05
	6	50.06	128.89	24.16	0.99	18.41	30.93	79.64	16.10	0.75	19.42
	7	74.16	154.10	30.17	1.04	18.77	45.89	95.37	20.14	0.79	19.86
Pteranodon	0.3	0.02	25.73	0.48	0.64	9.83	0.01	15.43	0.31	0.49	10.01
	1	0.52	64.08	2.50	0.82	12.81	0.32	38.89	1.66	0.62	13.51
	2	3.04	104.19	6.43	0.95	14.66	1.86	63.67	4.33	0.71	15.75
	3	8.55	139.04	11.16	1.04	15.75	5.24	85.32	7.58	0.78	17.09
	4	17.80	166.11	16.41	1.10	16.63	10.95	102.23	11.21	0.82	18.14
	5	31.44	193.56	22.17	1.15	17.26	19.39	119.38	15.12	0.86	18.83
	6	50.06	216.94	28.29	1.19	17.83	30.93	134.05	19.12	0.89	19.30
	7	74.16	235.66	34.55	1.22	18.31	45.89	145.84	23.21	0.91	19.72

Table S8. Pair-wise permutation test on estimated flight efficiency (COT^{-1}) using the neutral posture model.

Estimations based on Witton (2008)	*Pteranodon*	*Sinopterus*	*Pterodactylus*	*Rhamphorhynchus*
Anurognathids	Z = 2.1192, p-value = 0.01562	Z = 2.0872, p-value = 0.01562	Z = 2.1073, p-value = 0.01562	Z = -2.029, p-value = 0.007812
Rhamphorhynchus	Z = 2.0986, p-value = 0.007812	Z = 2.076, p-value = 0.01562	Z = 2.0937, p-value = 0.007812	
Pterodactylus	Z = -2.0779, p-value = 0.007812	Z = -2.2065, p-value = 0.007812		
Sinopterus	Z = -1.9318, p-value = 0.03125			
Estimations based on Henderson (2010)	*Pteranodon*	*Sinopterus*	*Pterodactylus*	*Rhamphorhynchus*
Anurognathids	Z = 0.39465, p-value = 0.8281	Z = 1.8151, p-value = 0.0625	Z = 2.0056, p-value = 0.03125	Z = -2.1403, p-value = 0.007812
Rhamphorhynchus	Z = 1.9634, p-value = 0.03125	Z = 1.9794, p-value = 0.03125	Z = 2.0555, p-value = 0.01562	
Pterodactylus	Z = -2.1119, p-value = 0.007812	Z = -2.2275, p-value = 0.007812		
Sinopterus	Z = -1.9873, p-value = 0.03125			

Table S9. Pair-wise permutation test on estimated glide ratio using the neutral posture model.

Estimations based on Witton (2008)	*Pteranodon*	*Sinopterus*	*Pterodactylus*	*Rhamphorhynchus*
Anurognathids	Z = -1.9123, p-value = 0.05469	Z = -2.0625, p-value = 0.04688	Z = -2.4975, p-value = 0.01562	Z = 2.7032, p-value = 0.007812
Rhamphorhynchus	Z = -2.5048, p-value = 0.007812	Z = -2.4134, p-value = 0.01562	Z = -2.627, p-value = 0.007812	
Pterodactylus	Z = 2.3853, p-value = 0.007812	Z = 0.95524, p-value = 0.375		
Sinopterus	Z = 1.9854, p-value = 0.04688			
Estimations based on Henderson (2010)	*Pteranodon*	*Sinopterus*	*Pterodactylus*	*Rhamphorhynchus*
Anurognathids	Z = -0.25025, p-value = 0.8281	Z = -1.1346, p-value = 0.2734	Z = -2.2012, p-value = 0.03125	Z = 1.0949, p-value = 0.3438
Rhamphorhynchus	Z = -1.3914, p-value = 0.1875	Z = -2.0253, p-value = 0.03906	Z = -2.1211, p-value = 0.007812	
Pterodactylus	Z = 0.44935, p-value = 0.6484	Z = -0.73892, p-value = 0.4766		
Sinopterus	Z = 1.6124, p-value = 0.1172			

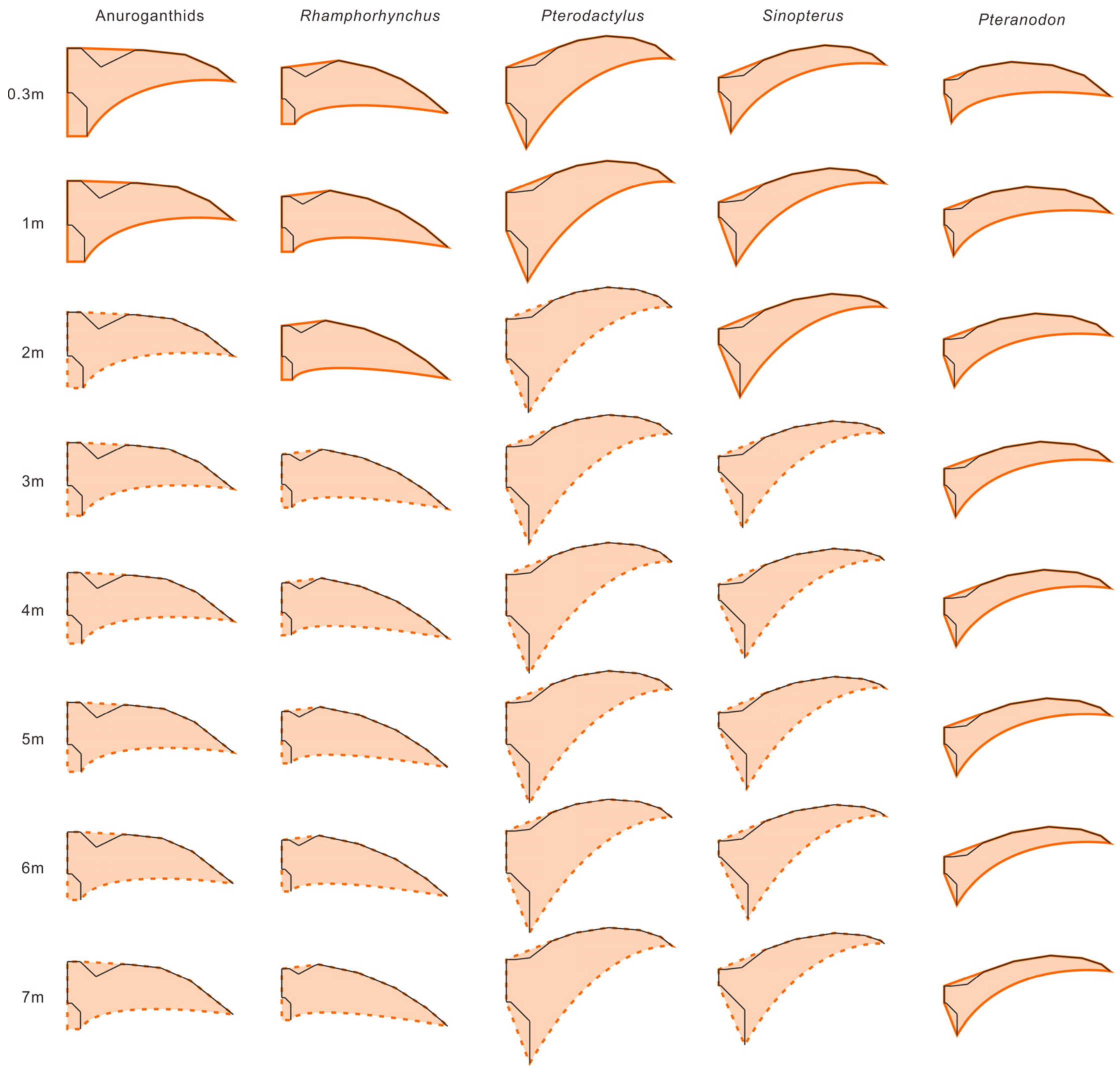


Figure S1. Wing planform changes from early juveniles (0.3 m wingspan) to giant adults (7 m wingspan) using taxon-specific postures. Solid and dashed outlines indicate actual and hypothetical growth, respectively.

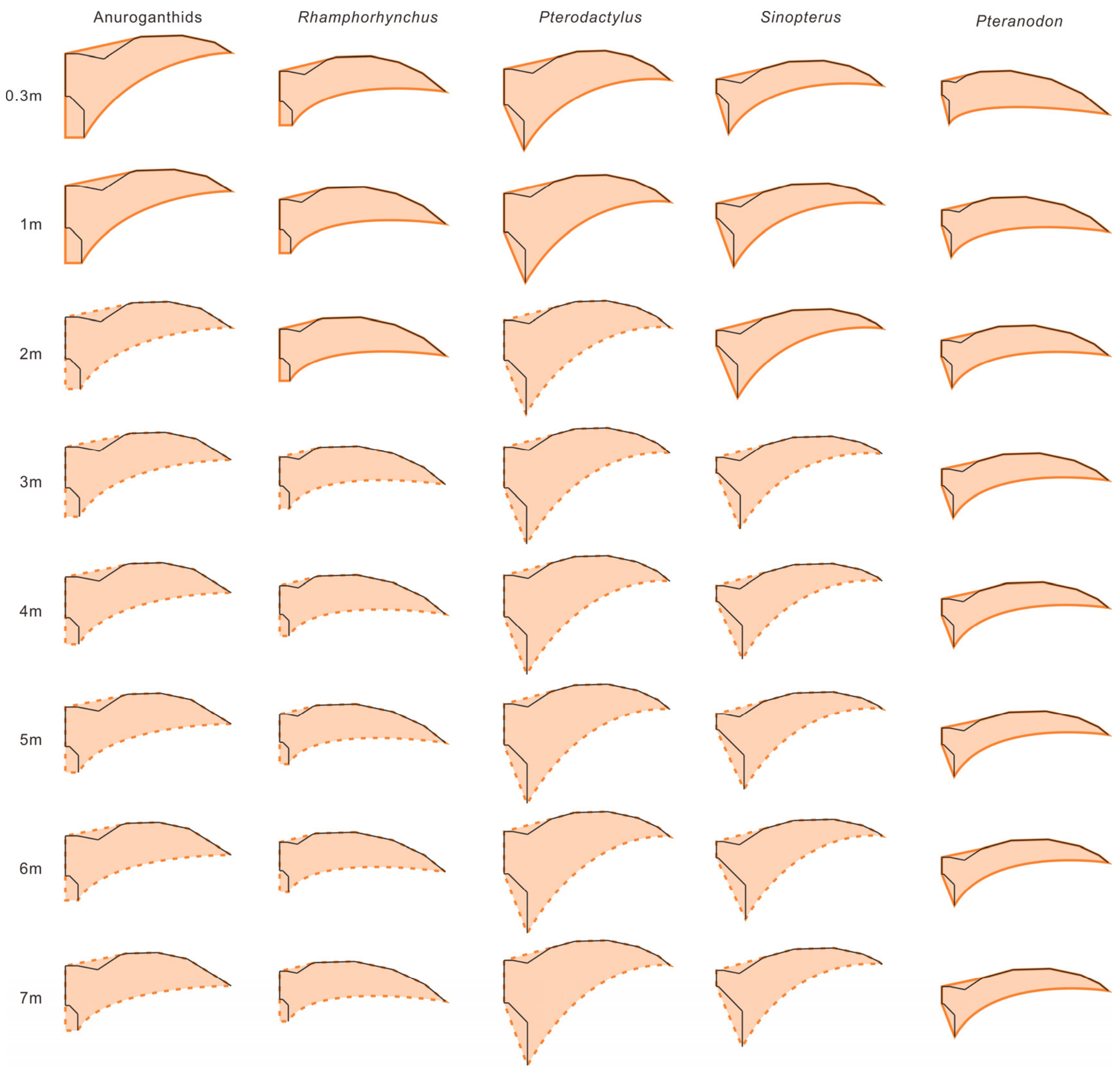
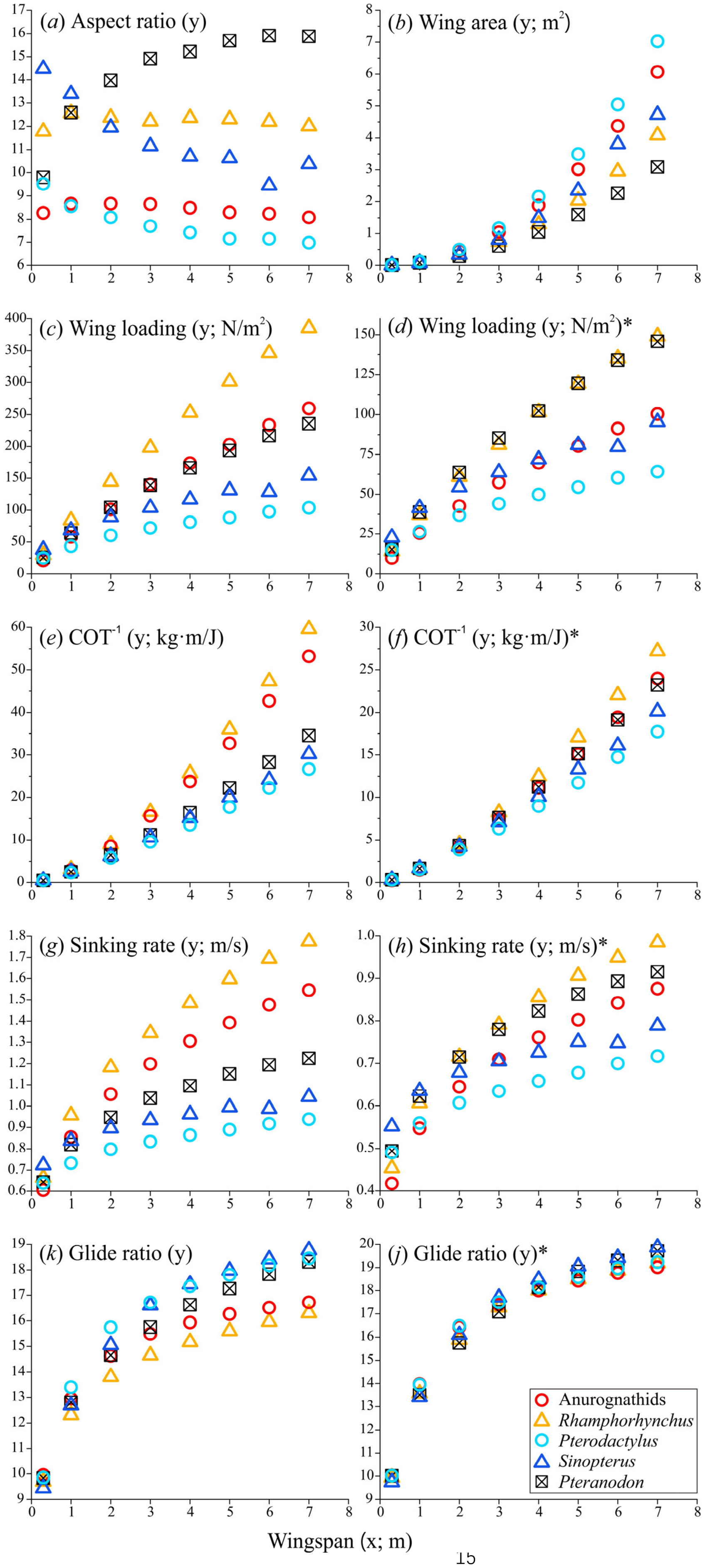


Figure S2. Wing planform changes from early juveniles (0.3 m wingspan) to giant adults (7 m wingspan) using the neutral posture. Solid and dashed outlines indicate actual and hypothetical growth, respectively.



(a) Aspect ratio (y)
(b) Wing area (y; m²)
(c) Wing loading (y; N/m²)
(d) Wing loading (y; N/m²)*
(e) COT⁻¹ (y; kg·m/J)
(f) COT⁻¹ (y; kg·m/J)*
(g) Sinking rate (y; m/s)
(h) Sinking rate (y; m/s)*
(k) Glide ratio (y)
(j) Glide ratio (y)*
Anurognathids
Rhamphorhynchus
Pterodactylus
Sinopterus
Pteranodon
Wingspan (x; m)

Figure S3. Wing aspect ratio (a), wing area (b), wing loading (c–d) and flight performance (e–j) during growth from an early juvenile of 0.3 m wingspan to a (hypothetical for all pterosaurs except *Pteranodon*) giant adult of 7 m wingspan; modelled using the neutral posture. In c–j, models with asterisks are based on the body mass estimation equations by Henderson [10] and those without asterisks are based on the equations by Witton [11].

References for Supplemental Material

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