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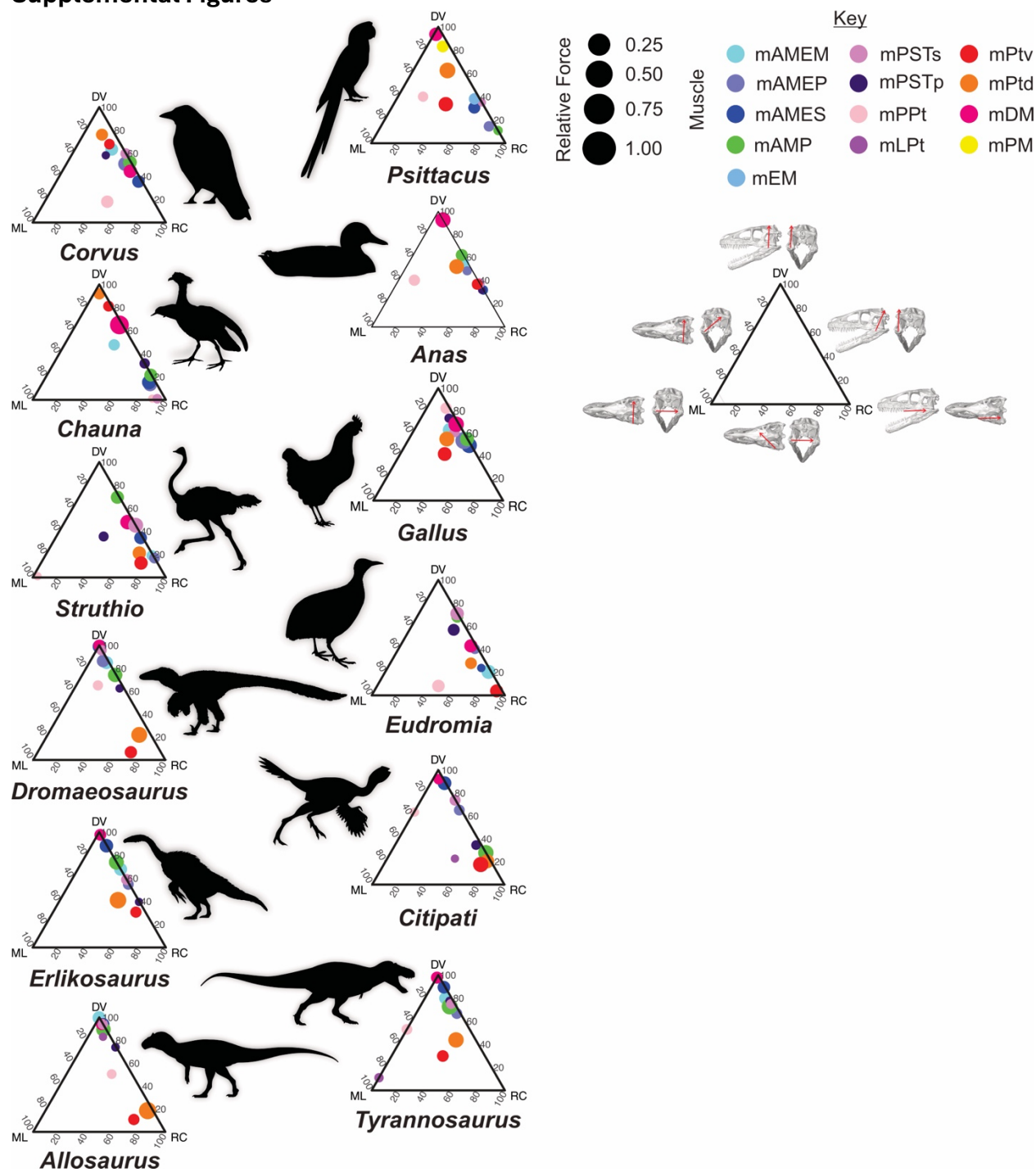
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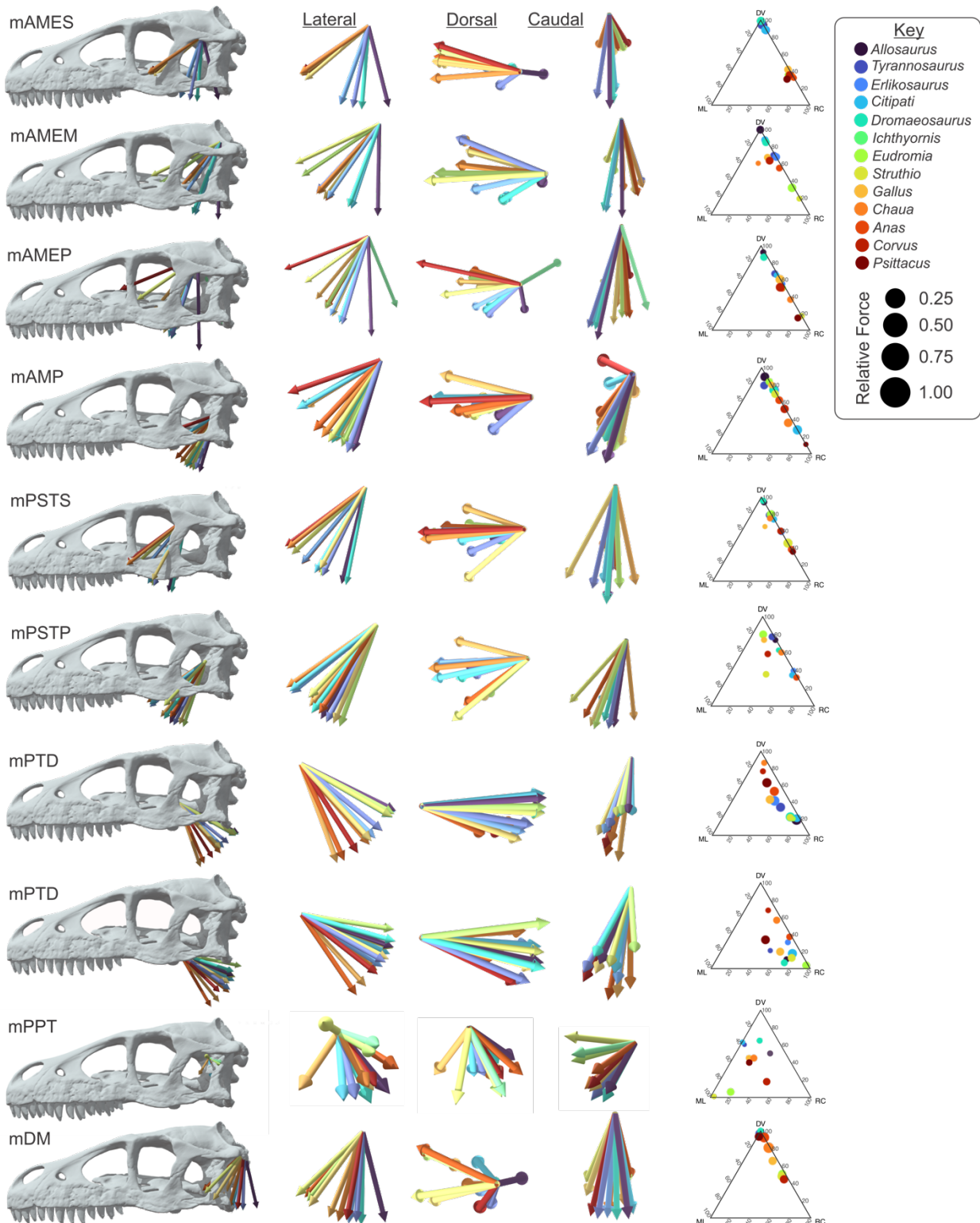
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13 Supplemental Figures



**Figure S1.** Ternary diagrams of jaw muscle vector orientation for sampled taxa.



**Figure S2.** 3D muscle resultants of jaw muscles across taxa collated by taxon and

anchored to common origin coordinates to illustrate evolution transformation across the

22 clade. Ternary plots also depict 3D muscle resultants grouped by muscle, across the  
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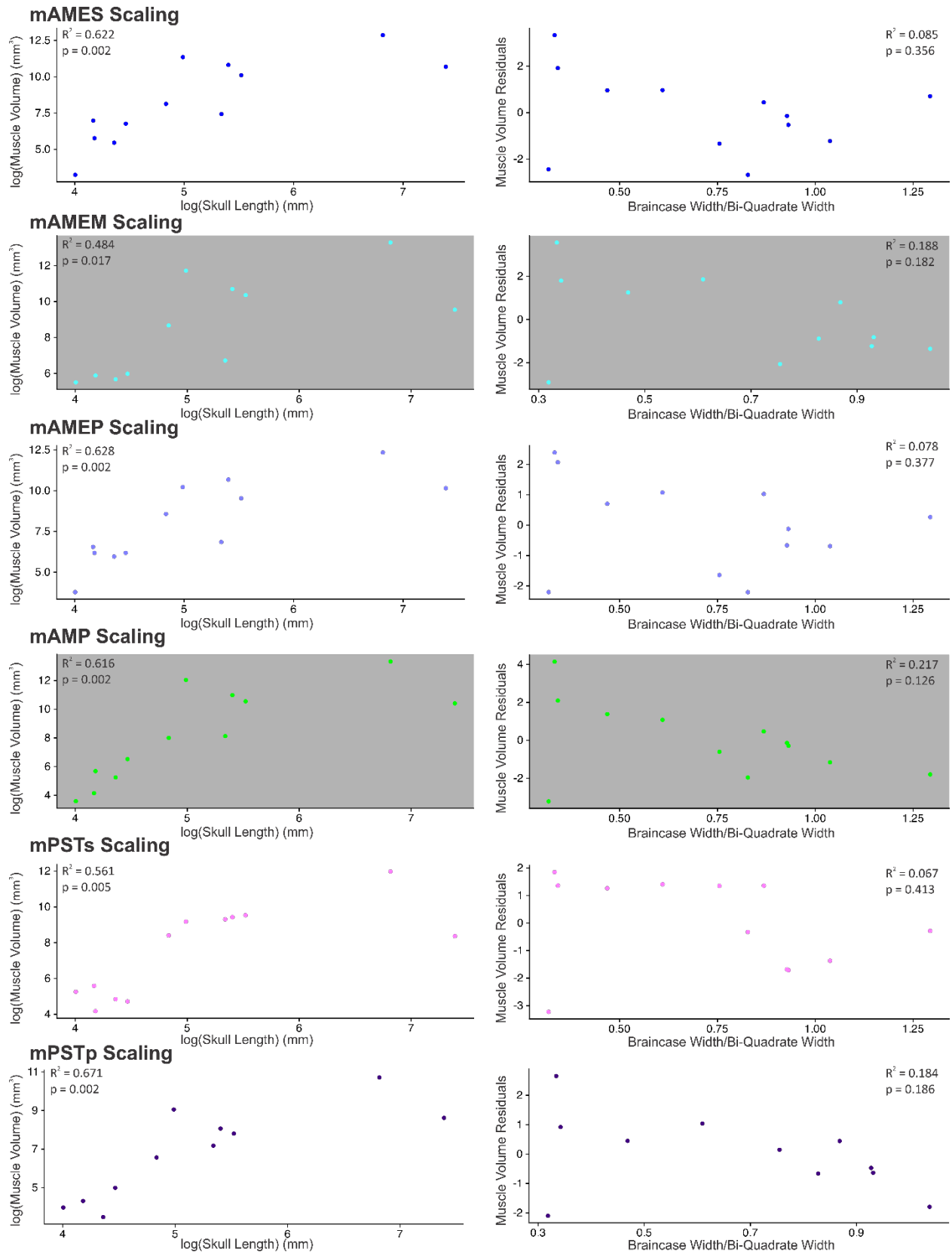
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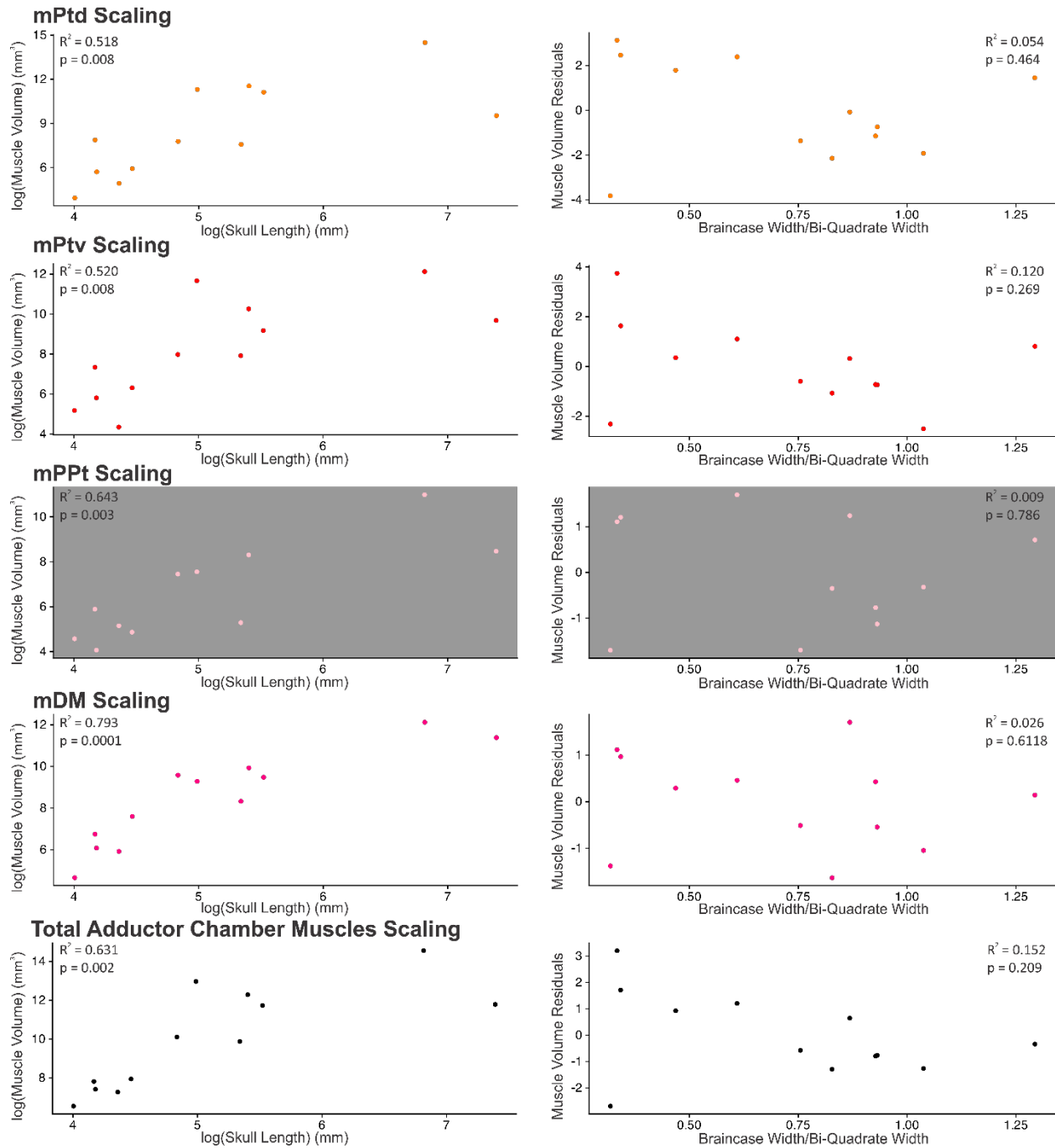
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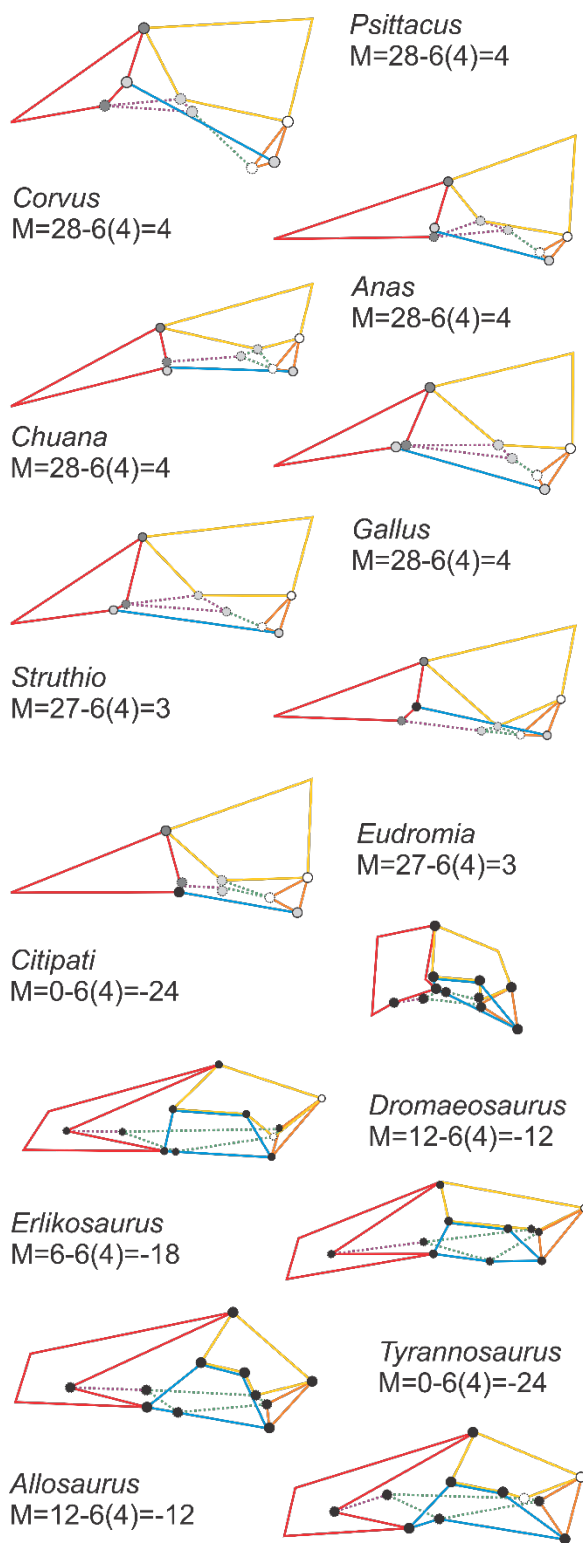
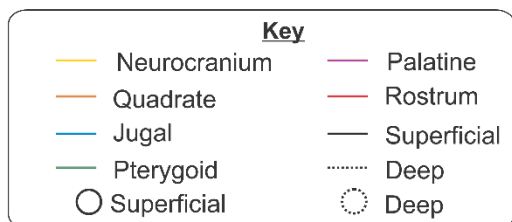
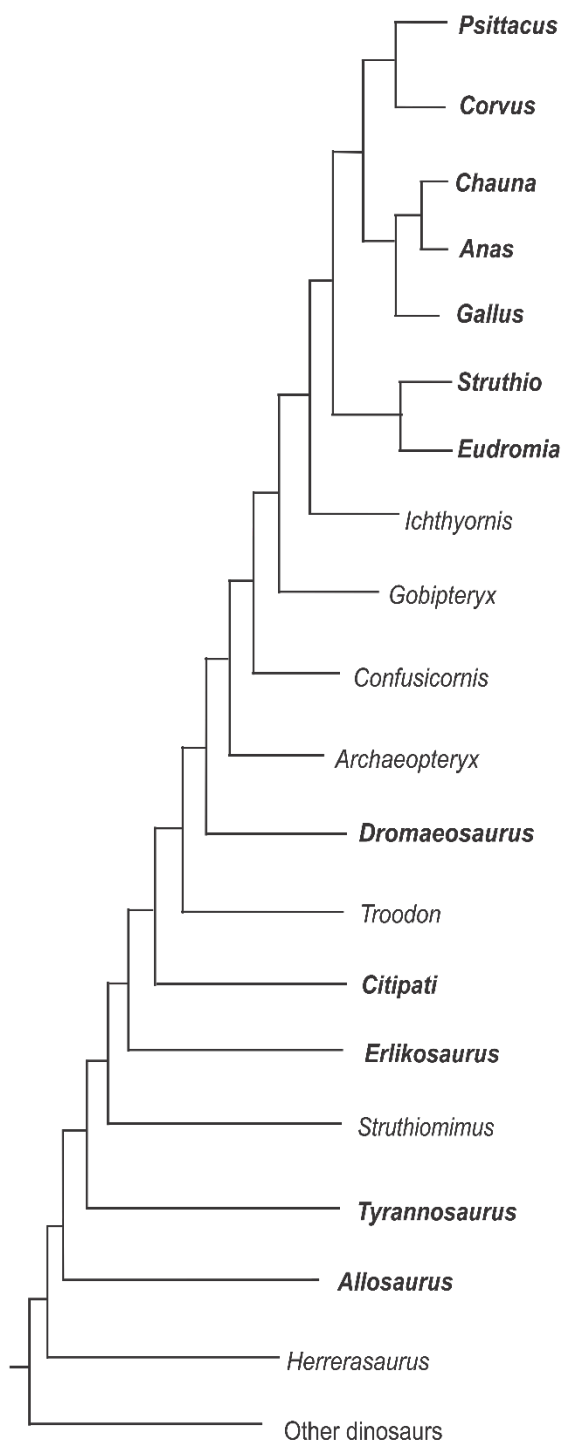


**Figure S3.** Scaling relationships of individual jaw muscle volumes (left column), jaw muscle residuals (right column) and braincase shape across taxa and muscles.



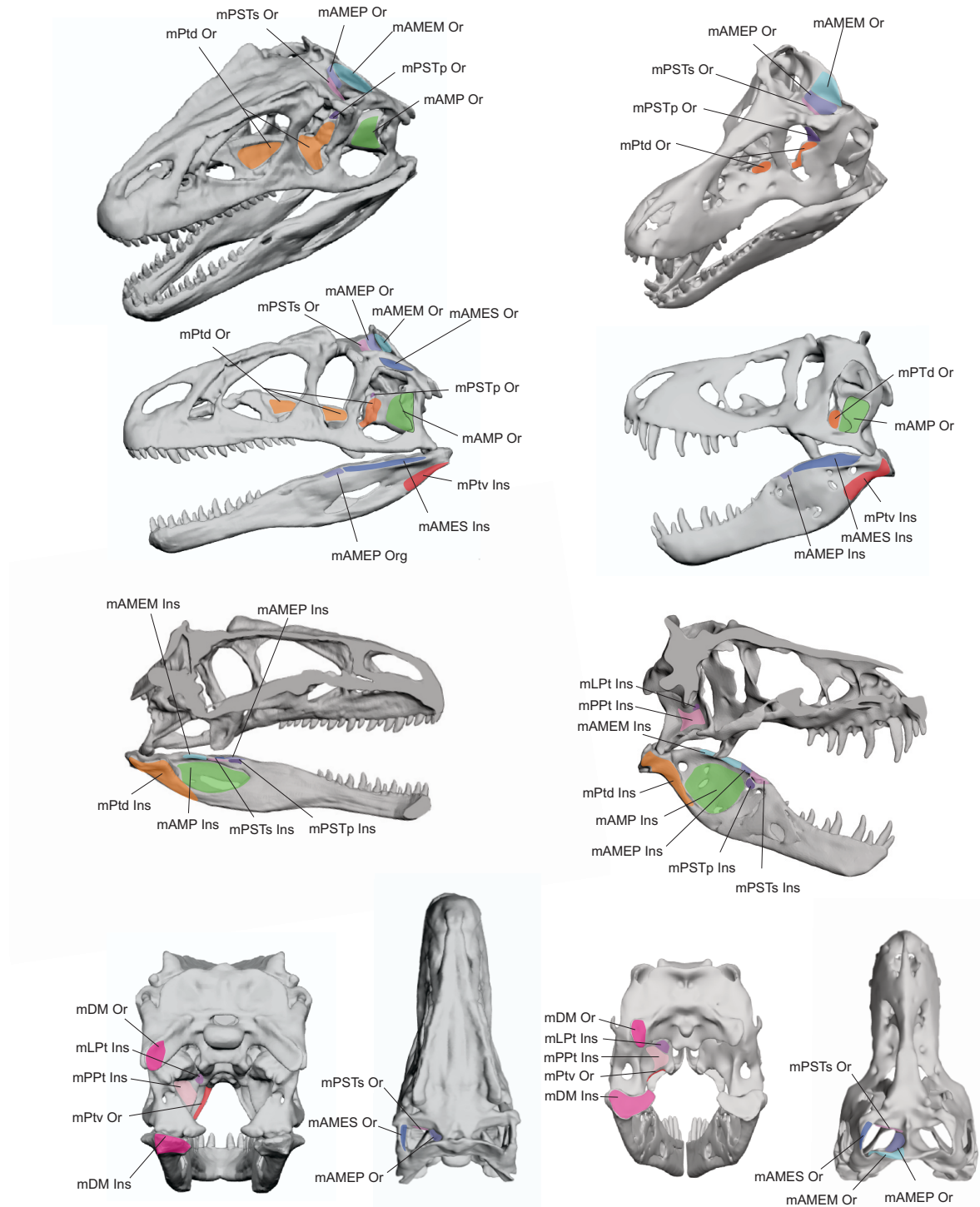
**Figure S4.** Fig. S3 continued: Scaling relationships of individual and total jaw muscle volumes (left column, jaw muscle residuals (right column) and braincase shape across taxa and muscles.





**Figure S5.** Cranial linkage diagrams and scores for all taxa used in analysis.

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**Figure S6.** Muscle maps of *Allosaurus* and *Tyrannosaurus* used in determining 3D jaw muscle resultants in analysis of the dinosaur-bird transition.

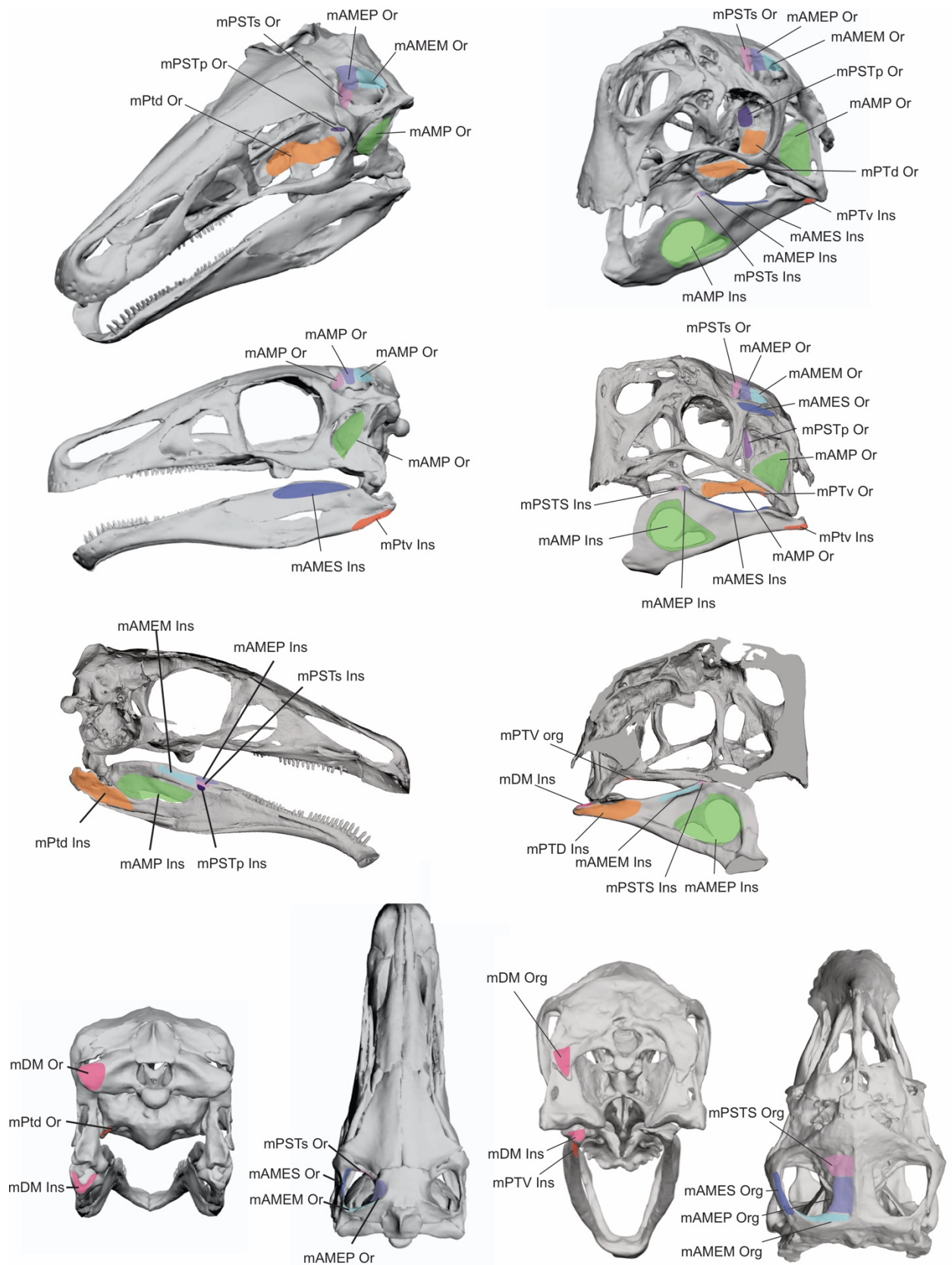
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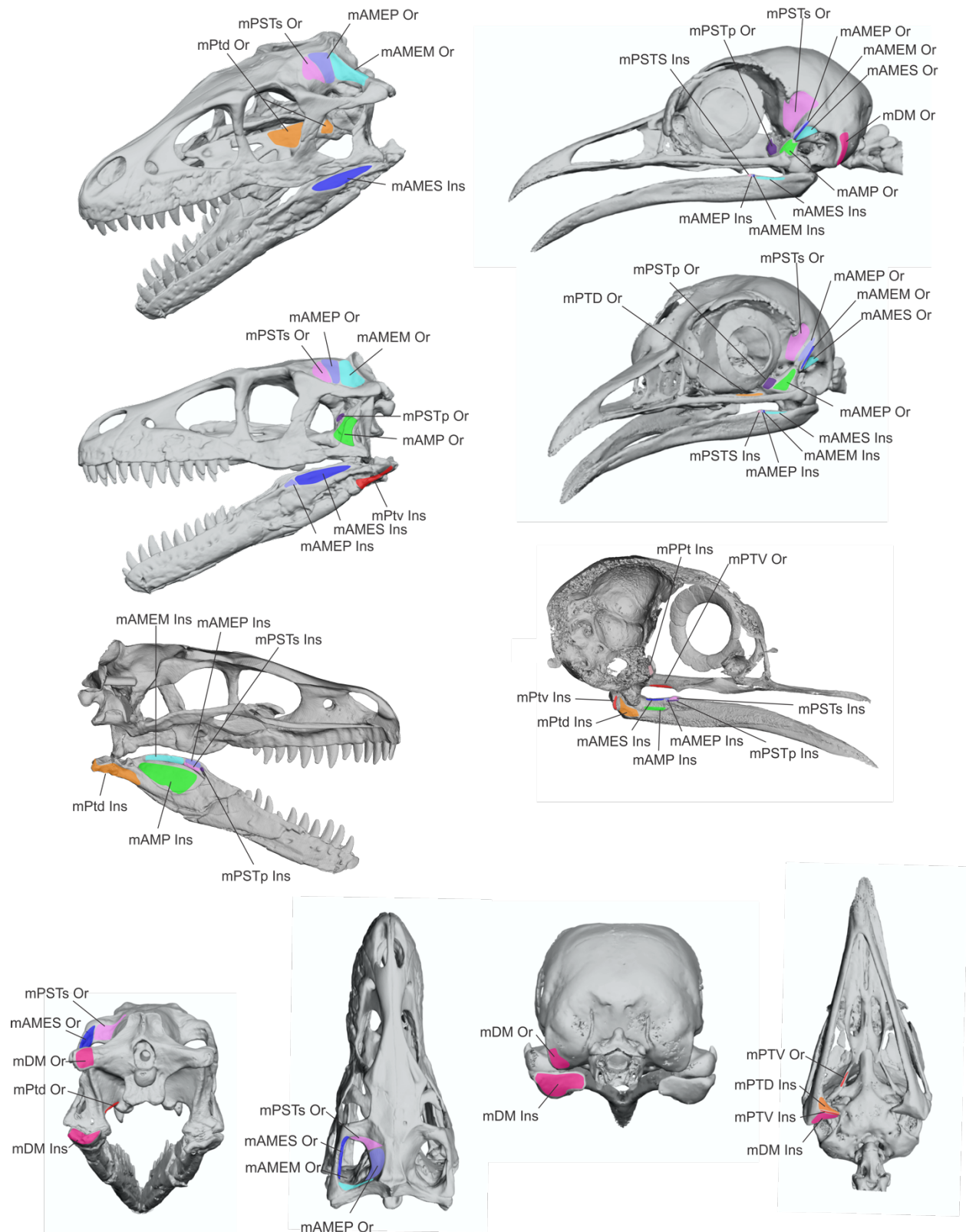
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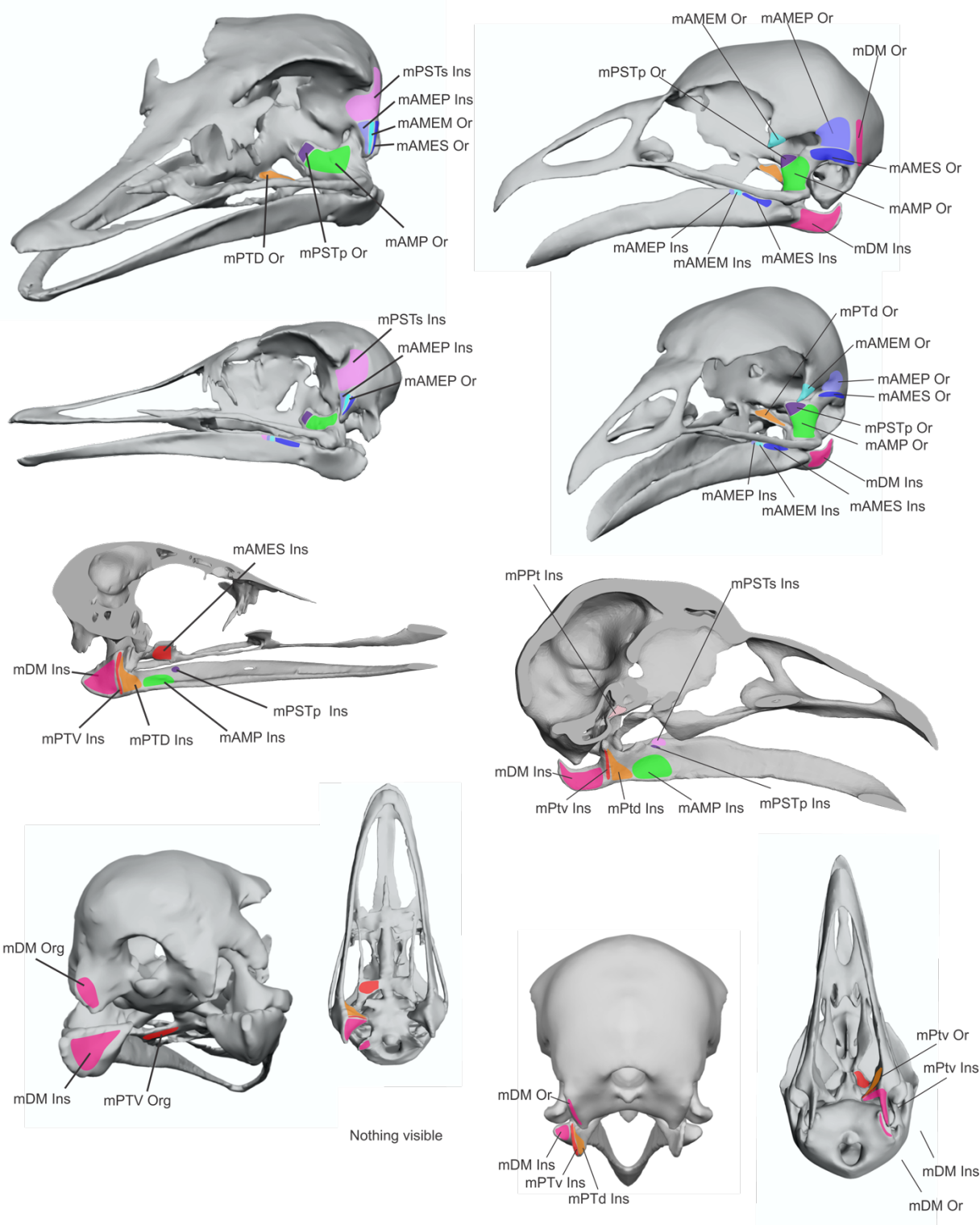


**Figure S7.** Muscle maps of *Erlikosaurus* and *Citipati* used in determining 3D jaw muscle resultants in analysis of the dinosaur-bird transition.



**Figure S8.** Muscle maps of *Dromaeosaurus* and *Eudromia* used in determining 3D jaw muscle resultants in analysis of the dinosaur-bird transition.

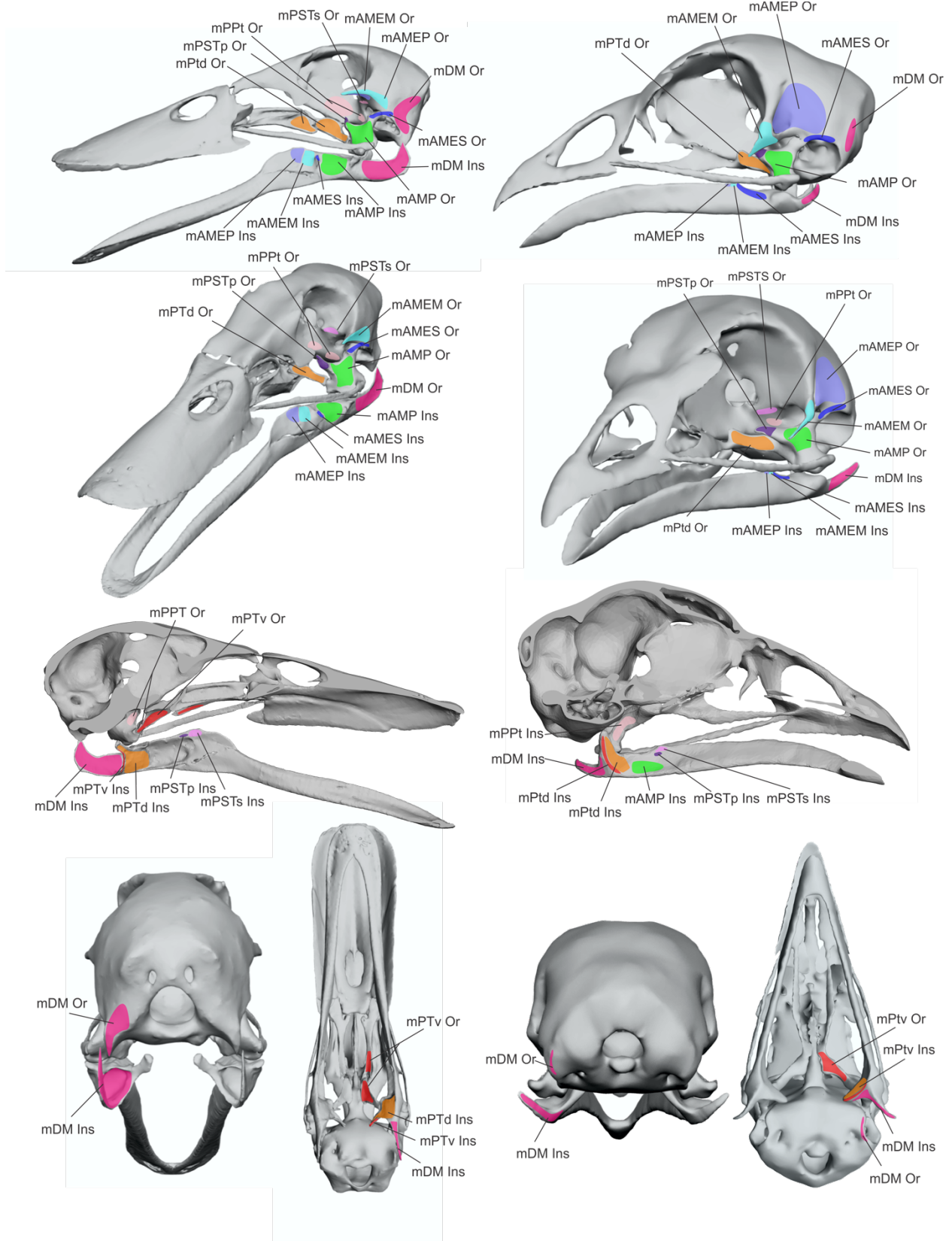
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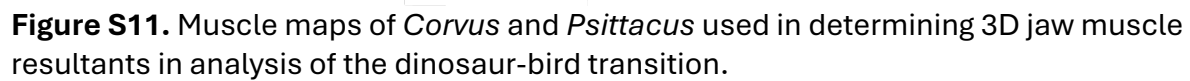
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**Figure S9.** Muscle maps of *Struthio* and *Chauna* used in determining 3D jaw muscle resultants in analysis of the dinosaur-bird transition.





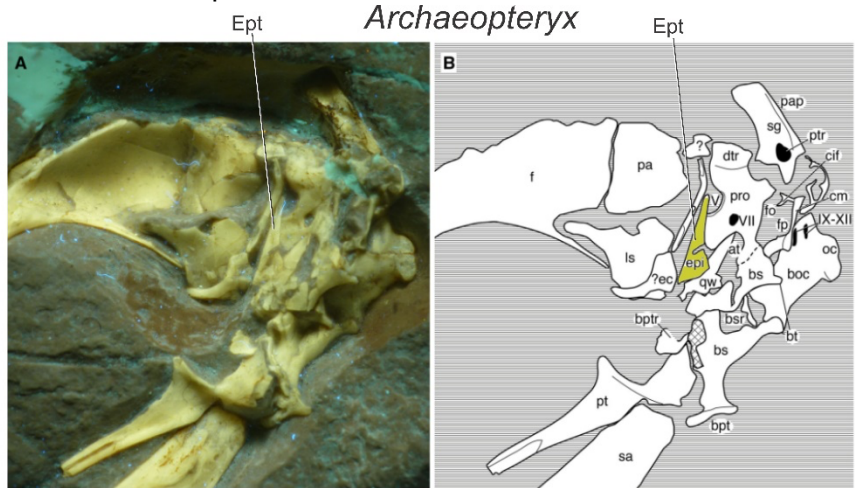
179 **Figure S10.** Muscle maps of *Anas* and *Gallus* used in determining 3D jaw muscle  
180 resultants in analysis of the dinosaur-bird transition.  
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**Notes and Corrections on the palates of Mesozoic birds: *Archaeopteryx***

Rauhut OWM. 2014. New observations on the skull of *Archaeopteryx*. *Palaontologische Zeitschrift* 88(2):211-221 [10.1007/s12542-013-0186-0](https://doi.org/10.1007/s12542-013-0186-0)

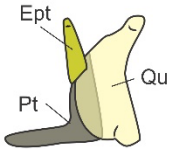
Rauhut (2014) and Holliday (pers obs) have identified the epipterygoid in the Munich specimen of *Archaeopteryx*. This element and the shapes of the quadrate and pterygoids of this and other specimens indicate *Archaeopteryx* has a palate similar to that of other non-avian theropod dinosaurs.



**Fig. 3** Cranial anatomy of the 7th (Munich) specimen of *Archaeopteryx* (BSPG 1999 I 50). Posterior skull elements and braincase on the main slab. **a** Photograph under ultraviolet light. **b** Interpretative drawing. *at* anterior tympanic recess, *boc* basioccipital, *bpt* basipterygoid process, *bptr* basipterygoid recess, *bs* basisphenoid, *bsr* basisphenoid recess, *bt* basal tubera, *cif* crista interfrenalis, *cm* crista metotica, *dtr* dorsal tympanic recess, *ec* ectopterygoid fragment,

*epi* epipterygoid, *f* frontal, *fo* fenestra ovale, *fp* fenestra pseudotunda, *ls* laterosphenoid, *oc* occipital condyle, *pa* parietal, *pap* paroccipital process, *pro* prootic, *pt* pterygoid, *ptr* posterior tympanic recess, *qw* quadrate wing of the pterygoid, *sa* surangular, *sg* stapedial groove. *Roman numerals* denote cranial nerves; *question marks* indicate unidentified elements. *Scale bar* is 5 mm

Rauhut (2014, *Paläontologische Zeitschrift*) and Holliday (pers obs) have identified the epipterygoid in the Munich specimen of *Archaeopteryx*. This element and the shapes of the quadrates and pterygoids of this and other specimens show the palate of *Archaeopteryx* is largely similar to that of Dromaeosaurs and other non-avian theropods.



**Figure S12.** Identification of the epipterygoid in *Archaeopteryx*.

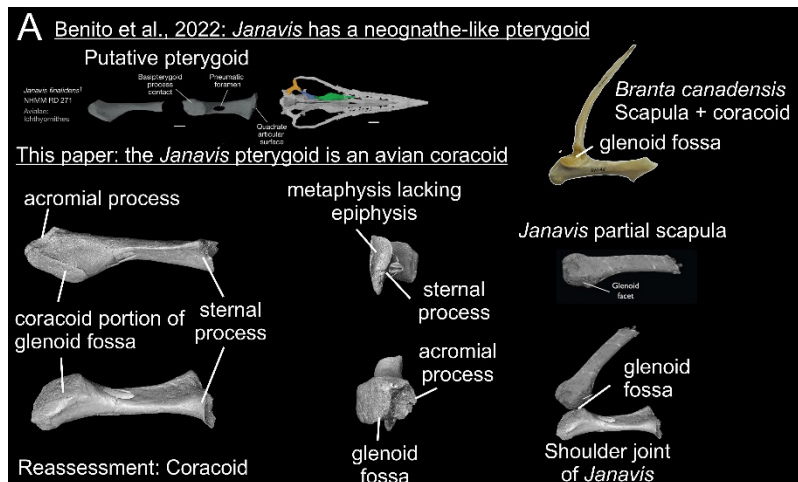


## Notes and Corrections on the palates of Mesozoic birds: *Ichthyornis*/*Janavis*

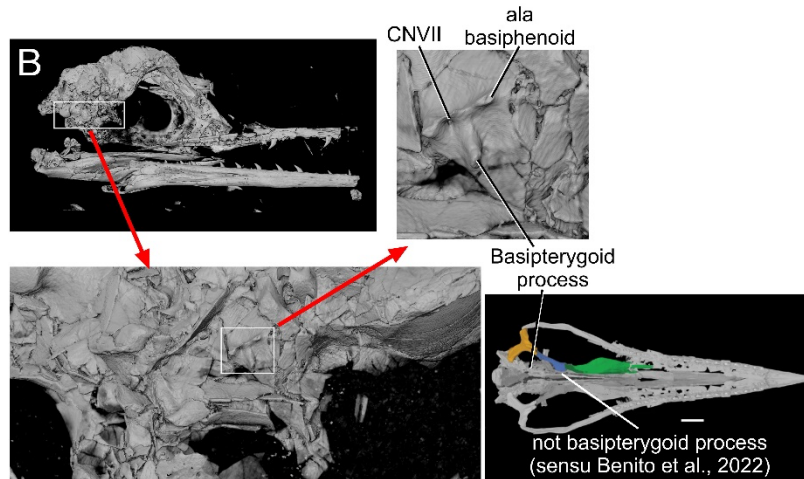
Benito et al., 2022. Cretaceous ornithurine supports a neognathous crown bird ancestor. Nature 612: 100–105. <https://www.nature.com/articles/s41586-022-05445-y>

Benito et al., 2022 (Nature, *Janavis*) describe the late Cretaceous bird *Janavis* as possessing a pterygoid that is markedly tubular in nature for this grade of bird, thus suggesting to them that *Janavis* and *Ichthyornis* have neognathous palates and thus modern avian cranial kinesis. Upon further inspection of the data, we agree with Dyke et al. (2002) that this element is instead a coracoid. Benito et al., 2022 do acknowledge they have reinterpreted this element as a pterygoid contrary to Dyke et al. Here we show that the element is indeed a coracoid of a still juvenile bird. The contact interpreted as the ‘basipterygoid process joint’ is the coracoid portion of the glenoid fossa with then the palatine articulation being the acromial process. The “quadrate articulation” is the sternal articulation with a

fossa indicative of the still growing epiphysis that would form in this end of this endochondral element. The internal anatomy is more akin to a coracoid as it has a markedly thin cortex along with several trabeculae. Neoavian and neognathe pterygoids have thick cortices that track with their propulsive loading environment. Additionally, the interpretation of the ‘basipterygoid process joint’ is far too rostral for a basipterygoid process but instead the inferred location of the novel, neognathe palatobasal joint formed by the hemipterygoid-parasphenoid rostrum articulation. Regardless, *Ichthyornis* does possess a small basipterygoid process just rostralateral to the facial foramen (CNVII) on the lateroventral surface of the basisphenoid, the same positional relationship all non-neognathan theropods possess. This coracoid should fit



A) The ‘pterygoid’ of *Janavis* is a coracoid, and *Janavis* is likely a juvenile bird.



B) *Ichthyornis* AMNH FARB 32773 has a basipterygoid process located in the primitive location on the ventrolateral portion of the braincase, just rostral to the CNVII foramen, not rostrally along the palate as suggested by Benito et al., 2022. Thanks to Christopher Torres for making data available.

242 nicely with the complete forelimb elements and shoulder of the rest of *Janavis*, that seems  
243 to be mysteriously lacking a coracoid. We thank the authors for sharing their data.

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245 **Figure S14.** Reinterpretation of the *Janavis* “pterygoid”.

246 **Supp Info Table 1: List of specimens and scanning details used in this analysis.**

Taxon	Specimen #	Voltage	Amperage	Slice Thickness/ Voxel Size	Scanner	Scanning Location	Citation
<i>Allosaurus jimmadseni</i> (Saurischia: Allosauridae)	MOR 693						Rayfield et al. (2001); Lautenschlager (2015)
<i>Tyrannosaurus rex</i> (Saurischia: Tyrannosauridae)	BHI 3033	120 kV	170 mA	625 µm slice thickness	General Electric LightSpeed Ultra Multislice CT scanner	OhioHealth O'Bleness Hospital, Athens, OH	Cost et al. (2019)
<i>Erlikosaurus andrewsii</i> (Saurischia: Therizinosauroidae)	IGM 100/111	180kV	145 µA	145 µm cubic voxel size	XT-H-225ST CT scanner	Nikon Metrology, Tring, Hertfordshire, U.K	Lautenschlager et al. (2014); Lautenschlager (2015)
<i>Dromaeosaurus albertensis</i> (Saurischia: Dromaeosauridae)	AMNH 5356	120 kV	170 mA	625 µm slice thickness	General Electric LightSpeed Ultra Multislice CT scanner	OhioHealth O'Bleness Hospital, Athens, OH	
<i>Struthio camelus</i> (Struthioniformes: Struthionidae)	OUVC 10491	120 kV	200 mA	625 µm slice thickness	General Electric LightSpeed Ultra Multislice CT scanner	OhioHealth O'Bleness Hospital, Athens, OH	
<i>Eudromia elegans</i> (Tinamiformes: Tinamidae)	OUVC 10602	70 kV	400 mA	90 µm cubic voxel size	General Electric GE eXplore Locus in vivo Small Animal µCT scanner	Ohio University, Athens, OH	
<i>Gallus gallus</i> (Galliformes: Phasianidae)	MUVC AV003			92.2 µm cubic voxel size	Siemens Inveon Spect/CT	VA Biomolecular Imaging Center, Columbia, MO	Wilken et al. (2020)
<i>Chauna chavaria</i> (Anseriformes: Anhimidae)	KU 81969			92.2 µm cubic voxel size	Siemens Inveon Spect/CT	VA Biomolecular Imaging Center, Columbia, MO	
<i>Anas platyrhynchos</i> (Anseriformes: Anatidae)	OUVC 10252	70 kV	400 mA	92 µm cubic voxel size	General Electric GE eXplore Locus in vivo Small	Ohio University, Athens, OH	

					Animal $\mu$ CT scanner		
<i>Corvus moneduloides</i> (Passeriformes: Corvidae)	USNM 561627	120 kV	32 mA	49.3 $\mu$ m cubic voxel size	TriFoil Imaging eXplore CT 120 Small Animal $\mu$ CT scanner	Ohio University, Athens, OH	
<i>Psittacus erithacus</i> (Psittaciformes: Psittacidae)	MUVC AV042			63.4 $\mu$ m cubic voxel size	Siemens Inveon Spect/CT	VA Biomolecular Imaging Center, Columbia, MO	Cost et al. (2019)
<i>Paraesperornis alexi</i>	KUVP 22087	80 kV		21.831 $\mu$ m cubic voxel size			
<i>Hesperornis sp.</i>	KUVP 71012	80 kV		33.39 $\mu$ m cubic voxel size			

Abbreviation	Muscles		Cartilages
mAMES	<i>m. Adductor Mandibulae Externus Superficialis</i>	OP	Otic process of quadrate cartilage
mAMEM	<i>m. Adductor Mandibulae Externus Medialis</i>	PtP	Pterygoid process of palatoquadrate cartilage
mAMEP	<i>m. Adductor Mandibulae Externus Profundus</i>	AP	Ascending process of palatoquadrate cartilage
mAMP	<i>m. Adductor Mandibulae Posterior</i>	Orbp	Orbital process of the quadrate cartilage and bone
mPSTs	<i>m. Pseudotemporalis Superficialis</i>		<b>Bones and joints</b>
mPSTp	<i>m. Pseudotemporalis Profundus</i>	Bs	Basisphenoid
mPtd	<i>m. Pterygoideus Dorsalis</i>	ECJ	Epipterygoid-cranial joint (epipterygoid-laterosphenoid joint)
mPtv	<i>m. Pterygoideus Ventralis</i>	Ect	Ectopterygoid
mDM	<i>m. Depressor Mandibulae</i>	Ept	Epipterygoid
mLPt	<i>m. Levator Pterygoideus</i>	JJ	Jaw joint (Quadrate-articular joint)
mPPt	<i>m. Protractor Pterygoideus</i>	Ls	Laterosphenoid
	<b>Nerves</b>	Mn	mandible
V1	Ophthalmic nerve	OJ	Otic joint (Quadrate-squamosal joint)
V2	Maxillary nerve	Qu	Quadrate
V3	Mandibular nerve	PBJ	Palatobasal Joint (pterygoid-basisphenoid joint)
Vg	Trigeminal ganglion	PPJ	Pterygoparabasisphenoid joint

251 **Supp Info Table 3. 3D models of skulls and muscle vectors hosted on Sketchfab.com**

Sketchfab Models	Skull and muscle vectors
<i>Allosaurus</i>	<a href="https://sketchfab.com/3d-models/allosaurus-updated-mppt-68881ade468b43afb1e883f8fccd2d26">https://sketchfab.com/3d-models/allosaurus-updated-mppt-68881ade468b43afb1e883f8fccd2d26</a>
<i>Tyrannosaurus</i>	<a href="https://sketchfab.com/3d-models/trex-final-5239d473e1a74467b3d18e5b38f47cc9">https://sketchfab.com/3d-models/trex-final-5239d473e1a74467b3d18e5b38f47cc9</a>
<i>Erlikosaurus</i>	<a href="https://sketchfab.com/3d-models/erlikosaurus-final-0cbfc95a867842c58e7159746d3c6daa">https://sketchfab.com/3d-models/erlikosaurus-final-0cbfc95a867842c58e7159746d3c6daa</a>
<i>Citipati</i>	<a href="https://sketchfab.com/3d-models/citipati-casey-muscles-c96d634024cc4be089ac72d366920a09">https://sketchfab.com/3d-models/citipati-casey-muscles-c96d634024cc4be089ac72d366920a09</a>
<i>Dromaeosaurus</i>	<a href="https://sketchfab.com/3d-models/dromie-updated-mppt-6a4cc60585ce4ebfabf1677becf0669c">https://sketchfab.com/3d-models/dromie-updated-mppt-6a4cc60585ce4ebfabf1677becf0669c</a>
<i>Eudromia</i>	<a href="https://sketchfab.com/3d-models/eudromia-final-d7d25bd9b1f54694994a4e46436cd389">https://sketchfab.com/3d-models/eudromia-final-d7d25bd9b1f54694994a4e46436cd389</a>
<i>Struthio</i>	<a href="https://sketchfab.com/3d-models/struthio-final-4894ed849c104b3db12c2c4db782c770">https://sketchfab.com/3d-models/struthio-final-4894ed849c104b3db12c2c4db782c770</a>
<i>Gallus</i>	<a href="https://sketchfab.com/3d-models/psittacus-final-60d259da372e408683a662eac92e99fc">https://sketchfab.com/3d-models/psittacus-final-60d259da372e408683a662eac92e99fc</a>
<i>Chauna</i>	<a href="https://sketchfab.com/3d-models/chuana-final-4d484e50f29549d7b43e00fdda790268">https://sketchfab.com/3d-models/chuana-final-4d484e50f29549d7b43e00fdda790268</a>
<i>Anas</i>	<a href="https://sketchfab.com/3d-models/anas-casey-muscles-a80c178a4066435291db04ad23b93358">https://sketchfab.com/3d-models/anas-casey-muscles-a80c178a4066435291db04ad23b93358</a>
<i>Corvus</i>	<a href="https://sketchfab.com/3d-models/corvus-final-57ff95ec57cc457f89bd76f0cb83a6e8">https://sketchfab.com/3d-models/corvus-final-57ff95ec57cc457f89bd76f0cb83a6e8</a>
<i>Psittacus</i>	<a href="https://sketchfab.com/3d-models/psittacus-final-60d259da372e408683a662eac92e99fc">https://sketchfab.com/3d-models/psittacus-final-60d259da372e408683a662eac92e99fc</a>

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254 **Supp Info Table 4. 3D models of distribution of muscle vectors across phylogeny.**

	Muscle vectors	Muscle vectors and <i>Dromaeosaurus</i> skull
mAMES	<a href="https://sketchfab.com/3d-models/vector-bouquets-mames-noskull-59ba2dc9ff914732ab484535bb966437">https://sketchfab.com/3d-models/vector-bouquets-mames-noskull-59ba2dc9ff914732ab484535bb966437</a>	<a href="https://sketchfab.com/3d-models/vector-bouquets-mames-bac04ab2239f456fae203a2cc544dc55">https://sketchfab.com/3d-models/vector-bouquets-mames-bac04ab2239f456fae203a2cc544dc55</a>
mAMEM	<a href="https://sketchfab.com/3d-models/vector-bouquets-mamem-noskull-95c57d77b89542e89be7e6d03c842429">https://sketchfab.com/3d-models/vector-bouquets-mamem-noskull-95c57d77b89542e89be7e6d03c842429</a>	<a href="https://sketchfab.com/3d-models/vector-bouquets-mamem-9862123d20d44afc857a22a488459a24">https://sketchfab.com/3d-models/vector-bouquets-mamem-9862123d20d44afc857a22a488459a24</a>
mAMEP	<a href="https://sketchfab.com/3d-models/mamep1-bouquet-eb90715012c3401f80bcb65eadc66473">https://sketchfab.com/3d-models/mamep1-bouquet-eb90715012c3401f80bcb65eadc66473</a>	<a href="https://sketchfab.com/3d-models/mamep1-bouquet-noskull-4c1d60870acb4cc09ecca502a648c4f2">https://sketchfab.com/3d-models/mamep1-bouquet-noskull-4c1d60870acb4cc09ecca502a648c4f2</a>
mAMP	<a href="https://sketchfab.com/3d-models/vector-bouquets-mamp-noskull-2fd14999ef9448d9a4a63e28e372daa0">https://sketchfab.com/3d-models/vector-bouquets-mamp-noskull-2fd14999ef9448d9a4a63e28e372daa0</a>	<a href="https://sketchfab.com/3d-models/vector-bouquets-mamp-a3f609366f3948a7abd6fff7d756c74d">https://sketchfab.com/3d-models/vector-bouquets-mamp-a3f609366f3948a7abd6fff7d756c74d</a>
mPSTS	<a href="https://sketchfab.com/3d-models/vector-bouquets-mpsts-noskull-df6333b8281648c9a320da03a9ad73a8">https://sketchfab.com/3d-models/vector-bouquets-mpsts-noskull-df6333b8281648c9a320da03a9ad73a8</a>	<a href="https://sketchfab.com/3d-models/vector-bouquets-mpsts-b76998c8c3bd483d81e7d04ccaff00e8">https://sketchfab.com/3d-models/vector-bouquets-mpsts-b76998c8c3bd483d81e7d04ccaff00e8</a>
mPSTP	<a href="https://sketchfab.com/3d-models/vector-bouquets-mpstp-noskull-ce8d9b3d7b13471494fd7f78b8a5418f">https://sketchfab.com/3d-models/vector-bouquets-mpstp-noskull-ce8d9b3d7b13471494fd7f78b8a5418f</a>	<a href="https://sketchfab.com/3d-models/vector-bouquets-mpstp-b6c6459d2e554848ba83c22b7e2c3ead">https://sketchfab.com/3d-models/vector-bouquets-mpstp-b6c6459d2e554848ba83c22b7e2c3ead</a>
mPTD	<a href="https://sketchfab.com/3d-models/vector-bouquets-mptd-noskull-62cb735a460247f88f8b8574cc344b3e">https://sketchfab.com/3d-models/vector-bouquets-mptd-noskull-62cb735a460247f88f8b8574cc344b3e</a>	<a href="https://sketchfab.com/3d-models/vector-bouquets-mptd-80d17d1898cc47549bdf4d4dbb1f83c99">https://sketchfab.com/3d-models/vector-bouquets-mptd-80d17d1898cc47549bdf4d4dbb1f83c99</a>
mPTV	<a href="https://sketchfab.com/3d-models/vector-bouquets-mptv-noskull-cfd652ad5d034431be3f2deae9bd1d29">https://sketchfab.com/3d-models/vector-bouquets-mptv-noskull-cfd652ad5d034431be3f2deae9bd1d29</a>	<a href="https://sketchfab.com/3d-models/vector-bouquets-mptv-4f8e25cbf53d421c965ed73a2d7f8ce3">https://sketchfab.com/3d-models/vector-bouquets-mptv-4f8e25cbf53d421c965ed73a2d7f8ce3</a>
mPPT	<a href="https://sketchfab.com/3d-models/vector-bouquets-mppt-noskull-2aa937307b9b40709cfcafa9b3eccc7">https://sketchfab.com/3d-models/vector-bouquets-mppt-noskull-2aa937307b9b40709cfcafa9b3eccc7</a>	<a href="https://sketchfab.com/3d-models/vector-bouquets-mppt-e44afcc5cc914f9e82b652584ae9f4b3">https://sketchfab.com/3d-models/vector-bouquets-mppt-e44afcc5cc914f9e82b652584ae9f4b3</a>
mDM	<a href="https://sketchfab.com/3d-models/vector-bouquets-mdm-noskull-5624b6409c994f59b96e383d6b547769">https://sketchfab.com/3d-models/vector-bouquets-mdm-noskull-5624b6409c994f59b96e383d6b547769</a>	<a href="https://sketchfab.com/3d-models/vector-bouquets-mdm-8b1d3520a8644b459335111fe3e1f91b">https://sketchfab.com/3d-models/vector-bouquets-mdm-8b1d3520a8644b459335111fe3e1f91b</a>

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- 257     **Supp Info Sheet 1 (Excel): Morphometrics, forces and linkages data used in analysis.**
- 258     **Supp Info Sheet 2 (Excel): 3D muscle reconstruction data and vectors in analysis.**