**Supplementary information**

**Cranial ontogenetic variation in early saurischians and the role of heterochrony in the diversification of predatory dinosaurs**

Christian Foth1,2,3, Brandon P. Hedrick4, Martín D. Ezcurra2,5,6

1 SNBS, Bayerische Staatssammlung für Paläontologie und Geologie, Richard Wagner-Str. 10, D-80333 München

2 Department of Earth and Environmental Sciences, Ludwig-Maximilians-Universität, Richard-Wagner-Str. 10, D-80333 München, Germany

3 Department of Geosciences, University of Fribourg/Freiburg, Chemin du Musée 6, 1700 Fribourg, Switzerland

4 Department of Earth and Environmental Science, University of Pennsylvania, 251 Hayden Hall, 240 S 33rd Street, Philadelphia, PA 19104, USA

5 School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

6 Sección Paleontología de Vertebrados, Museo Argentino de Ciencias Naturales “Bernardino Rivadavia”, Buenos Aires C1405DJR, Argentina

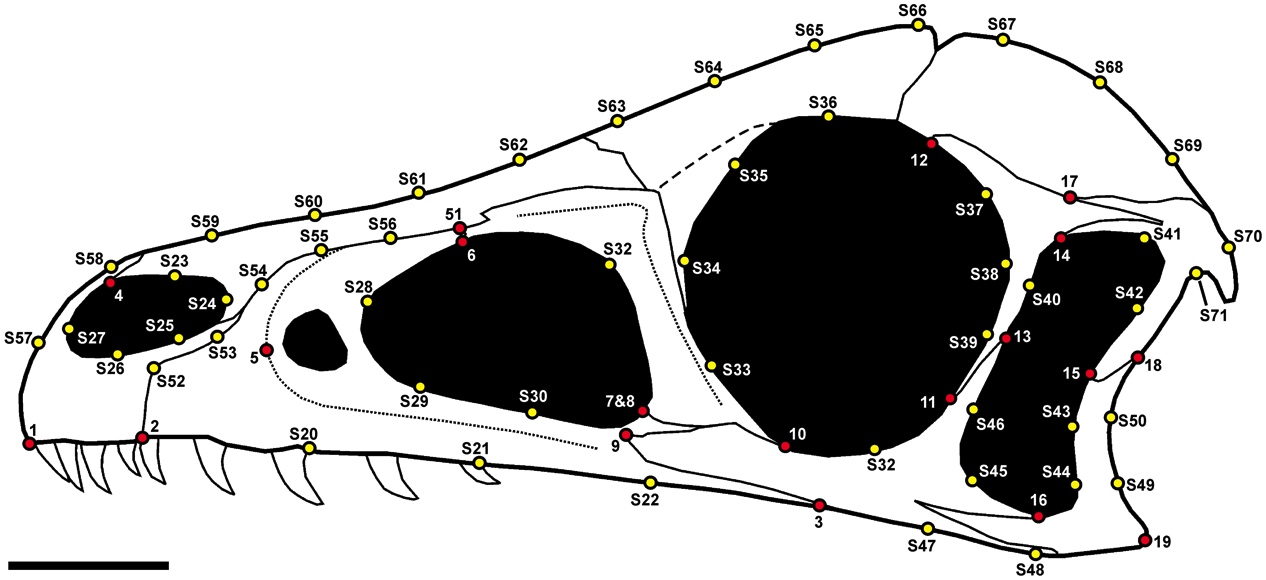
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**1. Landmark description**

**Table S1 List of landmarks and semi-landmark description. Semi-landmarks (semi-LMs) are marked with a ‘S’.**

|  |  |
| --- | --- |
| **LMs** | **Description** |
| **1** | Most anterior point of the premaxilla along the tooth row (This point is reconstructed for *Alioramus* and *Zupaysaurus*). |
| **2** | Contact between premaxilla and maxilla along the tooth row. |
| **3** | Contact between the maxilla and jugal along the ventral margin of the skull |
| **4** | Contact between the nasal process of the premaxilla and the anterodorsal process of the nasal along the dorsal margin of the external naris |
| **5** | Most anterior point of the antorbital fossa (in those taxa without an antorbital fossa, the most anterior point of the antorbital fenestra was marked). |
| **6** | Most anterior point of the anterior process of the lacrimal along the dorsal margin of the antorbital fenestra. |
| **7** | Most ventral point of the ventral process of the lacrimal along the posteroventral margin of the antorbital fenestra. |
| **8** | Most posterior point of the jugal process of the maxilla along the ventral margin of the antorbital fenestra. |
| **9** | Most anterior point of the jugal (Depending on the configuration of maxilla, lacrimal and jugal, the landmarks 7, 8 and 9 can be similarly located). |
| **10** | Contact between the ventral process of the lacrimal and the jugal along the anteroventral margin of the orbit. |
| **11** | Contact between the jugal and the postorbital along the posterior margin of the orbit. |
| **12** | Most dorsal point of the anterior process of the postorbital along the posterodorsal margin of the orbit. |
| **13** | Contact between the jugal and the postorbital along the anterior margin of the lateral temporal fenestra. |
| **14** | Ventral contact between postorbital and squamosal along the dorsal margin of the lateral temporal fenestra. |
| **15** | Contact between the descending process of the squamosal with the quadratojugal along the posterior margin of the lateral temporal fenestra (For those taxa, where these bones do not contact to each other, e.g. the juvenile *Coelophysis*, the most anteroventral point of the descending process of the squamosal was marked. |
| **16** | Contact between jugal and quadratojugal along the ventral margin of the lateral temporal fenestra. |
| **17** | Dorsal contact between postorbital and squamosal. |
| **18** | Contact between the descending process of the squamosal with the quadratojugal along the posterior margin of the skull (For those taxa, where these bones do not contact to each other, e.g. the juvenile *Coelophysis*, the most posteroventral point of the descending process of the squamosal was marked. |
| **19** | Posteroventral corner of the quadratojugal. |
| **S20-S22** | Three semi-LMs on the ventral margin of the maxilla from LM 2 to LM 3. |
| **S23-S27** | Five semi-LMs along the narial margin starting and ending in LM 4. |
| **S28-S30** | Three semi-LMs along the anterior margin of the antorbital fenestra from LM 6 to LM 8. |
| **S31** | One semi-LM along the posterior margin of the antorbital fenestra from LM 6 to LM 7. |
| **S32** | One semi-LM along the ventral margin of the orbit from LM 10 to LM 11. |
| **S33-S36** | Four semi-LMs along the anterodorsal margin of the orbit from LM 10 to LM 12. |
| **S37-S39** | Three semi-LMs along the posterodorsal margin of the orbit from LM 12 to LM 11. |
| **S40** | One semi-LM along the anterodorsal margin of the lateral temporal fenestra from LM 13 to LM 14. |
| **S41-S42** | Two semi-LMs along the posterodorsal margin of the lateral temporal fenestra from LM 14 to LM 15. |
| **S43-S44** | Two semi-LMs along the posteroventral margin of the lateral temporal fenestra from LM 15 to LM 16. |
| **S45-S46** | Two semi-LMs along the anteroventral margin of the lateral temporal fenestra from LM 16 to LM 13. |
| **S47-S48** | Two semi-LMs along the ventral margin of the skull from LM 3 to LM 19. |
| **S49-S50** | Two semi-LMs along the posterior margin of the quadratojugal from LM 19 to LM 18. |
| **51** | Most posterior point of the descending process of the maxilla contacting the nasal and/or the lacrimal. |
| **S52-S56** | Five semi-LMs along the anterodorsal margin of the maxilla from LM 2 to LM 51. |
| **S57-S71** | Fifteen semi-LMs along the dorsal margin of the skull from LM 1 to LM 18. |

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**Figure S1** **Illustration of the landmarks and semi-landmarks positions on the skull of *Sciurumimus albersdoerferi*.** Landmarks are shown as red dots, while semi-landmarks are marked with a ‘S’ and are shown as yellow dots.

**2. Landmark error after Singleton (2002)**

The percent error for digitizing landmarks and semi-landmarks by hand was estimated for the skull reconstruction of the juvenile *Coelophysis* (with n = 10 repetitions) using the method described by Singleton (2002). On the basis of the Procrustes coordinates the mean Procrustes distances to the respective consensus coordinates of each landmark were calculated. Then the relation of these distances to the mean distance of the consensus landmarks to the centroid of the consensus shape was calculated as a percentage of the former from the latter.Landmark and semi-landmark error varies between 0.117 percent (LM 51) and 0.738 percent (LM 3) with a mean of 0.283 percent, having no significant effect on shape analyses.

**Table S2 Percent error for each landmark for the skull of the juvenile specimens of *Coelophysis* with n = 10.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **(semi-)LMs** | **%Error** | **(semi-)LMs** | **%Error** | **(semi-)LMs** | **%Error** |
| **1** | 0.28511 | **S25** | 0.41778 | **S49** | 0.38979 |
| **2** | 0.25529 | **S26** | 0.34182 | **S50** | 0.73158 |
| **3** | 0.73792 | **S27** | 0.43597 | **51** | 0.11650 |
| **4** | 0.30159 | **S28** | 0.21879 | **S52** | 0.23100 |
| **5** | 0.17860 | **S29** | 0.28964 | **S53** | 0.20120 |
| **6** | 0.26985 | **S30** | 0.24673 | **S54** | 0.17211 |
| **7** | 0.24677 | **S31** | 0.29661 | **S55** | 0.19311 |
| **8** | 0.26012 | **S32** | 0.40849 | **S56** | 0.20648 |
| **9** | 0.16171 | **S33** | 0.26439 | **S57** | 0.20882 |
| **10** | 0.29555 | **S34** | 0.21973 | **S58** | 0.22091 |
| **11** | 0.35026 | **S35** | 0.15236 | **S59** | 0.23261 |
| **12** | 0.26430 | **S36** | 0.16457 | **S60** | 0.16824 |
| **13** | 0.28801 | **S37** | 0.25899 | **S61** | 0.18348 |
| **14** | 0.42348 | **S38** | 0.22989 | **S62** | 0.22272 |
| **15** | 0.19567 | **S39** | 0.26141 | **S63** | 0.21164 |
| **16** | 0.30716 | **S40** | 0.25160 | **S64** | 0.15887 |
| **17** | 0.27963 | **S41** | 0.26707 | **S65** | 0.23221 |
| **18** | 0.24562 | **S42** | 0.25013 | **S66** | 0.20976 |
| **19** | 0.20556 | **S43** | 0.65251 | **S67** | 0.19035 |
| **S20** | 0.27621 | **S44** | 0.24868 | **S68** | 0.20543 |
| **S21** | 0.36408 | **S45** | 0.20666 | **S69** | 0.27989 |
| **S22** | 0.50359 | **S46** | 0.26769 | **S70** | 0.22417 |
| **S23** | 0.32357 | **S47** | 0.52043 | **S71** | 0.27301 |
| **S24** | 0.35938 | **S48** | 0.38044 | **MEAN** | **0.28303** |

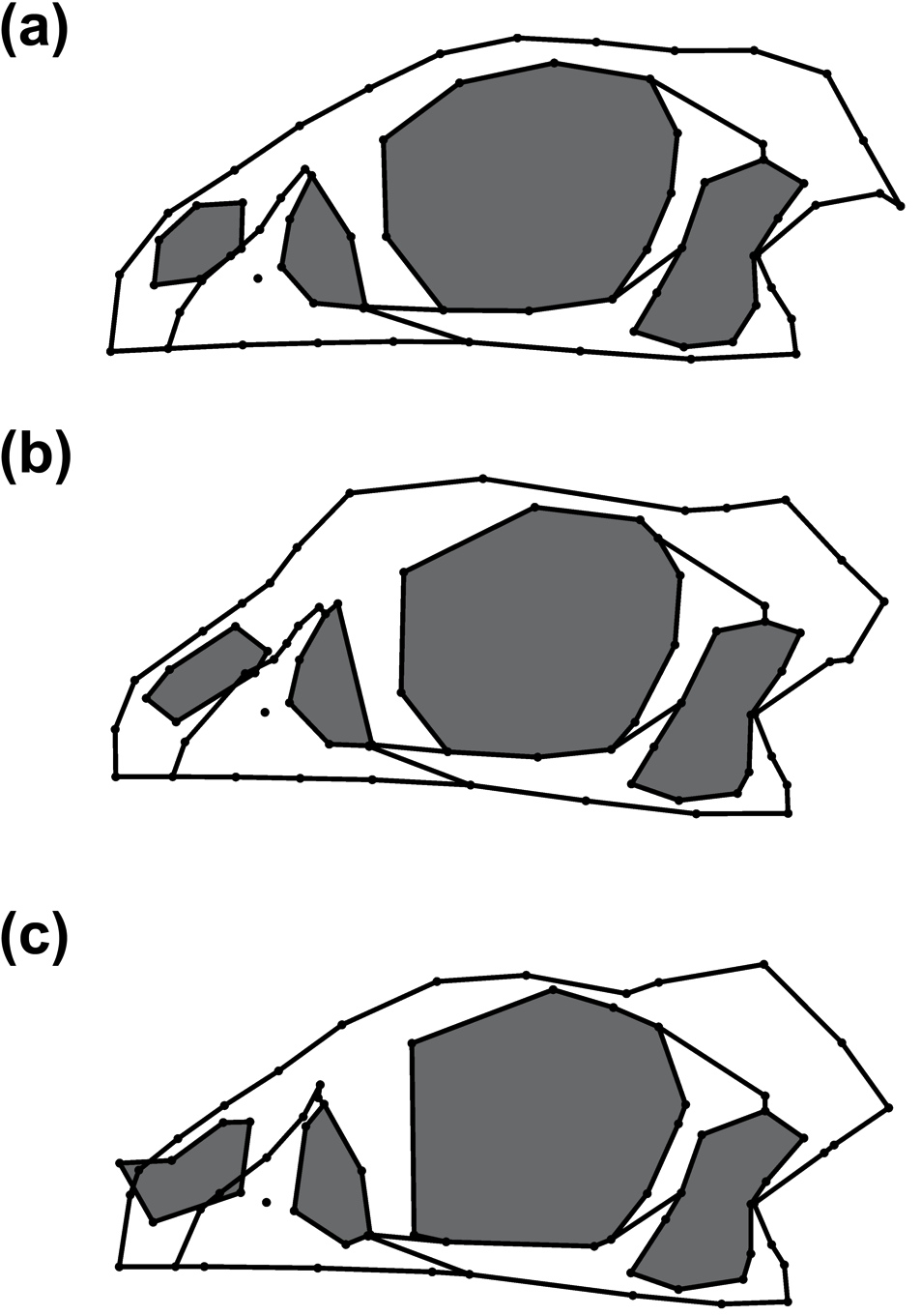
**3. Taxon sampling**

**Table S3 List of taxa used in the present analyses with data of occurrences (in million of years, Myr) and sources of images.** Bold taxa mark ontogenetic series used for the study.

|  |  |  |  |
| --- | --- | --- | --- |
| **Taxa** |  | **Age (Myr)** | **Source** |
| *Eoraptor* | Sauropodomorpha | 228.95 | Sereno, Martínez & Alcober, 2013 |
| *Pampadromaeus* | Sauropodomorpha | 228.95 | Cabreira *et al.*, 2011 |
| *Unaysaurus* | Sauropodomorpha | 222.45 | Leal *et al.*, 2004 |
| *Melanorosaurus* | Sauropodomorpha | 214.15 | Yates, 2007 |
| *Plateosaurus* | Sauropodomorpha | 209.65 | Yates, 2003 |
| *Jingshanosaurus* | Sauropodomorpha | 200.30 | Yates, 2012 |
| ***Massospondylus*** | **Sauropodomorpha** | **196.05** | **Gow, Kitching & Raath,1990; Reisz *et al.*, 2010** |
| *Adeopapposaurus* | Sauropodomorpha | 187.70 | Martínez, 2009 |
| *Shunosaurus* | Sauropodomorpha | 166.90 | Rauhut *et al.*, 2011 |
| *Mamenchisaurus* | Sauropodomorpha | 160.40 | Ouyang & Ye, 2002 |
| *Herrerasaurus* | basal Theropoda | 228.95 | Nesbitt, 2011 |
| *Tawa* | basal Theropoda | 209.50 | Nesbitt, 2011 |
| *Zupaysaurus* | basal Theropoda | 216.00 | modified after Ezcurra, 2007 |
| ***Coelophysis*** | **basal Theropoda** | 209.50 | **Nesbitt, 2011; own reconstruction** |
| *Syntarsus* | basal Theropoda | 191.00 | Tykoski, 2005 |
| *Limusaurus* | Ceratosauria | 160.40 | Xu *et al*., 2009 |
| *Carnotaurus* | Ceratosauria | 77.85 | Rauhut, 2003 |
| *Majungasaurus* | Ceratosauria | 69.05 | Sampson & Witmer, 2007 |
| **Megalosaurid taxon** | **basal Tetanurae** | **166.2** | **Allain 2002; own reconstruction** |
| *Monolophosaurus* | basal Tetanurae | 164.80 | Rauhut, 2003 |
| *Sinraptor* | basal Tetanurae | 160.40 | Currie & Zhao, 1993 |
| ***Allosaurus*** | **basal Tetanurae** | **151.15** | **Loewen, 2009** |
| *Acrocanthosaurus* | basal Tetanurae | 118.52 | Eddy & Clarke, 2011 |
| Spinosaurid taxon | basal Tetanurae | 127.73 | Rauhut, 2003 |
| *Haplocheirus* | Coelurosauria | 160.40 | own reconstruction |
| *Compsognathus* | Coelurosauria | 148.55 | Peyer, 2006 |
| *Dilong* | Coelurosauria | 126.23 | own reconstruction |
| *Erlikosaurus* | Coelurosauria | 92.05 | Rauhut, 2003 |
| *Garudimimus* | Coelurosauria | 92.05 | Makovicky, Kobayashi & Currie, 2004 |
| *Teratophoneus* | Coelurosauria | 77.05 | Loewen *et al*., 2013 |
| *Gorgosaurus* | Coelurosauria | 77.05 | Carr, 1999 |
| *Daspletosaurus* | Coelurosauria | 77.05 | Rauhut, 2003 |
| ***Tarbosaurus*** | **Coelurosauria** | **74.8** | **Hurum & Sabbath, 2003; modified after Tsuihiji *et al*., 2011** |
| *Tyrannosaurus* | Coelurosauria | 74.75 | Carr & Williamson, 2004 |
| *Alioramus* | Coelurosauria | 69.05 | Brusatte et al., 2009 |

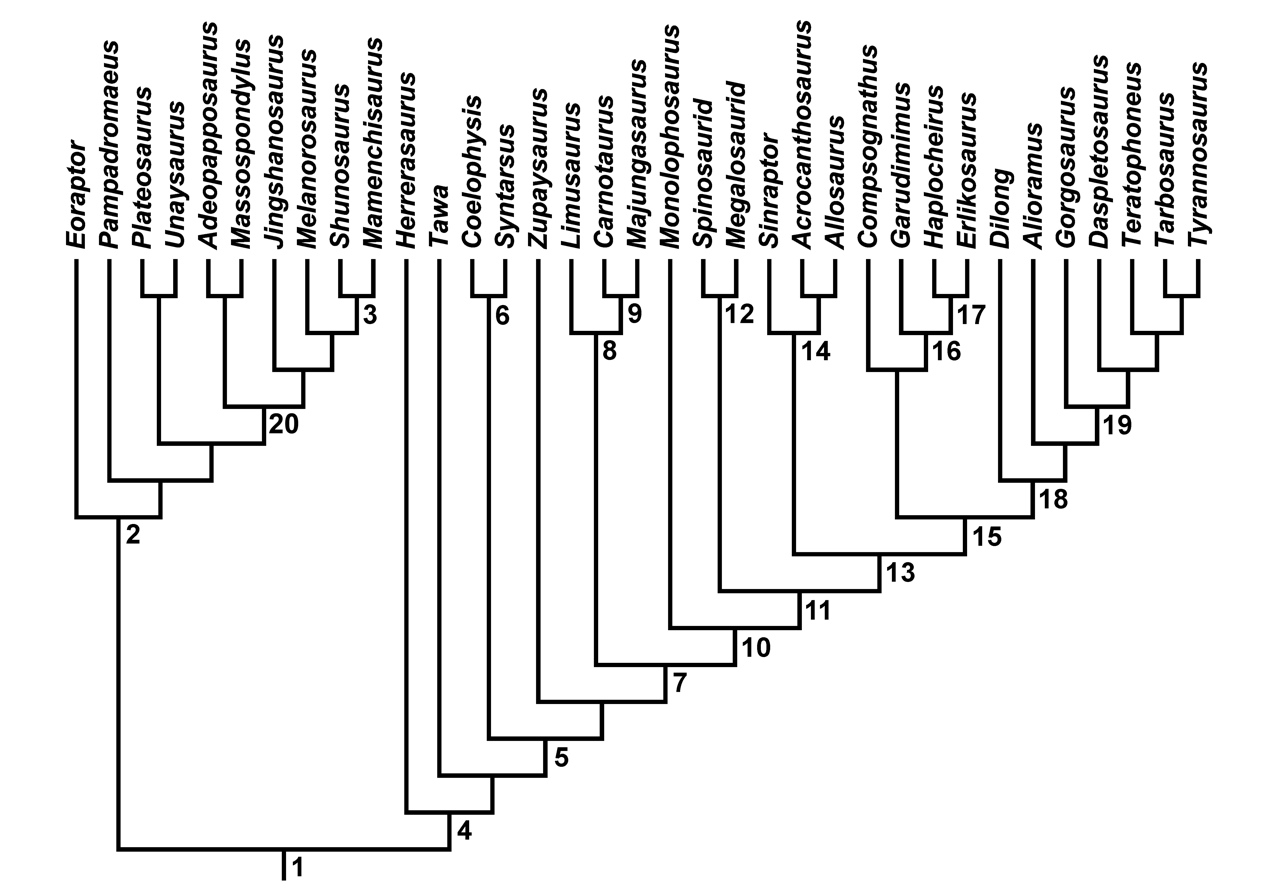
**4. Comments on sliding semi-landmarks**

To test the influence of sliding semi-landmarks during general Procrustes analysis (GPA) semi-landmarks were slid in tpsRelW (Rohlf, 2003) to minimize the bending energy and the Procrustes distance, both with a maximal iteration of ten. Afterwards, the resulting Procrustes shapes were compared with that of the regular GPA. The example at hand shows the results for the alignment for the skull of the juvenile *Massospondylus*. The minimization of the bending energy results on artificial elongation of the external naris and the formation of a frontal “crest”-like structure in front of the orbit, while the minimization of the Procrustes distance leads to deformation of the narial shape, the shape of the orbit and the shape of the skull roof in the postorbital region. As these artificial shape alignments affected several taxa within the data set (e.g. *Carnotaurus*, *Compsognathus*, *Mamenchisaurus*, *Shunosaurus*, *Syntarsus*), we decided to treat the semi-landmarks as landmarks. However, to appraise the influence of the semi-landmarks in the original data set, we repeated the shape analyses with a second data set containing only landmark information and compared it with the original results.

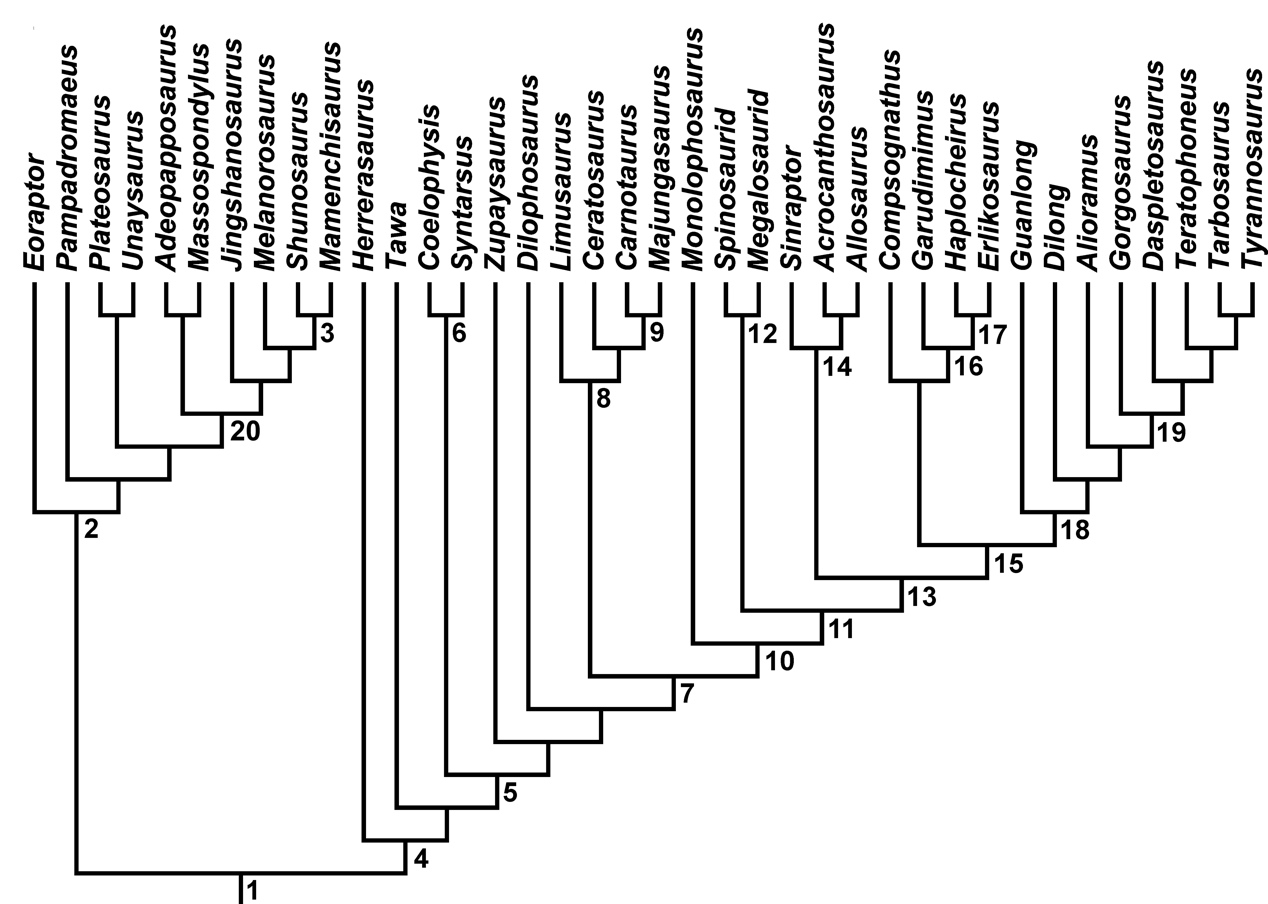
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**Figure S2 Procrustes shape of the juvenile *Massospondylus* specimen.** (a) Common General Procrustes Analysis (GPA). (b) GPA with slid semi-landmarks minimizing bending energy. (c) GPA with slid semi-landmarks minimizing Procrustes distance. Skull openings are shaded in grey.

**5. Phylogeny**

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**Figure S3 Phylogeny of Saurischia without taxa bearing an enlarged nasal crest. 1** Saurischia, **2** Sauropodomorpha, **3** Sauropoda, **4** Theropoda, **5** Neotheropoda, **6** Coelophysidae, **7** Averostra, **8** Ceratosauria, **9** Abelisauridae, **10** Tetanurae, **11** Orionides, **12** Megalosauria, **13** Avetheropoda, **14** Allosauroidea, **15** Coelurosauria, **16** Maniraptoriformes, **17** Maniraptora, **18** Tyrannosauroidea, **19** Tyrannosauridae, **20** Massopoda.

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**Figure S4 Phylogeny of Saurischia with the crested taxa *Dilophosaurus*, *Ceratosaurus* and *Guanlong* included.**  **1** Saurischia, **2** Sauropodomorpha, **3** Sauropoda, **4** Theropoda, **5** Neotheropoda, **6** Coelophysidae, **7** Averostra, **8** Ceratosauria, **9** Abelisauridae, **10** Tetanurae, **11** Orionides, **12** Megalosauria, **13** Avetheropoda, **14** Allosauroidea, **15** Coelurosauria, **16** Maniraptoriformes, **17** Maniraptora, **18** Tyrannosauroidea, **19** Tyrannosauridae, **20** Massopoda.

**6. Additional data**

**Table S4** **Angles of ontogenetic trajectories in PCA against PC 1 in the original data set with crested taxa excluded.**

|  |  |  |
| --- | --- | --- |
|  | **PC 1-2** | **PC 1-3** |
| ***Massospondylus*** | 85.6492 | 63.2316 |
| ***Coelophysis*** | 42.3458 | 10.1684 |
| **Megalosaurid taxon** | 83.3216 | 65.0464 |
| ***Allosaurus*** | 5.3228 | 18.5268 |
| ***Tarbosaurus*** | 3.7406 | 60.5157 |

**Table S5** **Pairwise angles between ontogenetic trajectories in the PCA of the original data set with crested taxa excluded.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **PC 1-2** | ***Massospondylus*** | ***Coelophysis*** | ***Megalosaurid taxon*** | ***Allosaurus*** | ***Tarbosaurus*** |
| ***Massospondylus*** | 0.0000 |  |  |  |  |
| ***Coelophysis*** | 43.3033 | 0.0000 |  |  |  |
| ***Megalosaurid taxon*** | 2.3276 | 40.9757 | 0.0000 |  |  |
| ***Allosaurus*** | 89.0280 | 132.3313 | 91.3556 | 0.0000 |  |
| ***Tarbosaurus*** | 98.0914 | 141.3947 | 100.4190 | 9.0634 | 0.0000 |
|  |  |  |  |  |  |
| **PC 1-3** | ***Massospondylus*** | ***Coelophysis*** | ***Megalosaurid taxon*** | ***Allosaurus*** | ***Tarbosaurus*** |
| ***Massospondylus*** | 0.0000 |  |  |  |  |
| ***Coelophysis*** | 73.4000 | 0.0000 |  |  |  |
| ***Megalosaurid taxon*** | 128.2780 | 54.8780 | 0.0000 |  |  |
| ***Allosaurus*** | 98.2417 | 171.6416 | 133.4803 | 0.0000 |  |
| ***Tarbosaurus*** | 177.2841 | 109.3159 | 54.4379 | 79.0425 | 0.0000 |

**Table S6** **Correlation between shape and centroid size (log-transformed) for the overall skull and different skull regions.** AOF, antorbital fenestra; ITF, infratemporal fenestra; JU, jugal; QU, quadratojugal.

|  |  |  |
| --- | --- | --- |
| **Skull region** | **Correlation** | ***p* value** |
| Overall skull | 48.19 % | <0.0001 |
| Skull outline | 36.12 % | 0.0004 |
| External naris | 15.79 % | 0.1004 |
| Maxilla | 40.65 % | 0.0001 |
| AOF | 44.34 % | <0.0001 |
| Orbit | 39.01 % | 0.0005 |
| ITF | 49.84 % | <0.0001 |
| JU-QJ regions | 42.89 % | 0.0002 |
| Postorbital | 35.43 % | <0.0001 |
| Skull roof | 58.64 % | <0.0001 |

**Table S7 Angles of ontogenetic trajectories on plot of shape versus skull centroid size (log-transformed) for the overall skull and specific skull regions.** AOF, antorbital fenestra; ITF, infratemporal fenestra; JU, jugal; QU, quadratojugal.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Overall skull** | **Skull outline** | **Naris** | **Maxilla** | **AOF** |
| **Saurischia** | 4.3762 | 4.6195 | 3.0948 | 3.0323 | 0.6762 |
| ***Massospondylus*** | 3.8814 | 3.7533 | 1.7088 | 1.3152 | 2.1765 |
| **Neotheropoda** | 5.1181 | 4.0061 | 1.0950 | 5.6001 | 6.4229 |
| ***Coelophysis*** | 6.0560 | 4.5819 | 25.2885 | 8.4747 | 8.3024 |
| **Orionides** | 4.1743 | 2.0605 | 4.6142 | 7.3535 | 8.3288 |
| **Megalosaurid taxon** | 5.0290 | 2.8630 | 3.5974 | 9.0915 | 9.8989 |
| **Avetheropoda** | 3.0083 | 1.0832 | 3.5056 | 6.0017 | 8.7106 |
| ***Allosaurus*** | 1.1845 | 1.6643 | 1.6495 | 3.0316 | 2.6568 |
| ***Tarbosaurus*** | 0.7153 | 0.5440 | 24.4236 | 1.3797 | 2.2283 |
|  |  |  |  |  |  |
|  | **Orbit** | **ITF** | **JU-QJ region** | **Postorbital** | **Skull roof** |
| **Saurischia** | 1.9662 | 7.0084 | 9.5510 | 5.0285 | 4.3223 |
| ***Massospondylus*** | 0.9788 | 6.0146 | 2.3018 | 2.1083 | 4.2488 |
| **Neotheropoda** | 3.2249 | 10.0885 | 8.1976 | 4.7391 | 6.1113 |
| ***Coelophysis*** | 1.3778 | 8.2740 | 5.5734 | 3.6532 | 7.8701 |
| **Orionides** | 7.5821 | 7.7413 | 5.3205 | 7.4705 | 5.3704 |
| **Megalosaurid taxon** | 11.8387 | 7.6313 | 5.0411 | 9.5484 | 6.6104 |
| **Avetheropoda** | 7.2509 | 8.2383 | 5.2166 | 5.7626 | 3.8640 |
| ***Allosaurus*** | 6.2096 | 5.6211 | 5.5515 | 6.8435 | 1.0643 |
| ***Tarbosaurus*** | 8.2836 | 0.6793 | 6.0240 | 14.0129 | 0.1647 |

**7. Influence of nasal crests on the results**

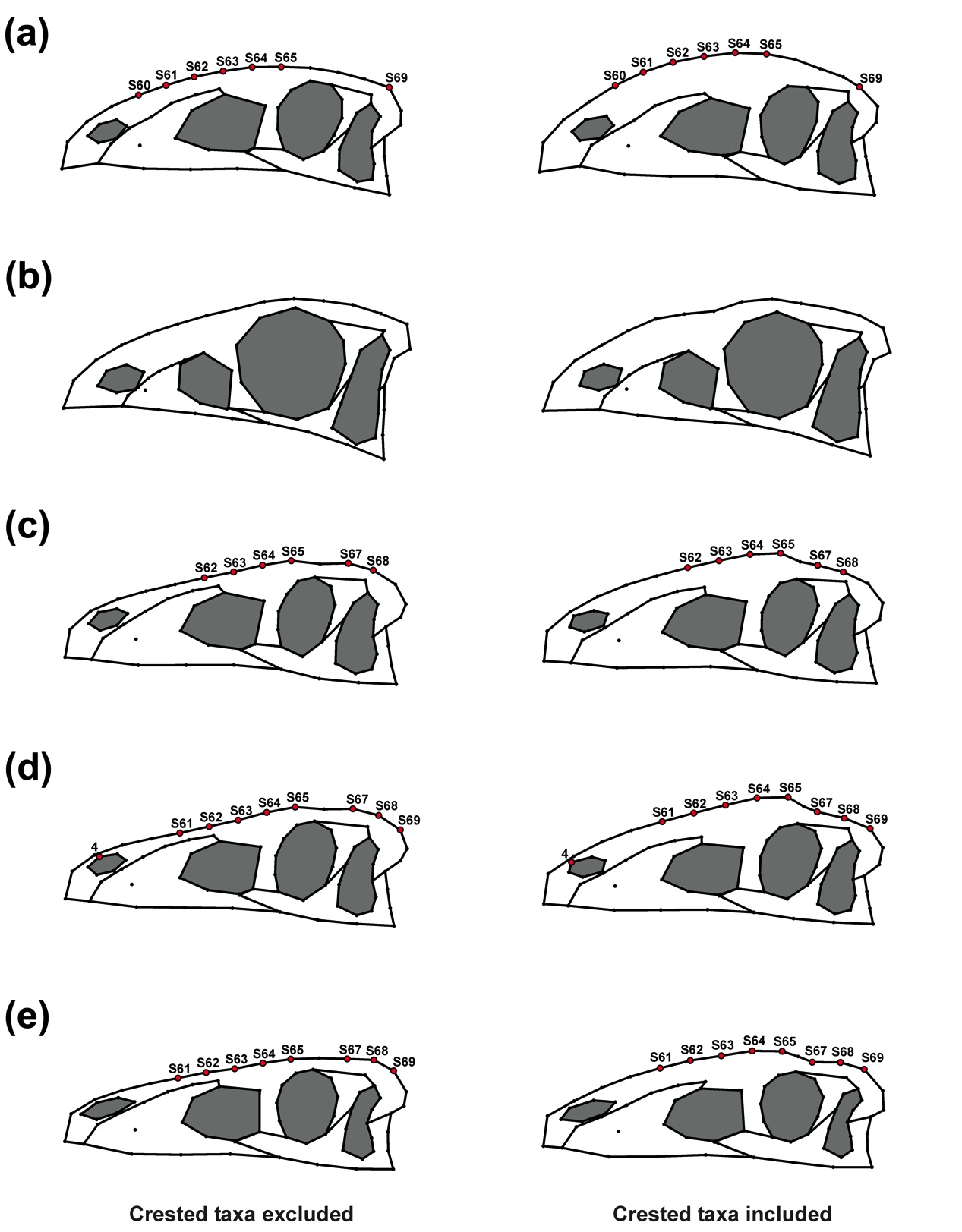
**Table S8 List of taxa with nasal crest with data of occurrences (in million of years, Myr) and sources of images.**

|  |  |  |  |
| --- | --- | --- | --- |
| **Taxa** |  | **Age (Myr)** | **Source** |
| *Dilophosaurus* | Basal Theropoda | 191.00 | Rauhut, 2003 |
| *Ceratosaurus* | Ceratosauria | 151.15 | Sampson & Witmer, 2007 |
| *Guanlong* | Coelurosauria | 160.40 | Xu *et al.*, 2006 |

To test the influence of taxa with nasal crest *Dilophosaurus*, *Ceratosaurus* and *Guanlong* were included into the data set. After performing a GPA the Procrustes coordinates were loaded into Mesquite 2.72 (Maddison & Maddison, 2009) and mapped as continuous character onto the phylogeny (Fig. S4). For those hypothetical ancestors, which may affected by the inclusion of crested taxa (i.e. Averostra,Ceratosauria,Avetheropoda,Coelurosauria andTyrannosauroidea), the Procrustes coordinates were exported and compared with the respective data of the original data set by computing the percentage divergence between both shapes using the method described by Singleton (2002). The inclusion of the crested taxa lead to significant shape changes in most of the hypothetical ancestors mentioned above affecting primarily the shape of the skull roof (Table S10, Fig. S10). Here, in the data set containing crested taxa the skull roofs of the hypothetical ancestors show signs of artificial crests, which could potentially falsify the trajectories of the ancestors in the regression analyses, and thus the interpretation of the heterochronic events. Only the shape of hypothetical ancestor of Ceratosauria seems unaffected by the nasal crest of *Ceratosaurus*. Nevertheless, the results of the PCA when crested taxa are included resemble those of original data set (Fig. 2, S11, Tables S4, S5, S11, S12, S17), indicating that at least trajectories of the terminal taxa are not strongly affected by the inclusion of crested taxa.

**Table S9 Percentage divergence of Procrustes coordinates of some hypothetical ancestors when crested taxa are included.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **LMs** | **Averostra** | **Avetheropoda** | **Coelurosauria** | **Tyrannosauridae** |
| **4** | < 5 | < 5 | 5.2137 | < 5 |
| **S60** | 5.2124 | < 5 | < 5 | < 5 |
| **S61** | 6.8402 | < 5 | 5.7688 | 5.0366 |
| **S62** | 7.4140 | 5.2973 | 7.0886 | 6.1963 |
| **S63** | 7.4131 | 6.1263 | 8.2894 | 7.1421 |
| **S64** | 7.3031 | 6.4497 | 8.8181 | 7.5216 |
| **S65** | 6.8977 | 5.7463 | 7.8951 | 6.6629 |
| **S67** | < 5 | 5.8798 | 8.4059 | 8.0697 |
| **S68** | < 5 | 5.5051 | 7.7255 | 7.2441 |
| **S69** | 5.2810 | < 5 | 5.5560 | 5.1951 |

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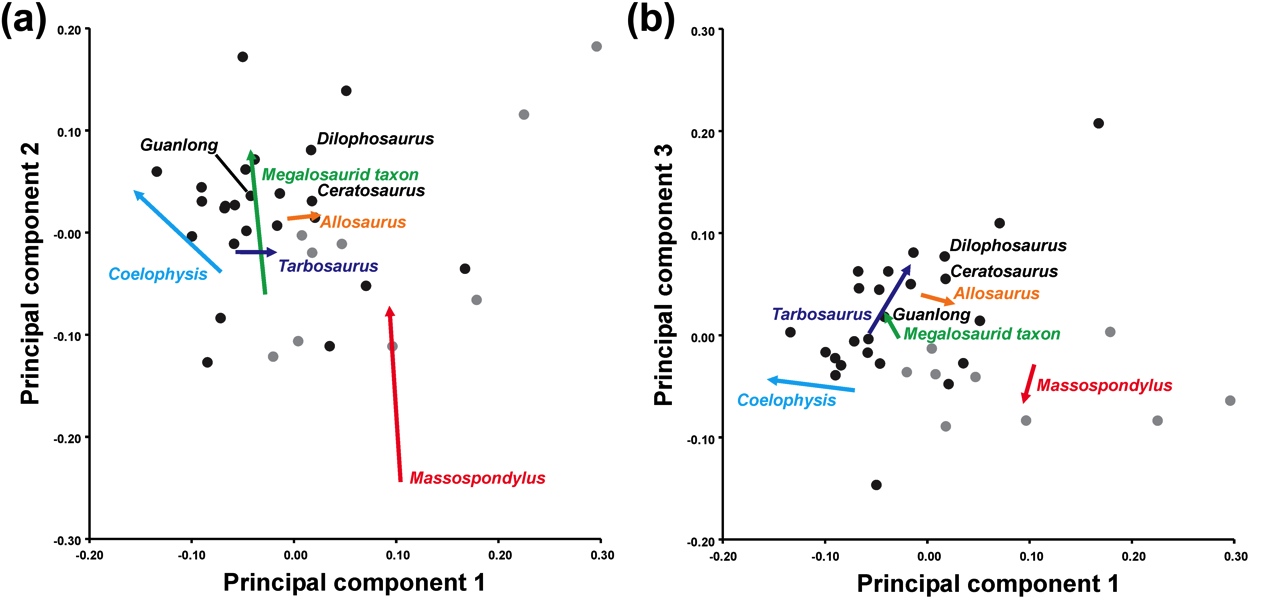
**Figure S5 Shape differences in ancestors when crested taxa are included or excluded. (a)** Averostra, **(b)** Ceratosauria, **(c)** Avetheropoda, **(d)** Coelurosauria, **(e)** Tyrannosauroidea (clade including *Dilong* and *Tarbosaurus* with *Guanlong* as outgroup). Red dots mark (semi-)landmarks, which shows significant differences from each other. Skull openings are shaded in grey.

**Table S10 Angles of ontogenetic trajectories in PCA against PC 1 when crested taxa are included in the data set.**

|  |  |  |
| --- | --- | --- |
|  | **PC 1-2** | **PC 1-3** |
| ***Massospondylus*** | 86.3695 | 73.9781 |
| ***Coelophysis*** | 43.1616 | 7.2269 |
| **Megalosaurid taxon** | 84.2163 | 60.9371 |
| ***Allosaurus*** | 5.8852 | 14.7089 |
| ***Tarbosaurus*** | 0.1579 | 59.0058 |

**Table S11 Pairwise angles between ontogenetic trajectories in PCA when crested taxa are included in the data set.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **PC 1-2** | ***Massospondylus*** | ***Coelophysis*** | **Megalosaurid taxon** | ***Allosaurus*** | ***Tarbosaurus*** |
| ***Massospondylus*** | 0.0000 |  |  |  |  |
| ***Coelophysis*** | 43.2079 | 0.0000 |  |  |  |
| **Megalosaurid taxon** | 2.1533 | 41.0546 | 0.0000 |  |  |
| ***Allosaurus*** | 87.7453 | 130.9532 | 89.8985 | 0.0000 |  |
| ***Tarbosaurus*** | 93.7883 | 136.9962 | 95.9416 | 6.0431 | 0.0000 |
|  |  |  |  |  |  |
| **PC 1-3** | ***Massospondylus*** | ***Coelophysis*** | **Megalosaurid taxon** | ***Allosaurus*** | ***Tarbosaurus*** |
| ***Massospondylus*** | 0.0000 |  |  |  |  |
| ***Coelophysis*** | 81.2050 | 0.0000 |  |  |  |
| **Megalosaurid taxon** | 134.9152 | 53.7102 | 0.0000 |  |  |
| ***Allosaurus*** | 91.3130 | 172.5180 | 133.7718 | 0.0000 |  |
| ***Tarbosaurus*** | 165.0277 | 113.7673 | 60.0571 | 73.7147 | 0.0000 |

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**Figure S6 PCA when crested taxa are included.** (a) Ontogenetic trajectories of terminal taxa for PC 1 against PC 2. (b) Ontogenetic trajectories of terminal taxa for PC 1 against PC 3. Theropod taxa are shown as black dots, while sauropodomorph taxa are shown as grey dots.

**8. Influence of semi-landmarks on the results**

After exclusion of the semi-landmarks from the data set the differences in the ontogenetic trajectories retains, but the courses of the trajectories changed relative to each other. This primarily impacts the diagnosis of heterochronic events in the regression analysis, which differs from the original data set with respect to the cranial evolution in early sauropodomorphs and tyrannosaurids. However, as less shape variation in dorsoventral dimension is captured after the exclusion of semi-landmarks, the results for early sauropodomorphs and tyrannosaurids are somewhat misleading. The mapping of the Procrustes shapes onto the phylogeny clearly shows a relative increase of the dorsoventral height of the skull in both groups.

**Table S12 Angles of ontogenetic trajectories in PCA against PC 1 when semi-landmarks are excluded from the data set.**

|  |  |  |
| --- | --- | --- |
|  | **PC 1-2** | **PC 1-3** |
| ***Massospondylus*** | 81.1710 | 59.6961 |
| ***Coelophysis*** | 81.3625 | 32.3194 |
| **Megalosaurid taxon** | 52.1091 | 23.0962 |
| ***Allosaurus*** | 32.4126 | 7.4444 |
| ***Tarbosaurus*** | 1.1564 | 55.0223 |

**Table S13 Pairwise angles between ontogenetic trajectories in PCA when semi-landmarks are excluded from the data set.**

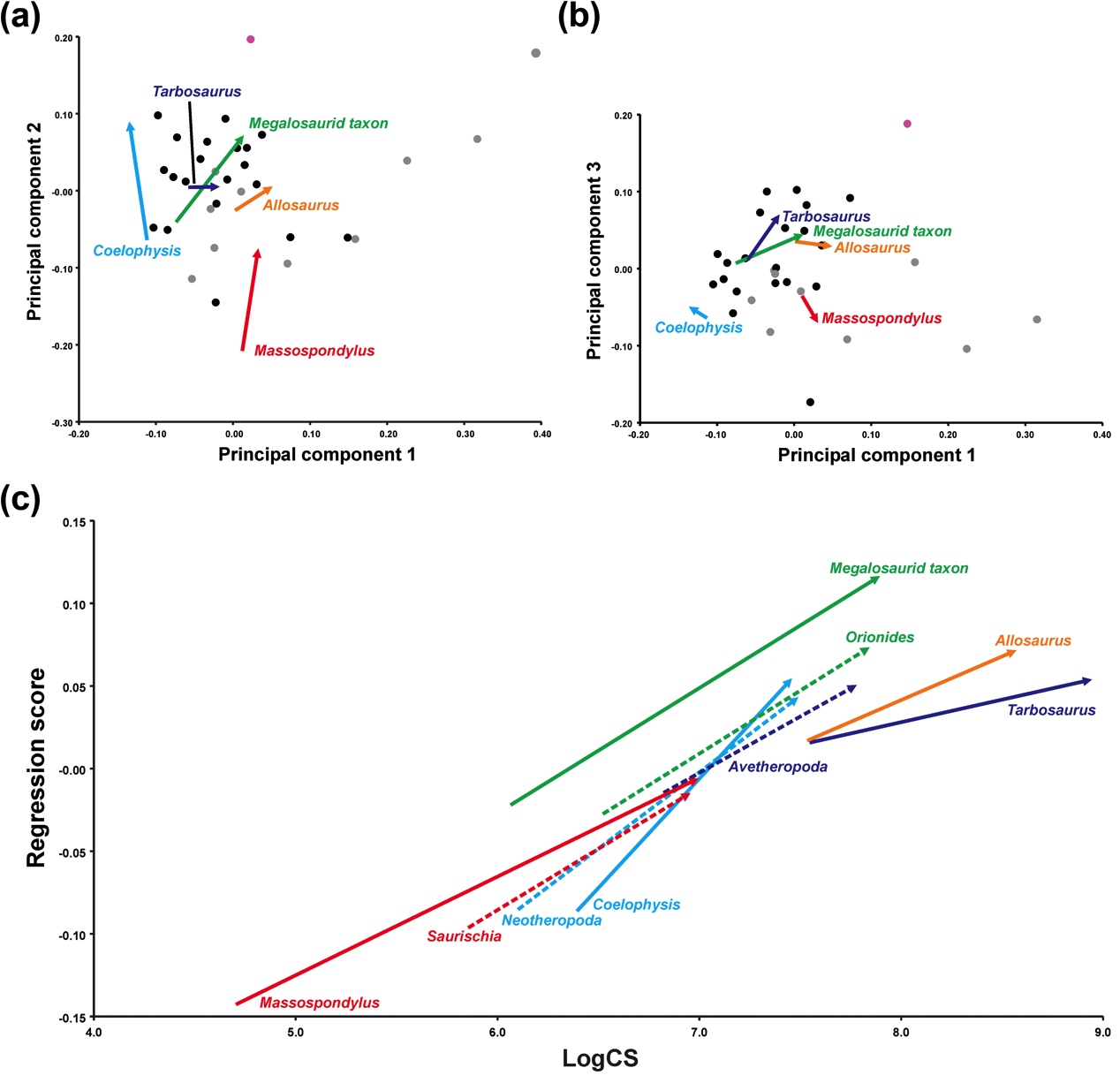
|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **PC 1-2** | ***Massospondylus*** | ***Coelophysis*** | **Megalosaurid taxon** | ***Allosaurus*** | ***Tarbosaurus*** |
| ***Massospondylus*** | 0.0000 |  |  |  |  |
| ***Coelophysis*** | 17.4665 | 0.0000 |  |  |  |
| **Megalosaurid taxon** | 29.0620 | 46.5285 | 0.0000 |  |  |
| ***Allosaurus*** | 48.7585 | 66.2249 | 19.6965 | 0.0000 |  |
| ***Tarbosaurus*** | 80.0146 | 97.4811 | 50.9526 | 31.2562 | 0.0000 |
|  |  |  |  |  |  |
| **PC 1-3** | ***Massospondylus*** | ***Coelophysis*** | **Megalosaurid taxon** | ***Allosaurus*** | ***Tarbosaurus*** |
| ***Massospondylus*** | 0.0000 |  |  |  |  |
| ***Coelophysis*** | 152.6233 | 0.0000 |  |  |  |
| **Megalosaurid taxon** | 82.7922 | 124.5844 | 0.0000 |  |  |
| ***Allosaurus*** | 52.2517 | 155.1250 | 30.5406 | 0.0000 |  |
| ***Tarbosaurus*** | 114.7184 | 92.6583 | 31.9262 | 62.4667 | 0.0000 |

**Table S14 Angles of ontogenetic trajectories on plot of shape versus centroid size (log-transformed) when semi-landmarks are excluded from the data set.**

|  |  |
| --- | --- |
|  | **Angle** |
| **Saurischia** | 4.2406 |
| **Massospondylus** | 3.4176 |
| **Neotheropoda** | 5.2886 |
| **Coelophysis** | 7.5316 |
| **Orionides** | 4.3657 |
| **Megalosauridae** | 4.3320 |
| **Avetheropoda** | 3.8961 |
| **Allosaurus** | 3.1168 |
| **Tarbosaurus** | 1.5063 |

**Table S15 Heterochronies within Saurischia when semi-landmarks are excluded based on the regression analysis.** The table shows the differences of Procrustes distances (ΔPD) between ancestor-descendent relationships of adult species from the regression analysis. Positive values\* = peramorphic trends; negative values\*\* = paedomorphic trends; values in brackets = non-significant trends

|  |  |
| --- | --- |
|  | **ΔPD** |
| **Saurischia-*Massospondylus*** | (0.0088) |
| **Saurischia-Theropoda** | 0.0579\* |
| **Neotheropoda-*Coelophysis*** | (0.0114) |
| **Neotheropoda-Orionides** | 0.0303\* |
| **Orionides-megalosaurid taxon** | 0.0430\* |
| **Orionides-Avetheropoda** | -0.0229\*\* |
| **Avetheropoda-*Allosaurus*** | (0.0210) |
| **Avetheropoda-*Tarbosaurus*** | (0.0033) |

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**Figure S7 PCA and regression analysis when semi-landmarks are excluded.** (a) Ontogenetic trajectories of terminal taxa for PC 1 against PC 2. (b) Ontogenetic trajectories of terminal taxa for PC 1 against PC 3. Theropod taxa are shown as black dots, while sauropodomorph taxa are shown as grey dots. (c) Ontogenetic trajectories of terminal taxa (solid lines) and hypothetical ancestors (dashed lines) against log-transformed centroid size (LogCS).

**Table S16 Comparison of the results of the PCA and the regression test (shape vs. log-transformed centroid size) for all tree data sets.**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **PCA** | **Saurischia (original)** |  | **Saurischia (without semi- landmarks)** |  | **Saurischia (taxa with nasal crests)** |  |
| **PC 1** | 30.75 % |  | 28.37 % |  | 28.58 % |  |
| **PC 2** | 23.94 % |  | 19.98 % |  | 22.73 % |  |
| **PC 3** | 13.26 % |  | 15.64 % |  | 12.96 % |  |
|  |  |  |  |  |  |  |
| **Regression** | **Correlation** | ***p* value** | **Correlation** | ***p* value** | **Correlation** | ***p* value** |
| **All** | 15.32 % | <0.0001 | 14.98 % | <0.0001 | 14.71 % | <0.0001 |
| **PC 1** | 0.46 % | 0.6735 | 4.80 % | 0.178 | 0.30 % | 0.7333 |
| **PC 2** | 45.68 % | <0.0001 | 51.23 % | <0.0001 | 48.82 % | <0.0001 |
| **PC 3** | 27.30 % | 0.0007 | 19.66 % | 0.0039 | 22.03 % | 0.0016 |
| **PC 4** | 6.35 % | 0.1183 | 0.79 % | 0.5896 | 0.64 % | 0.6143 |

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