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SUPPLEMENTARY ONLINE MATERIAL FOR

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Ontogenetic changes in the craniomandibular skeleton of abelisaurid dinosaur *Majungasaurus crenatissimus* from the Late Cretaceous of Madagascar

Published in *Acta Palaeontologica Polonica* 2016 61 (2): 281-292.
<http://dx.doi.org/10.4202/app.00132.2014>

Supplementary Online Material

SOM 1. List of anatomical landmarks used in geometric morphometric analysis.

SOM 2. Whole and partial skulls (A–C) of *Majungasaurus crenatissimus* in left lateral view used in this study to illustrate relative completeness of the materials.

SOM 3. QuickTime movie illustrating quadrate shape change through ontogeny, anterior view. Animations were created by warping the 3D volume of the smallest specimen (UA 10000) to fit the landmark configuration of the largest specimen (FMNH PR 2100) using thin-plate spline interpolation (Wiley et al. 2005)

http://app.pan.pl/SOM/app61-Ratsimbaholison_etal_SOM/SOM_3.mov

SOM 4. QuickTime movie illustrating quadrate shape change through ontogeny, lateral view. Protocol for development follows that outlined for SOM 3.

http://app.pan.pl/SOM/app61-Ratsimbaholison_etal_SOM/SOM_4.mov

SOM 1.

List of anatomical landmarks used in geometric morphometric analysis.

I. Whole Skull (Figure 1)

A. Whole Skull-Landmarks

1. Anteroventral corner of the maxillary body
2. Posteroventral corner of the maxilla at the jugal contact surface
3. Anterior limit of maxillary process of the jugal
4. Anterodorsal limit of the lacrimal contact of the jugal
5. Posterodorsal limit of the lacrimal contact of the jugal
6. Posterior margin of the postorbital at the origin of the jugal process of the postorbital
7. Dorsal limit on the contact between jugal and postorbital
8. Anterior limit of ventral jugal process of the quadratojugal
9. Posterior limit of ventral quadratojugal process of the jugal
10. Anterior limit of dorsal jugal process of the quadratojugal
19. Dorsal limit of the quadratojugal at the contact between squamosal and quadratojugal
20. Posterior limit of the quadratojugal
21. Posteroventral limit of squamosal process of the postorbital
22. Anterior limit of suborbital process of postorbital
31. Ventral contact between postorbital and lacrimal
32. Dorsal margin of the maxillary border at the posterior limit of the internal contour of the maxillary ascending ramus
33. Anterodorsal limit of the maxillary contribution to the external naris

A. Whole Skull-Semilandmarks

11-18: Curve connecting the anterior limit of dorsal jugal process of the quadratojugal and the dorsal limit of the quadratojugal at the contact between squamosal and quadratojugal
23-30: Curve connecting the anterior limit of suborbital process of postorbital and the ventral contact between postorbital and lacrimal.

II. Premaxilla (Figure 3)

A. Premaxilla-Landmarks

1. Rostroventral corner of the premaxillary corpus
2. Rostrocaudal midpoint along the ventral margin of the premaxillary corpus
3. Caudoventral corner of the premaxillary corpus
4. Intersection of the caudal margin of the premaxillary corpus and the ventral margin of the maxillary process of the premaxilla
5. Intersection of the caudal margin of the premaxillary corpus and the dorsal margin of the maxillary process of the premaxilla
14. Apex of the nasal process of the premaxilla
15. Point on the rostral margin of the premaxilla at an equivalent to the dorsal margin of the corpus

B. Premaxilla-Semilandmarks

6-13. Curve connecting the apex of the nasal process of the premaxilla and the caudodorsal corner of the premaxillary corpus

III. Maxilla (Figure 4)

Given the complexity of the maxilla, a rectangular grid was used in the following manner: fixed landmarks 1 and 7 below define the endpoints of the major axis demarcating the mid-height (~dorsoventral) of a rectangle overlaying the ventral margin of the maxilla. This

rectangle was subdivided into quarters, with the resulting points at the intersection the perpendicular quartile lines used to characterize the ventral margin of the maxilla (landmarks #8-10).

A. Maxilla-Landmarks

1. Posteroventral corner of the maxilla at the jugal contact surface
2. Dorsal margin of the external maxillary surface at anterior limit of jugal contact
3. Dorsal margin of the maxillary border at the posterior limit of the internal contour of the maxillary ascending ramus
4. Dorsal margin of the maxillary border at the posterior limit of the external contour of the maxillary ascending ramus
5. Anterodorsal limit of the maxillary contribution to the external nares
6. Anterior prong of the maxilla at the premaxillo-maxillary contact.
7. Anteroventral corner of the maxillary body
8. Ventral maxillary margin at $\frac{1}{4}$ anteroposterior length (see above)
9. Ventral maxillary margin at $\frac{1}{2}$ anteroposterior length (see above)
10. Ventral maxillary margin at $\frac{3}{4}$ anteroposterior length (see above)

IV. Lacrimal (Figure 5)

A. Lacrimal-Landmarks

1. Caudal edge of vertical ramus at the jugal articulation point
2. Ventral termination of the lacrimal ramus
3. Rostral edge of the vertical ramus at the jugal articulation point
12. Rostral terminus of external antorbital fenestra (along the vertical ramus)
13. Inflection point between vertical ramus and rostral ramus
14. Rostral terminus of the rostral ramus (at the rostroventral margin)
15. Inflection point between the rostral ramus and the lacrimal corpus
16. Rostrodorsal corner of the lacrimal corpus
17. Caudodorsal corner of the lacrimal corpus (note: that this could include a fused prefrontal element as part of the “lacrimal corpus”)
18. Caudoventral corner of the lacrimal corpus
27. Suborbital process (sop)

B. Lacrimal-Semilandmarks

4-11: Curve connecting rostral edge of the vertical ramus at the jugal articulation point to the rostral terminus of eaof (along the vertical ramus)

19-26: Curve connecting the caudoventral corner of the lacrimal corpus to the suborbital process (sop)

V. Postorbital (Figure 6)

A. Postorbital-Landmarks

1. Posterior margin of the postorbital at the origin of the jugal process
2. Posterior extent of the squamosal process
3. Inflection point between dorsal margin and squamosal process
4. Posterior limit at postorbital-frontal contact
5. Anterodorsal limit of postorbital-lacrimal contact
6. Anteroventral limit postorbital-lacrimal contact
17. Anterior limit of suborbital process

B. Postorbital—Semilandmarks

7-16: 10 equally spaced semi landmarks between landmarks 6 and 17 along orbital margin

VI. Jugal (Figure 7)

Two reference lines were used to establish landmark placement on the jugal. The first is aligned along the anterior edge of the postorbital process. A second line is drawn perpendicular to the first at a point where it intersects both the dorsal margin of the dorsal quadratojugal process (#4) and the posterior limit (#3) of the dorsal quadratojugal process.

A. Jugal-Landmarks

1. Posterior limit of ventral quadratojugal process
2. Anterior limit of quadratojugal contact
3. Posterior limit of dorsal quadratojugal process
4. Intersection of reference line (see above) and dorsal margin of the dorsal quadratojugal process
5. Dorsal limit of the postorbital process
6. Intersection point between reference line (A) and reference line (B) along the anterior aspect of the postorbital process of the jugal.
7. Posterodorsal limit of the lacrimal contact
8. Anterior limit of maxillary process

VII. Quadrate (Figure 8)

A. Quadrate-Landmarks

1. Dorsomedial margin of lateral hemicondyle
2. Anterior aspect of intercondylar sulcus
3. Dorsolateral margin of medial hemicondyle
4. Base of the quadrate shaft at the dorsal margin of the medial hemicondyle
5. Base of quadrate head at origin of pterygoid process
6. Base of quadrate head at dorsal end of quadratojugal process
17. Inflection point between the dorsolateral margin and lateral margin of quadratojugal process
18. Base of quadrate head, posterior surface
29. Posterodorsal margin of medial hemicondyle

B. Quadrate-Semilandmarks

- 7-16: Ten (10) equally spaced semilandmarks between landmarks 6 and 17 along dorsolateral contour of the quadratojugal process
- 19-28: Ten (10) equally spaced semilandmarks between landmarks 18 and 29 along posteromedial margin of quadrate shaft

VIII. Dentary (Figure 9)

A. Dentary—Landmarks

1. Ventral margin of the dentary at the rostral limit of the external mandibular fenestra
2. 25% length position on ventral margin of the dentary (from rostral margin of external mandibular fenestra)
3. 50% length position on ventral margin of the dentary (from rostral margin of external mandibular fenestra).
4. 75% length position on ventral margin of the dentary (from rostral margin of external mandibular fenestra)
13. Rostrodorsal corner of the dentary
14. 75% length position on dorsal margin of the dentary (from rostral margin of external mandibular fenestra)
15. 50% length position on dorsal margin of the dentary (from rostral margin of external mandibular fenestra)

16. 25% length position on dorsal margin of the dentary (from rostral margin of external mandibular fenestra)
17. Dorsal margin of the dentary at the rostral limit of the external mandibular fenestra
18. Caudal extent of the dorsal surangular process
28. Caudal extent of the ventral surangular process
36. Caudodorsal margin of the external mandibular fenestra (on the ventral surangular process)

B. Dentary- Semilandmarks

5-12: Curve connecting LM 4 and LM 13, characterizing the rostroventral margin of the dentary

19-27: Curve connecting the caudal extent of the dorsal and ventral surangular processes

29-35: Curve connecting the Rostrodorsal limit of the external mandibular fenestra

IX. Surangular (Figure 10)

A. Surangular-Landmarks

1. Inflection point between the two components of the curve marking the caudodorsal margin of the external mandibular fenestra
2. Rostral extent of the dentary process
3. Rostral limit of the angular-surangular contact
9. Caudal limit of the angular-surangular contact
10. Caudal extent of the surangular

B. Surangular- Semilandmarks

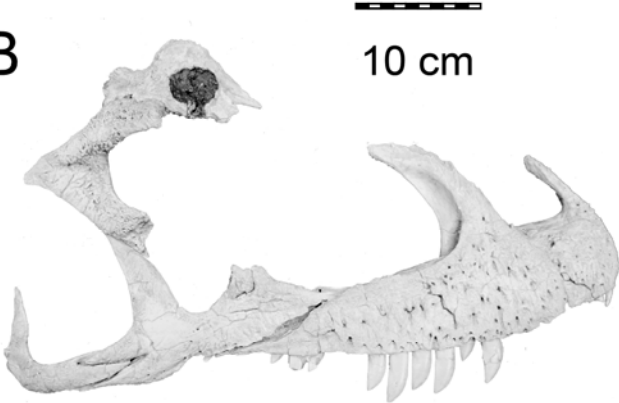
4-8: Curve connecting the rostral (3) and caudal (4) extent of the angular-surangular contact

SOM 2. Whole and partial skulls (A–C) of *Majungasaurus crenatissimus* in left lateral view used in this study to illustrate relative completeness of the materials.

A



B



C

