SUPPLEMENTARY FILE
Supplementary Dataset

MODELING NECK MOBILITY IN FOSSIL TURTLES

by

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Supplementary Figures

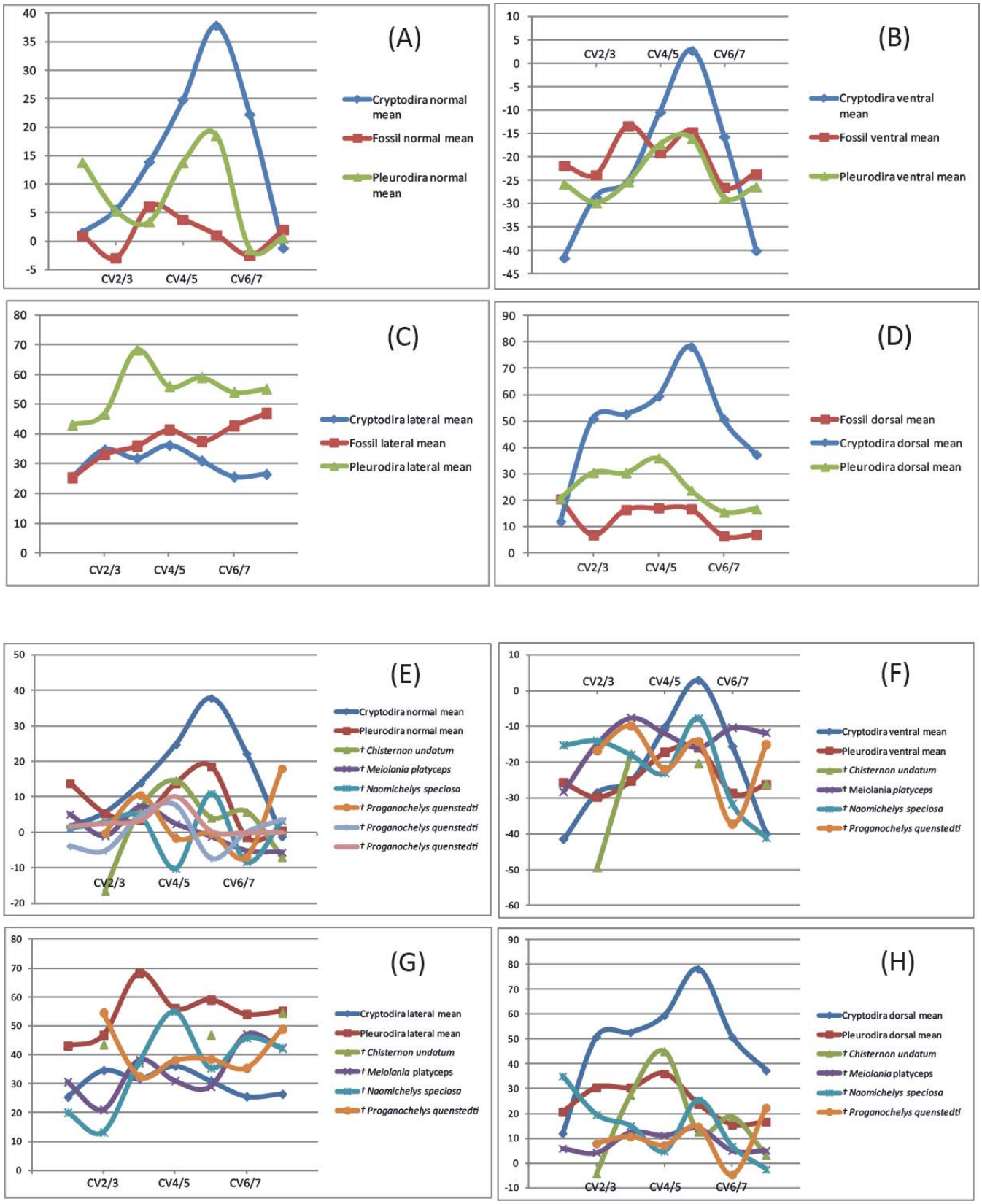

Figure S1. Comparison of measured angles of raw mobility between the vertebrae at different positions of the neck. A, E) neutral position, B, F) maximal ventral flexion, C, G) maximal lateral flexion, D, H) maximal dorsal flexion. A-D) mean of pleurodires, cryptodires, and fossil taxa , E-H) mean of pleurodires and cryptodires, fossil taxa separated.

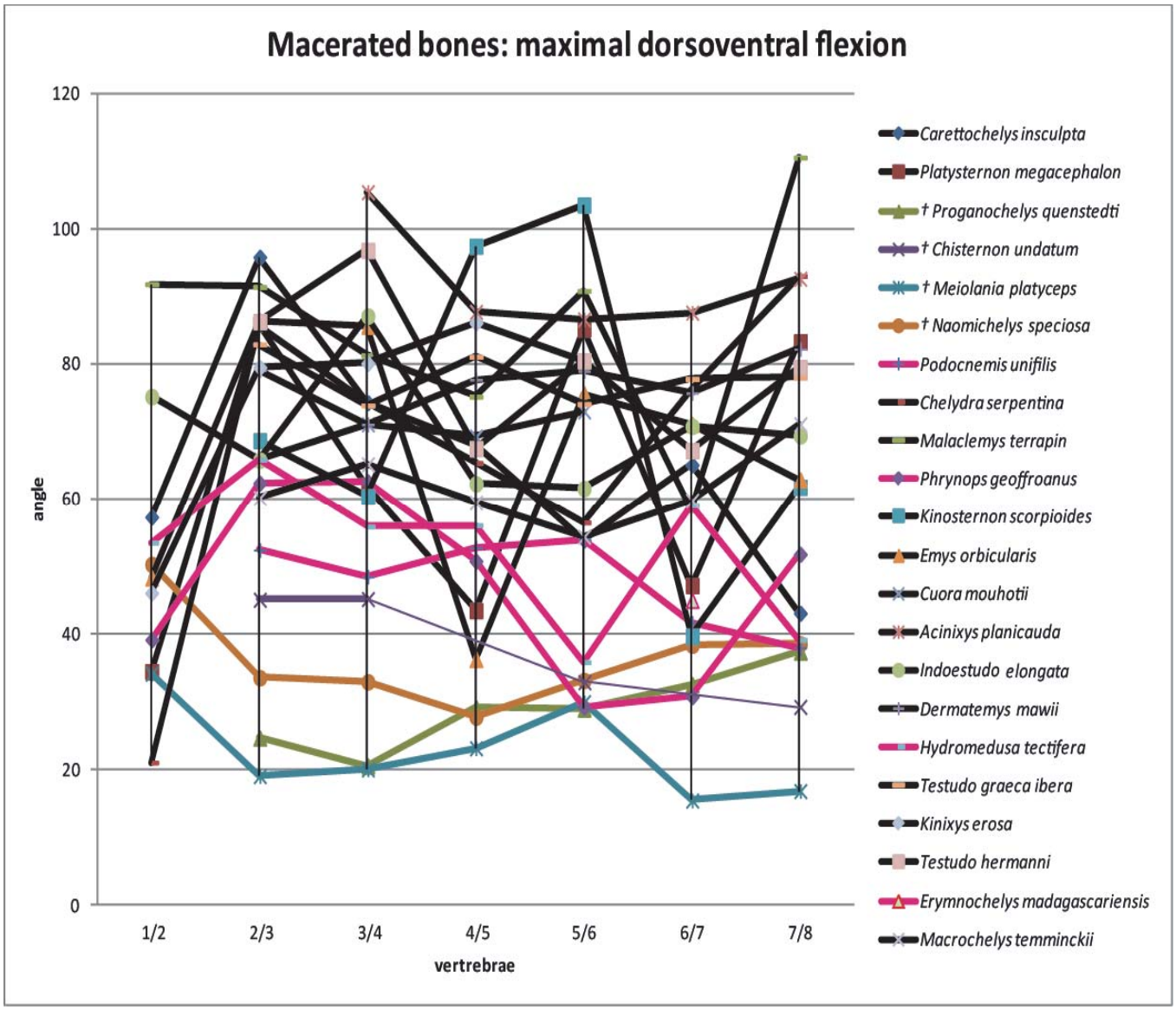

Figure S2. Maximal dorsoventral flexion in macerated bones. Stem taxa show the lowest degree of dorsoventral flexion of raw mobility between the vertebrae. A higher degree is visible in pleurodires (red) and the highest degree is visible in cryptodires (black). *Chisternon undatum* shows the highest affinity to extant turtles among fossil taxa. See Table S4B-C for data.

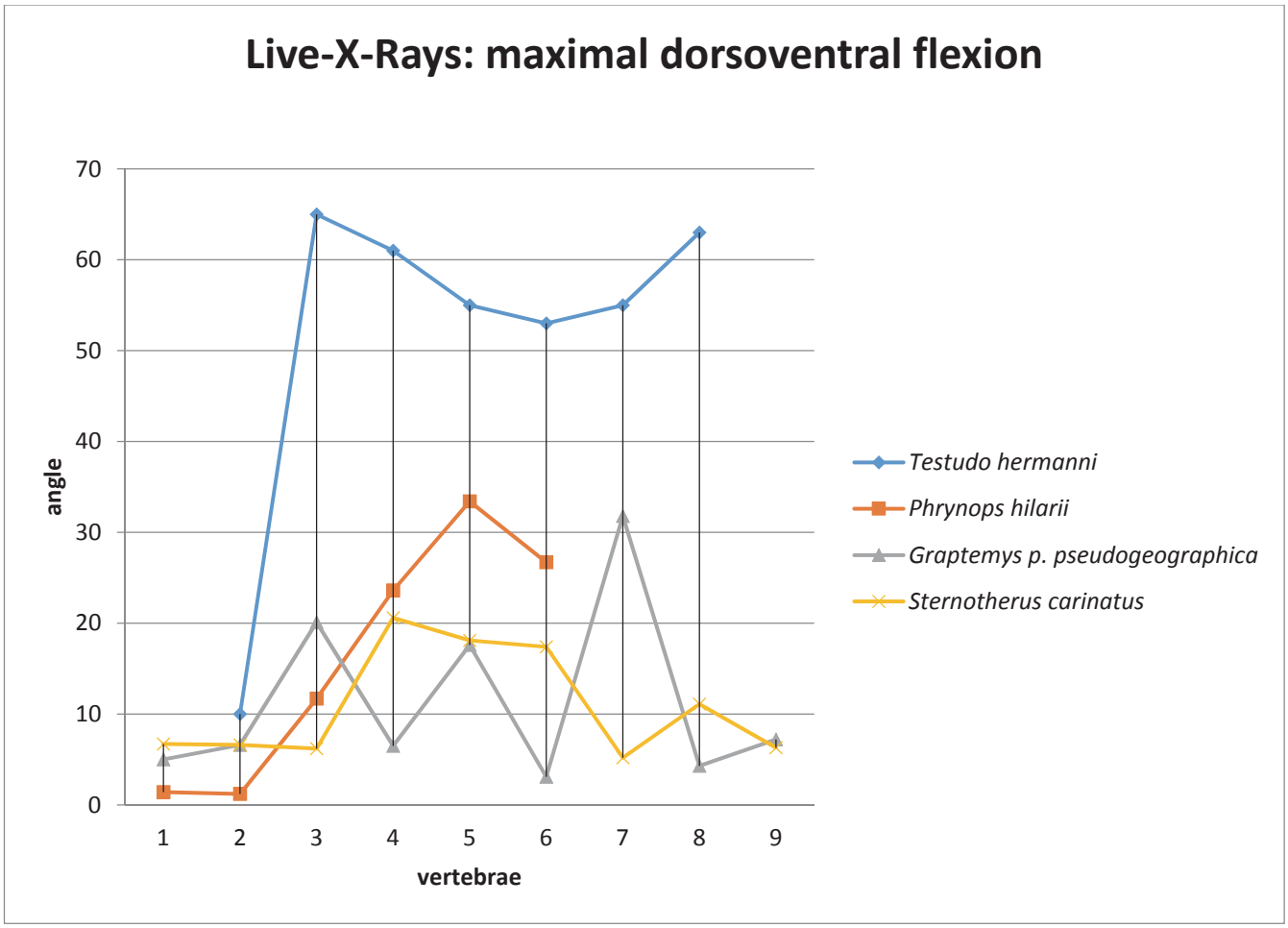

Figure S3. Maximal dorsoventral flexion in living turtles. The land turtle *Testudo hermanni* shows the largest dorsoventral flexion. The aquatic pleurodire *Phrynops hilarii* and the aquatic cryptodires *Graptemys pseudogeographica* and *Sternotherus carinatus* show similar dorsoventral flexions. The maximum amount of flexion measured on radiographs in either direction has a certain amount of imprecision due to artefacts created by the perspective and by superimposition. For data see Table S7.

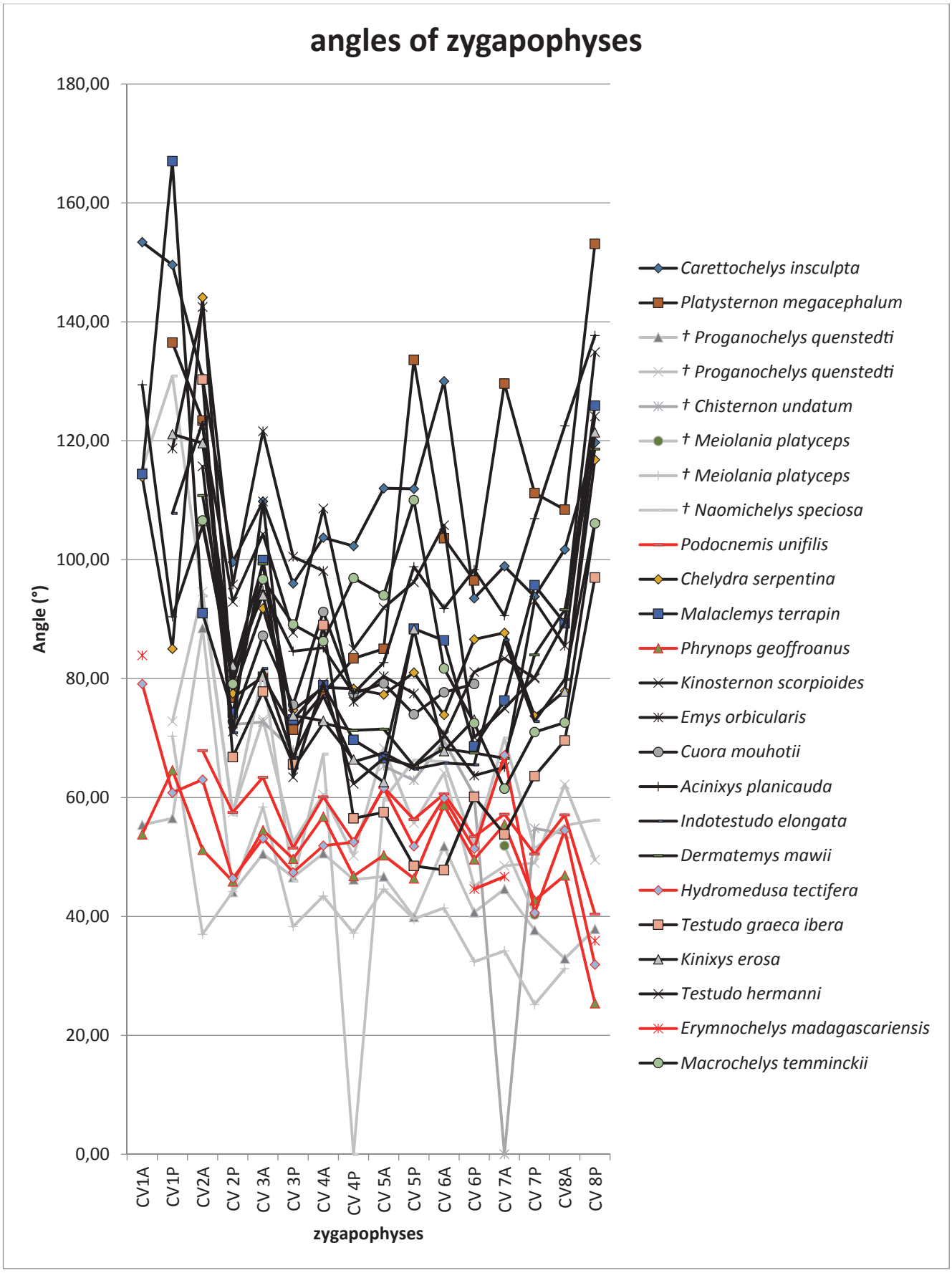

Figure S4. Angles measured between the zygapophyses and the centre of the centrum in anterior view. Black = cryptodires, red = pleurodires, grey = fossil turtles, CV = cervical vertebra, A = anterior half, P = posterior half

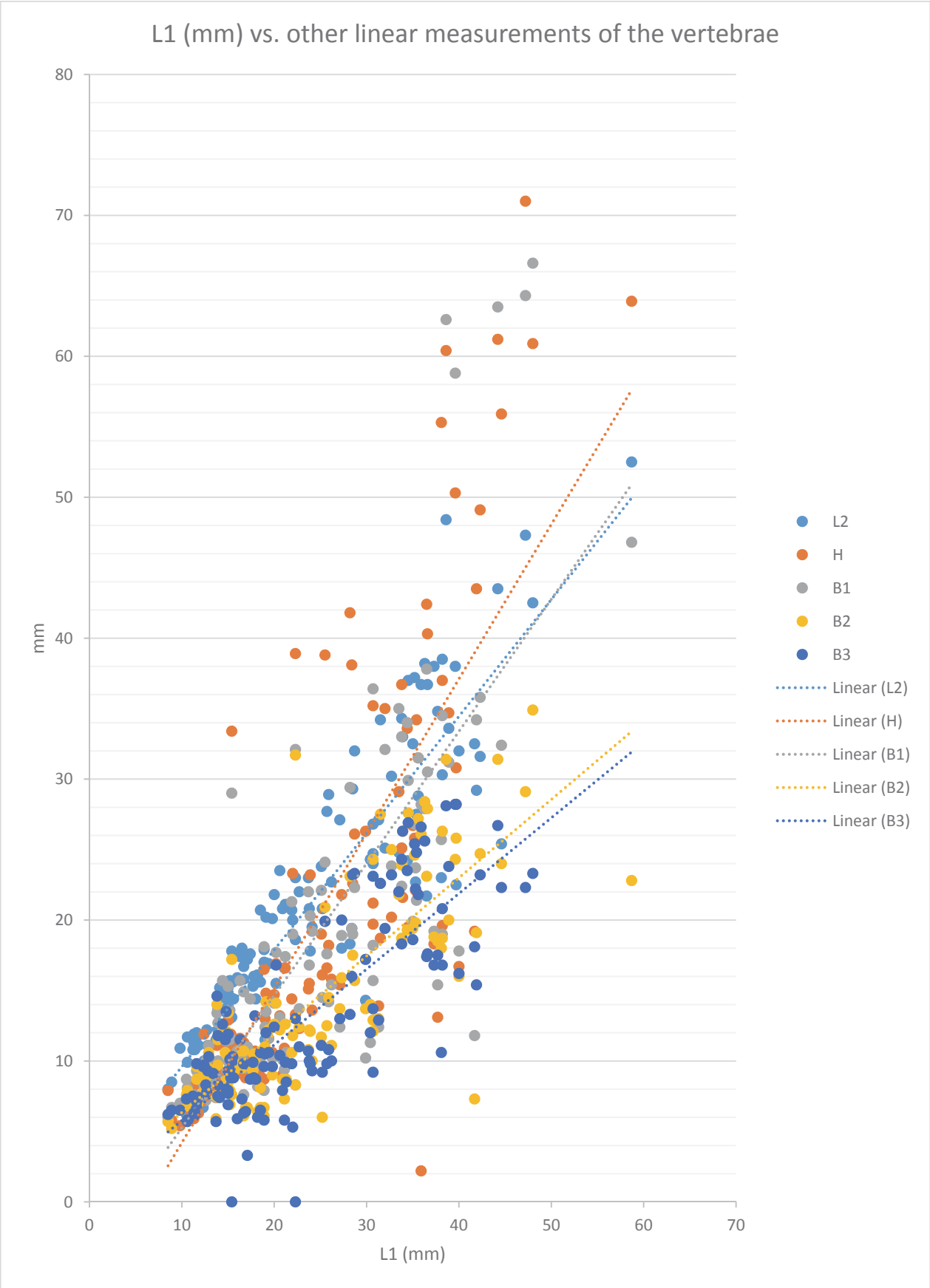

Figure S5. L1 (mm) vs. other linear measurements of the vertebrae. For linear regressions of other lengths against each other and against angles see Table S6.

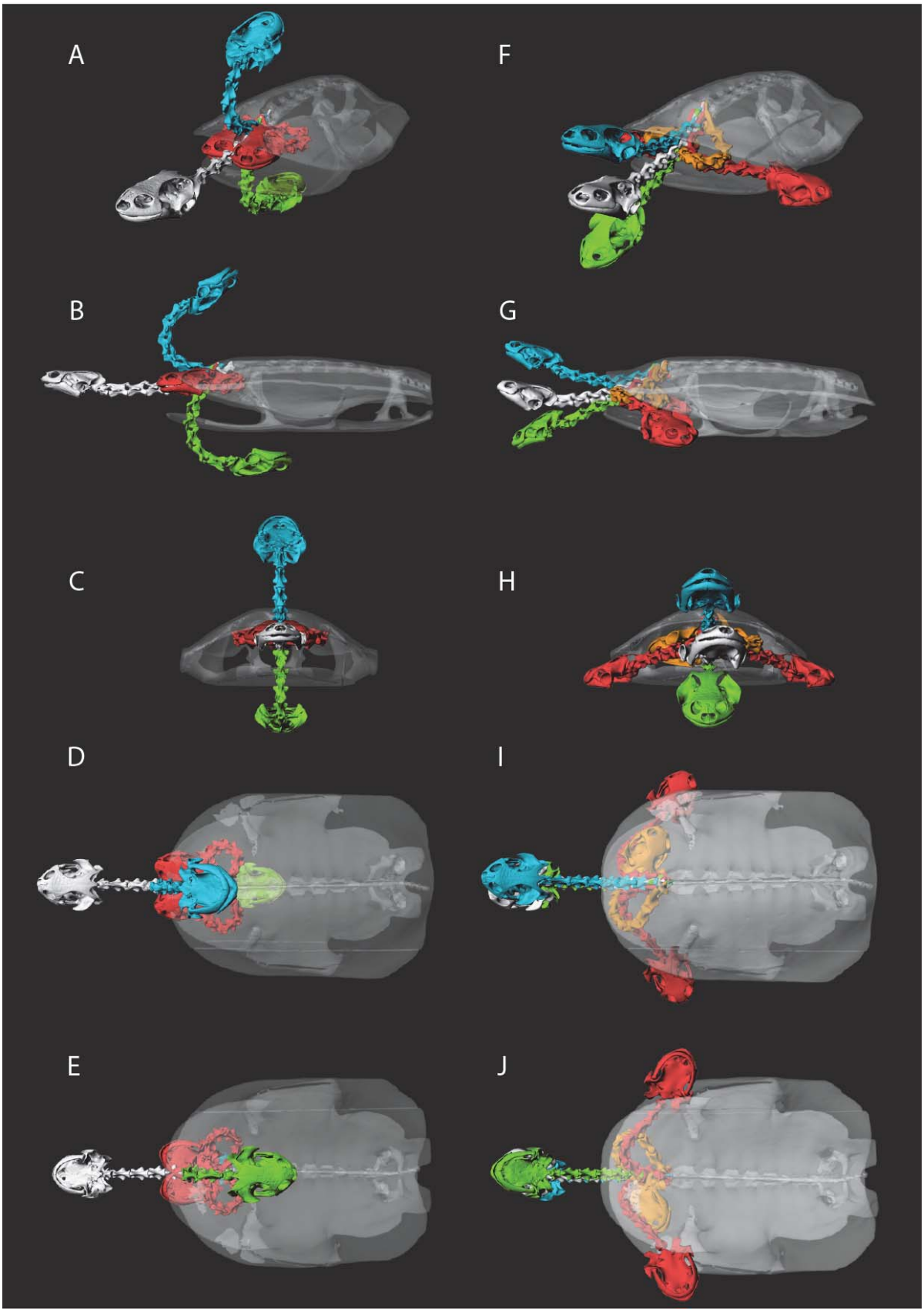

Figure S6. Neck movements in pleurodires illustrated for *Phrynops*. A-E) Raw neck movement in *P. geoffroanus* (with the carapace of *P. hilarii*). F-J) Live movement of the neck in *P. hilarii* based on CT-scans. Views: A, F) perspective frontolateral; B, G) lateral; C, H) frontal; D, I) dorsal, E, J) ventral view. Colors as in Fig. 5; compare also to this Figure.

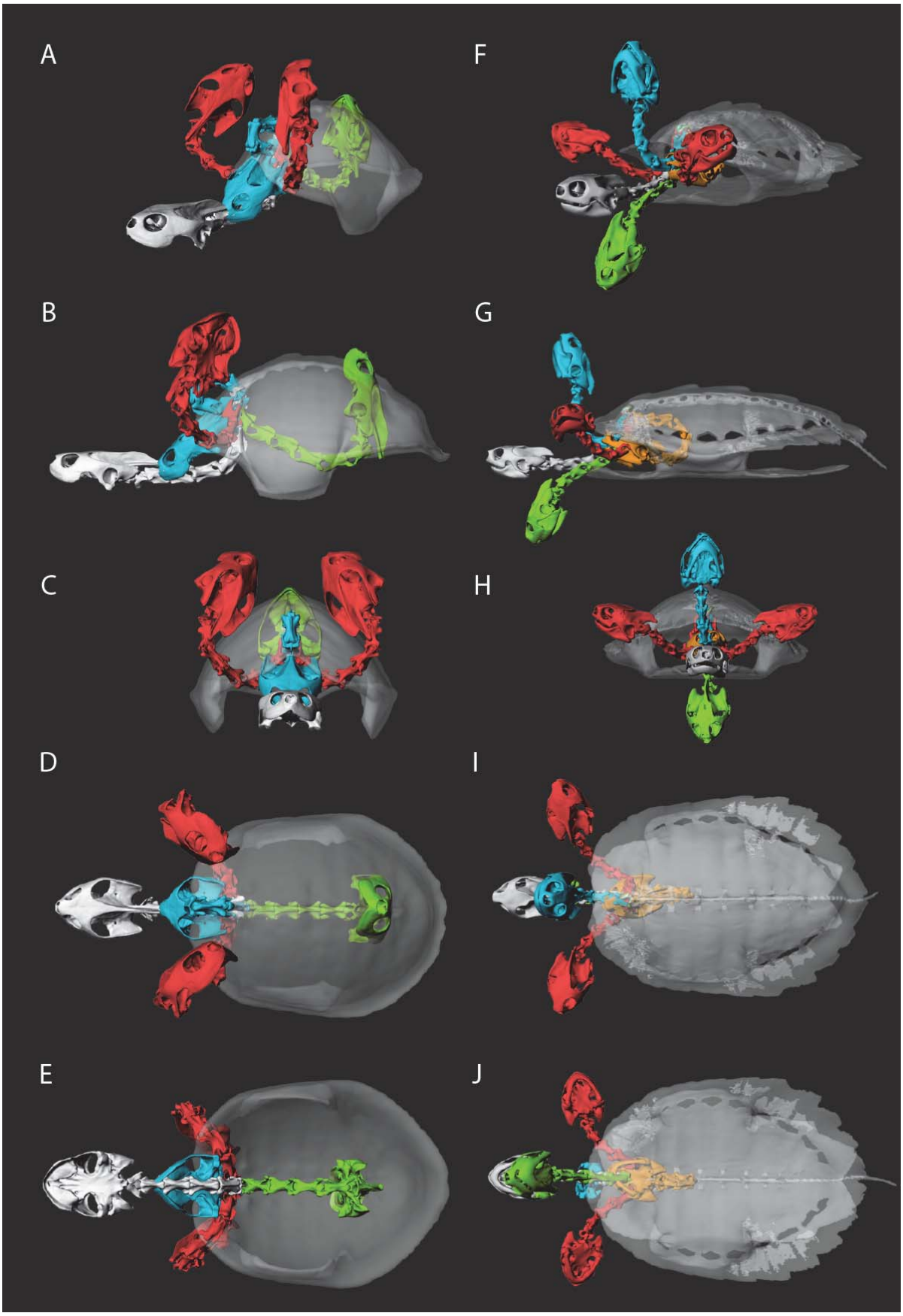

Figure S7. Neck movements in cyptodires illustrated in emydids. A-E) Raw neck movement in *Malaclemys terrapin* (no plastron was available). F-J) Live movement of the neck in *Graptemys nigrinoda* based on CT-scans. Views: A, F) perspective frontolateral; B, G) lateral; C, H) frontal; D, I) dorsal, E, J) ventral view. Compare to Fig. 6. Colors as in Fig. 5.

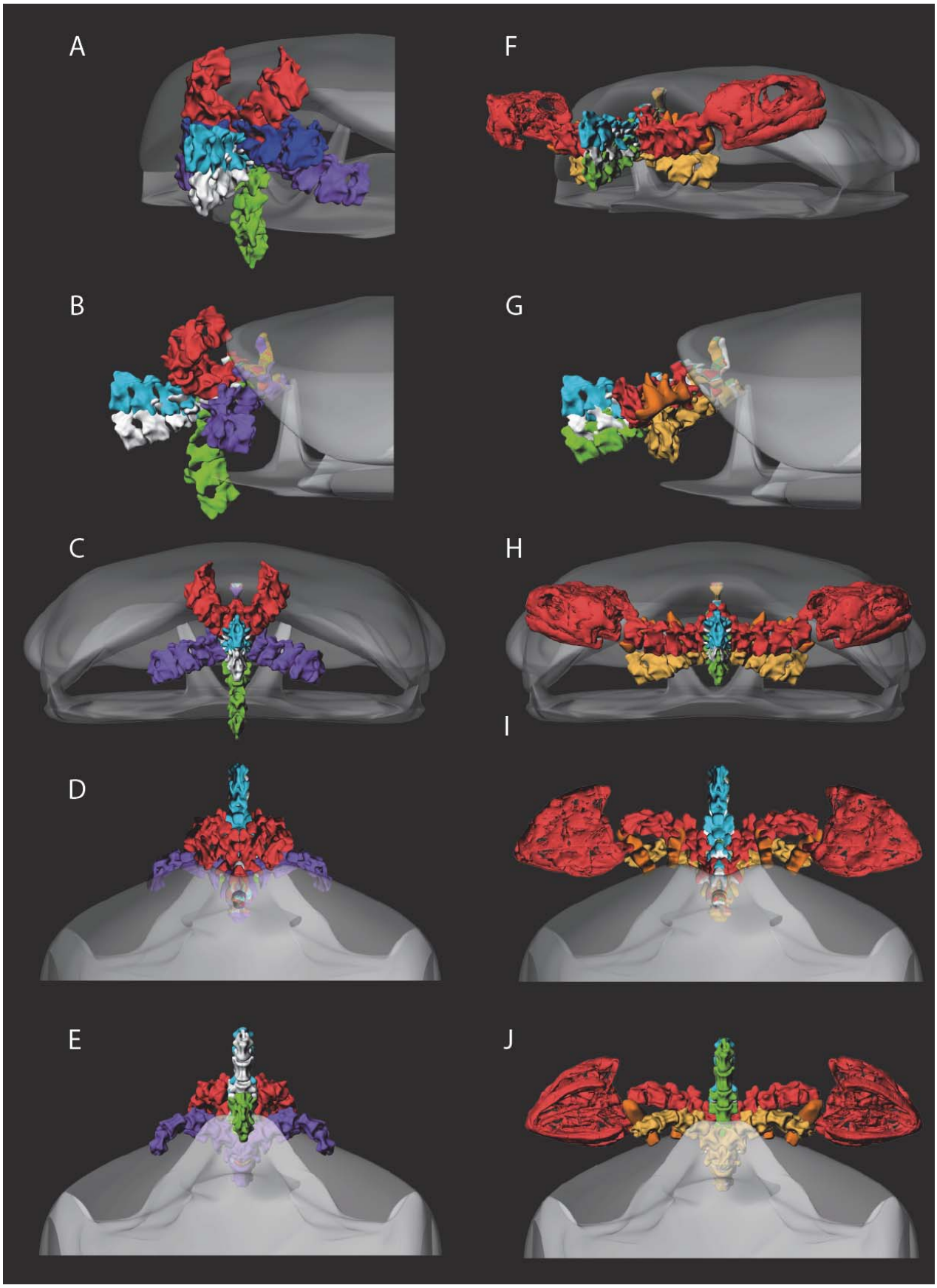

Figure S8. Neck movements in the stem turtle *Proganochelys quenstedti*. The shell and osteoderms were reconstructed with the software Maya based on the images from Gaffney (Gaffney, 1990). **A-E)** Raw neck movement. **F-J)** Calculated live movement of the neck. Views: **A, F)** perspective frontolateral; **B, G)** lateral; **C, H)** frontal; **D, I)** dorsal, **E, J)** ventral view. Compare to Figure 7.

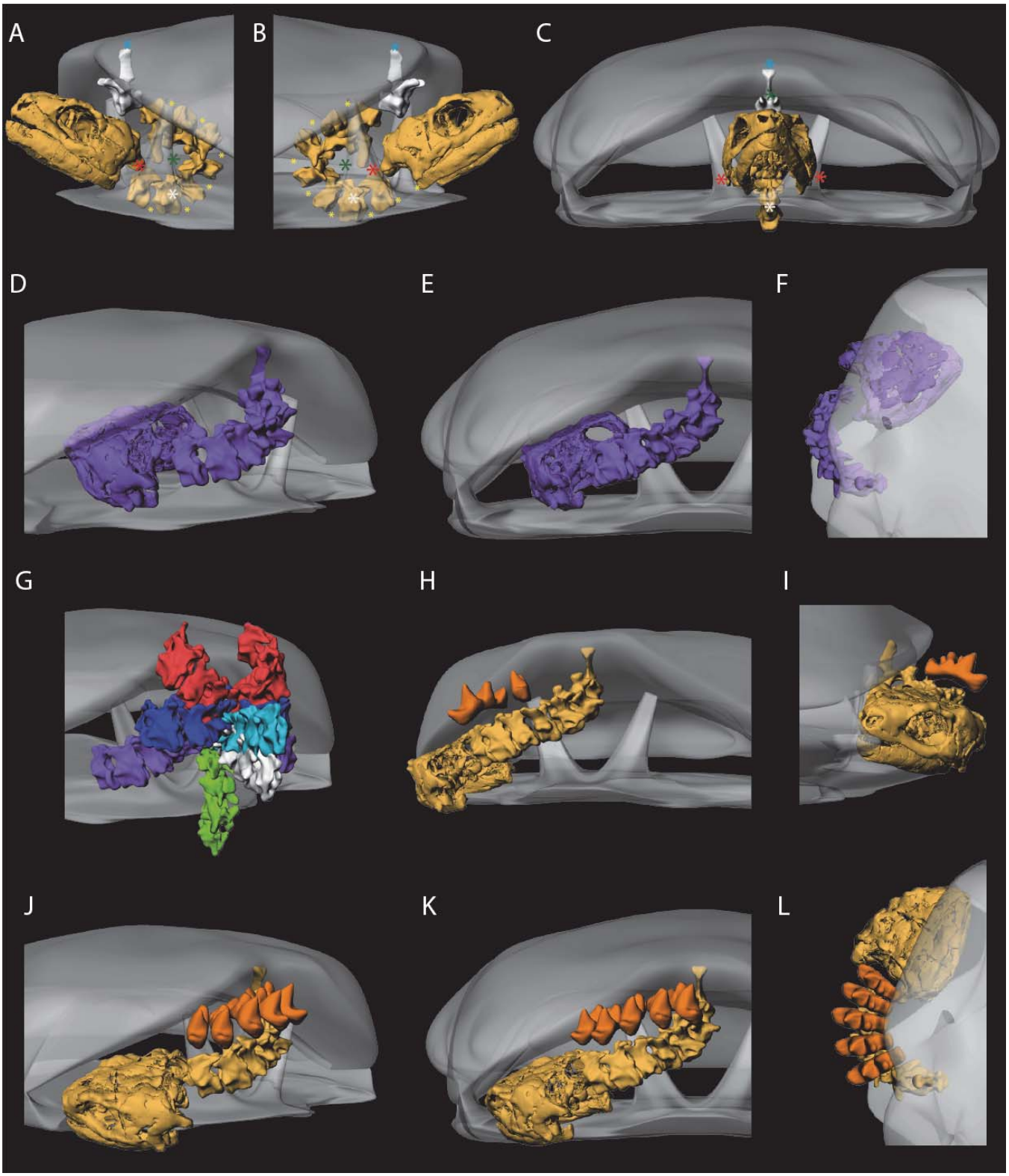

Figure S9. Modelling of neck retractions in *Proganochelys quenstedti*.
A-C) Reconstruction of the consistently bended, cryptodiran-like retracted neck (compare to Figure 6D: orange) in left anterolateral **(A)**, right lateral **(B)**, and frontal **(C)** view. Asterisks indicate plausible and obvious restrictions that hinder cryptodiran-like neck retraction: 1. extreme overstretching (yellow *); 2. a possible strong connection of the 8th cervical vertebra to the carapace (blue *) would dislocate the remaining vertebrae completely; 3. cone shaped osteoderms on the neck (green *); 4. the epiplastral processes (red *; ribs and head would not be able to pass), and 5. the plastron itself (white *). Further restriction has to be assumed by soft tissue. Compare with Figs 6 and 7.

D-F) Reconstruction of the lateral neck retraction with the theoretically allowed (purple) mobility between vertebrae without hypermobility. The osteoderms were not included in this model. Note that in theory much more mobility between vertebrae is possible than reconstructed for live retraction on P. quenstedti (compare to Figure 7D-F and G-I of this Figure). **G)** All theoretical movements without hypermobility for comparison (corresponds to Figure S8A).
H-I) Further illustrations of lateral retraction. Compare to Figure 7D-F,
J-K) Reconstruction of neck retraction with a theoretical number of five osteoderm-rows as suggestively modelled by Gaffney ((Gaffney, 1990): figures 1, 2 upper, 3). Similar to our 2-osteoderm reconstruction (H-I, Figure 7D-F), also five osteoderms would not impede neck retraction. Note that a large space is allowed between vertebrae and osteoderms in our model, which would be occupied by soft tissue in the living animal (skin, musculature). There is not any evidence that more than two large osteoderm-rows have been present in *P. quenstedti* (Jaekel, 1915). The existing osteoderms do not indicate to a live-suturing with other osteoderms or with neural arches of the vertebrae and must have been interpreted as pure and separate ossification within the skin (‘osteoderms’). As such, a stiffening of the neck, as suggested by Gaffney (Gaffney, 1990) can be rejected. The skin itself is moveable against the underlying musculature due to felxible connective tissue in all living tetrapods in order to ensure neck movement in general (Werneburg, 2011). Hence, also when assuming more than two large osteoderm-rows in *P. quenstedti*, mobility must have been possible. Please note that Jaekel ((Jaekel, 1915): figures 23) only found 2 large osteoderm-rows in the Berlin specimen of *P. quenstedti* (MB 1910.45.2.) and already proposed a certain degree of retraction-like neck movement. In addition to the both large osteoderm-rows, Jaekel ((Jaekel, 1915): figures 9, 29) figured several smaller osteoderms, which most likely – as suggested by the author – were situated laterally to the large ones on the top of the neck. Gaffney ((Gaffney, 1990): figure 122) reconstructed the Berlin specimen with more than two osteoderm-rows but also mentioned that “the basis for this arrangement is not definitely known”. In actual fact, not only the arrangement but also the large number of vertebrae is highly subjective and suggestive. The *P. quenstedti* specimens were found in an almost complete preservation, including the small tarsals and carpals. If further large osteoderms on the neck would have been present in the living animals, they would have been preserved for a longer term during fossilization that many smaller bones. Nevertheless, also with a hypothetical series of more than two osteoderm-rows, the neck would have been able to laterally retract easily as we modeled for the Stuttgart specimen (SMNS 16980) herein. Gaffney (Gaffney, 1990) attached the osteoderms directly onto the vertebrae, which leaves the impression of a stiffened neck. Our reconstruction allows space between vertebrae and osteoderms, which introduces a greater radius around the neck axis – nonetheless, the larger neck radius does not impede the modelled retraction at all. It it worth mentioning that Gaffney (Gaffney, 1990) mode his life-reconstruction with oblique osteoderm positions. This suggestive modelling unintentionally points to the actual possibility that osteoderms might have been flexible against each other to fit the space restrictions between skull and carapace. When laterally retracting the neck, as *P. quenstedti* did, the osteoderms must have been aligned and rotated against each other in a cascading, millipede-like series of segments (compare to J).

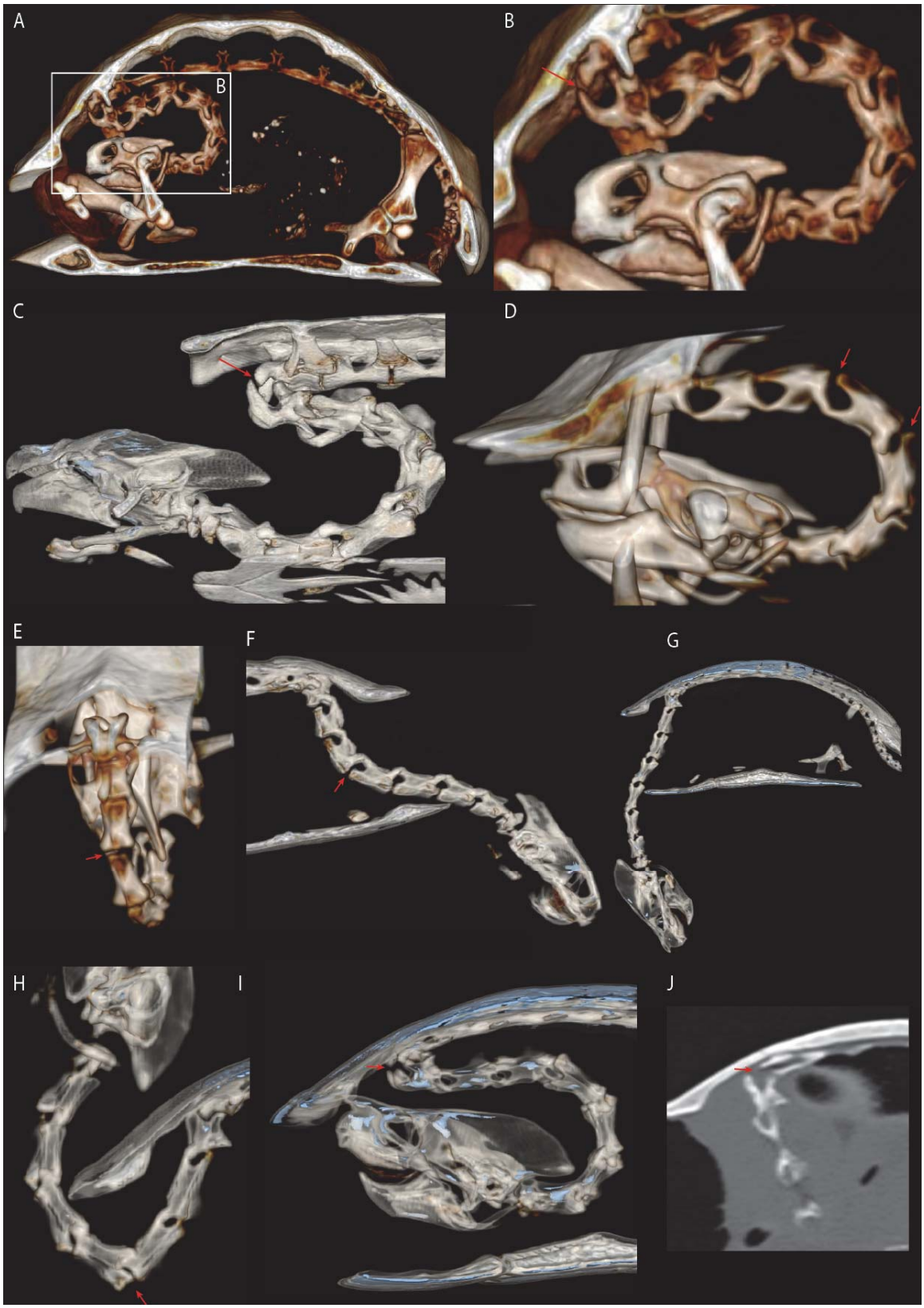

Figure S10. Illustration of neck movements and hypermobility 1/3. Cryptodira. A-B) *Astrochelys radiata* (IW1114), retraction. C) *Chelydra serpentina*, partial retraction. D-F) *Graptemys pseudogeographica* (IW1138); D) retraction; E) retraction in posterodorsal view; F) ventral flexion. G-J) *Sternotherus carinatus* (IW1145); G) ventral flexion; H) dorsal flexion, I) retraction; J) CT-section through the articulation between CV8 and DV1. Arrows indicate hyperstretching. Images in lateral view except otherwise described. Not to scale.

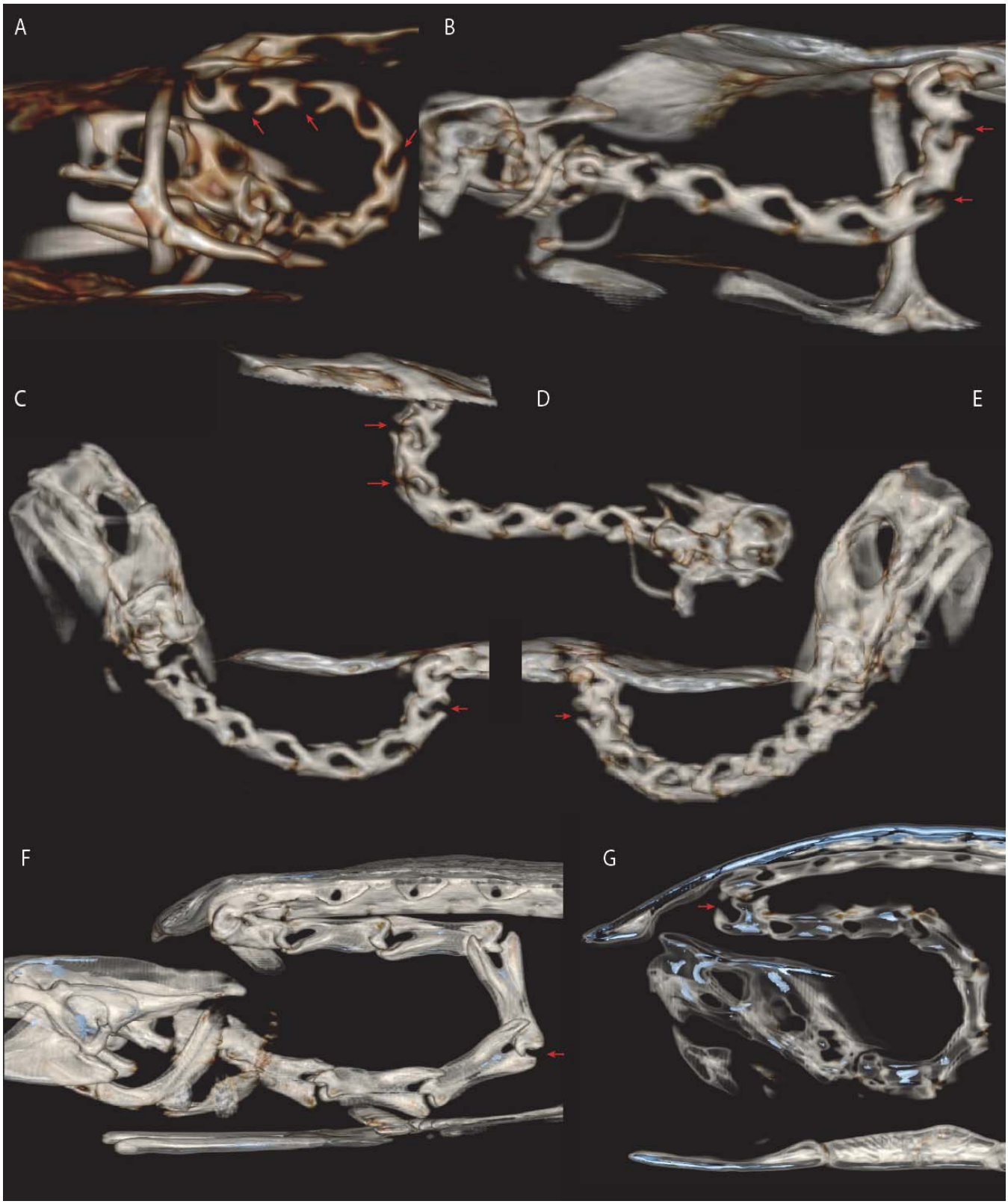

Figure S11. Illustration of neck movements and hypermobility 2/3. Cryptodira. A-E) *Malacochersus tornieri* (IW1142); A) retraction; B) lateral flexion; C) dorsal flexion; D) extended neck; E) dorsal flexion, anterolateral view. F) *Pelodiscus sinensis* (IW1163), retraction. G) *Trachemys scripta* (IW1131), retraction. Arrows indicate hyperstretching. Images in lateral view except otherwise described. Not to scale.

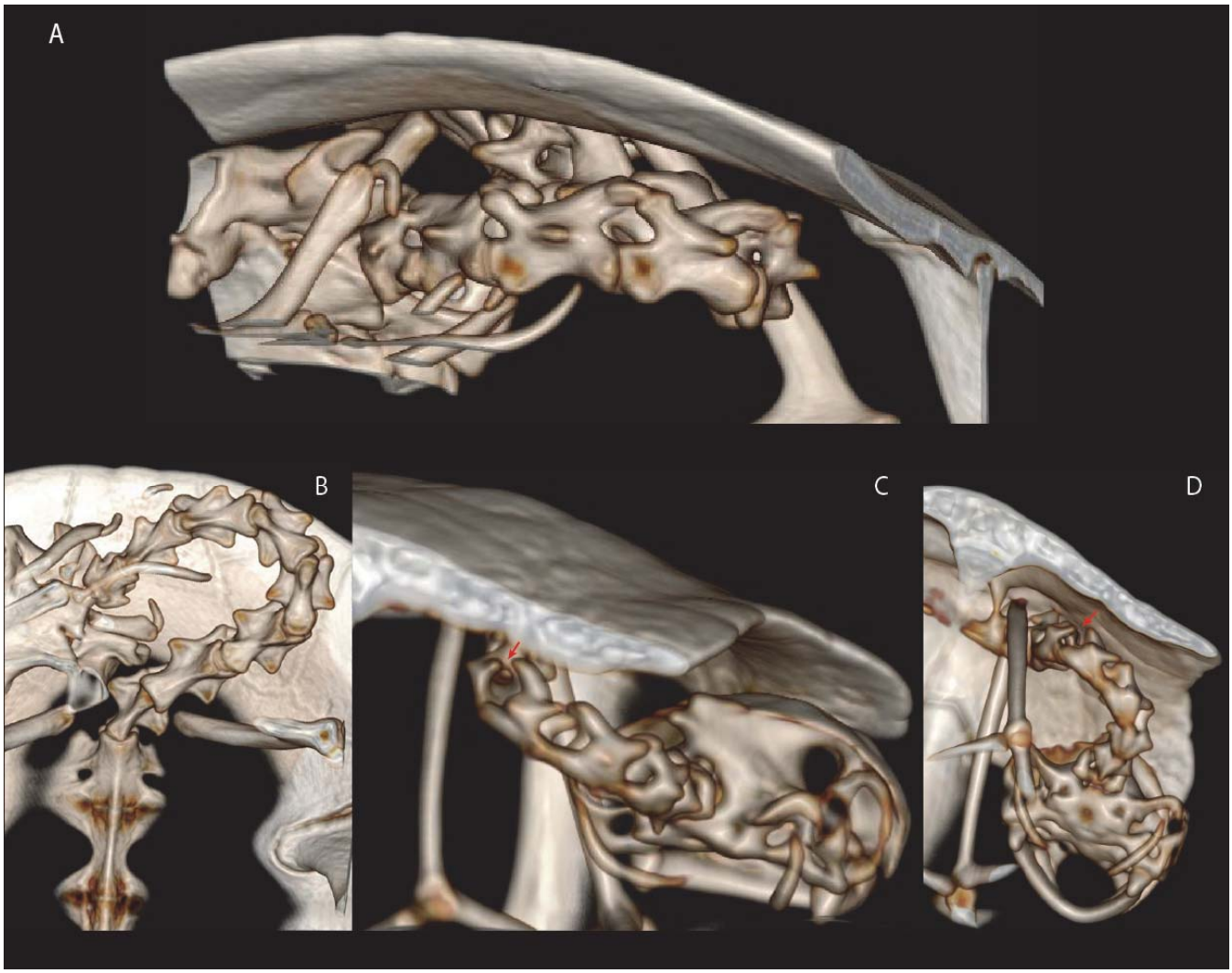

Figure S12. Illustration of neck movements and hypermobility 3/3. Pleurodira. A-B) *Phrynops hilarii* (IW1140), retraction; A) posterolateral view; B) ventral view. C-D) *Podocnemis unifilis* (IW1141), retraction(Gaffney, 1990); C) anterolateral view, D) ventrolateral view. Arrows indicate hyperstretching. Images in lateral view except otherwise described. Not to scale.

Supplementary Tables

Table S1. Fossil and macerated bones used in this study. CV1 to CV8 = cervical vertebrae 1 to 8. Collections: AMNH = American Museum of Natural History, New York, USA; FMNH = Field Museum of Natural History, Chicago, USA; SGP = Sino-German Project, Specimens currently housed at the University of Tübingen, Germany; SMF = Senckenberg Forschungsinstitut und Naturmuseum Frankfurt, Frankfurt am Main, Germany. B1 = maximum distance between the transverse processes. B2 = maximum distance between the anterior zygapophyses. B3 = maximum distance between the posterior zygapophyses. H1 = height. ID = index number of IW. M = measurements. L1 = maximum length between zygapophyses. L2 = length of centrum. X = vertebrae not present. ? = distance not measurable. For measurements compare to Fig. 2.

ID	species	collection number	M	CV1	CV2	CV3	CV4	CV5	CV6	CV7	CV8
		Fossil turtles									
IW921A	*† Proganochelys quenstedti*	ANMH uncat (= cast of SMNS 16980)	L1	?	28.4	25.5	15.4	22.3	28.2	36.5	38.1
			L2	13.8	19.4	19.9	17.8	18.6	18.3	21.7	23
			H1	?	38.1	38.8	33.4	38.9	41.8	42.4	55.3
			B1	?	19.4	24.1	29	32.1	29.4	37.8	25.7
			B2	?	?	20.9	17.2	31.7	23.1	23.1	18
			B3	?	16	19.9	?	?	13.3	17.4	10.6
IW922	*† Chisternon undatum*	ANMH 5904	L1	X	32.7	33.5	22?	34.4	35.6	38?	41.9
			L2	X	22.9	24.8	21.8	24.2	28.8	30.7	29.2
			H1	X	26	29.1	33?	33.6	31.5	36.3	43.5
			B1	X	27	35	40	34	31.5	34.4	34.2
			B2	X	?	21.8	?	19.3	27.2	?	19.1
			B3	X	21.2	22	?	23.5	21.8	19.9	15.4
IW923	*† Meiolania platyceps*	ANMH 19433 (AMNH)	L1	X	X	X	X	X	X	31.3	X
			L2	X	X	X	X	X	X	28.5	X
			H1	X	X	X	X	X	X	53.1	X
			B1	X	X	X	X	X	X	43	X
			B2	X	X	X	X	X	X	23.5	X
			B3	X	X	X	X	X	X	21.1	X
IW924A	*† Meiolania platyceps*	AMNH 57984. Cast of Australian Museum (Late Pleistocene. Lord Howe Island. New South Wales. Australia. *Meiolania platyceps*)	L1	36	39.6	48	38.6	44.2	47.2	46.7	58.7
			L2	38.7	38	42.5	48.4	43.5	47.3	51.3	52.5
			H1	47.6	50.3	60.9	60.4	61.2	71	80.7	63.9
			B1	69.5	58.8	66.6	62.6	63.5	64.3	60.5	46.8
			B2	?	24.3	34.9	31.4	31.4	29.1	26.5	22.8
			B3	33.8	28.2	23.3	28.1	26.7	22.3	18.3	?
IW931	*† Naomichelys speciosa*	FNMH PR273	L1	29.9	35.4	32	30.7	33.8	38.2	42.3	44.6
			L2	14.3	27.5	25.1	24	25.1	30.3	31.6	25.4
			H1	26.3	34.2	35	35.2	36.7	37	49.1	55.9
			B1	10.2	21.4	32.1	36.4	33	34.5	35.8	32.4
			B2	13.7	?	?	24.3	23.9	26.3	24.7	24
			B3	17.2	24.8	19.4	23.1	24.3	20.8	23.2	22.3
IW1166	*† Xinjiangchelys chowi*	SPG 2000/5– five neck and the first dorsal vertebrae (A articulates with B. C articulates with D. E articulates with F=1st dorsal vertebrae)		A:	B:	C:	D:	E:			
			L1	40	41.7	39.3	45.6	?			
			L2	32	32.5	33.6	34.7	28.1			
			H1	16.7	19.2	15.8	20.7	?			
			B1	17.8	11.8	21	22.5	17.3			
			B2	16	7.3	17.2	17.5	14			
			B3	16.2	18.1	9.3	19	?			
		Pleurodira									
IW932	*Podocnemis unifilis*	SMF55470	L1	X	18.9	24.1	22.4	21.9	23.7	25.1	23.9
			L2	X	17.9	19.5	18.5	20.7	23	23.8	17.8
			H1	X	16.5	13.6	16.6	14.4	15.1	19	23.2
			B1	X	18.1	19.2	20.6	21.3	22	22.1	20.3
			B2	X	6.7	10	9.8	10.6	10.8	11.7	12.1
			B3	X	9.6	9.3	9.5	9.8	10.7	11.1	9.8
IW935	*Phrynops geoffroanus*	SMF45470	L1	12.4	25.2	26.2	23.8	21.2	25.7	30.7	22
			L2	10	20.8	22.7	20.8	21.1	27.7	24.7	20
			H1	11.9	16.1	15.8	15.5	16.6	16.6	19.7	23.3
			B1	7.9	14.5	15.4	16.8	17.4	17.6	18.2	19
			B2	7.9	6	11.1	12.2	12.6	12.5	12.1	11.8
			B3	9.7	9.2	10	10	9.9	9.8	9.2	5.3
IW1040	*Hydromedusa tectifera*	SMF 70500	L1	13.7	16.7	18.9	16.9	18.2	18.5	21.1	17.1
			L2	11.5	16.7	17	17.2	16.1	15.6	16.6	17.2
			H1	7.4	9	8.7	8.8	9.8	10.3	10.9	10.7
			B1	7.4	7.6	7.9	9.5	8.2	9.8	9.4	11
			B2	5.9	6.1	6.1	6.7	6.4	6.7	7.3	6.7
			B3	5.7	6.3	5.8	6.4	6	6.5	5.8	3.3
IW1048	*Erymnochelys madagascariensis*	SMF7979	L1	12.2	16.6	20.8	20.7	21.2	22.5	23.5	23.3
			L2	10.3	16.6	17.4	17	18.4	20.6	17.9	15.9
			H1	14	17.1	15.9	14.8	16.7	19.5	22.9	25.1
			B1	18	22.2	24.1	26	26.5	22.5	24.2	22
			B2	6.3	?	9.7	10.7	12.3	12.7	10.5	12.2
			B3	7.8	8.8	9.5	10.7	10.3	9.7	11.2	9.7
		Cryptodira									
IW919	*Carettochelys insculpta*	SMF56626	L1	20.6	28.5	32.7	33.9	34.5	31.5	31	30.4
			L2	18.3	29.3	30.2	33	37	34.2	31.3	19.9
			H	22.3	22.6	20.2	21.6	19.5	18.7	17.9	13.6
			B1	8	19	23.83	24.1	29.9	22.6	20.4	24.3
			B2	?	17.5	25	26.3	27.6	27.5	22.1	26.5
			B3	27.2	23.2	23.2	26.3	26.9	22.6	26	27.3
IW920	*Platysternon megacephalum*	SMF69484	L1	8.9	15.2	16.7	16.3	14.4	15	14.8	13.8
			L2	8.7	13	15.8	17.4	14.5	13.9	11.6	9.1
			H	12	11.8	11.3	11.6	11.9	12.9	12	11.1
			B1	6.7	13.6	14.9	15.7	15.7	15.3	11.4	13.4

			B2	9	7.9	10.7	10.7	12.1	13.4	12.1	14
			B3	9.5	10.1	9.8	11.5	12.6	11.9	13.5	14.6
IW933	*Chelydra serpentina*	SMF32846	L1	17.6	27.6	37.3	38.2	37.7	33.8	35	35.3
			L2	15.8	26.2	38	38.5	34.8	34.3	32.5	22.7
			H	18	19.3	18.3	19.6	13.1	25.1	26.7	22.1
			B1	10.9	13.4	19.2	19	15.4	22.4	19.9	23.7
			B2	9.3	12.9	18.8	18.7	18.5	18.7	19.4	19.8
			B3	13.1	16.6	16.8	16.8	17.5	18.3	18.6	22.2
IW937	*Emys orbicularis*	SMF68814	L1	7.1	9.7	12.8	13.9	12.7	11.6	13.4	11.6
			L2	6.7	8.9	11.1	13.7	12.2	12	9.6	7.1
			H	8.1	7.6	7.9	9.4	7.5	7.4	8.7	8.6
			B1	3.1	9	9.6	10	10.1	9.3	8.4	9.8
			B2	5	6.6	9.5	9.7	8.9	8.7	7.6	9.6
			B3	4	9.4	9.3	8.3	7.8	7.1	9.1	9.8
IW936	*Kinosternon scorpioides*	SMF71893	L1	X	8.9	11.3	9.8	11.8	10.6	11.6	10.5
			L2	X	8.5	11.3	10.9	11.1	11.7	11.7	6.2
			H	X	5.8	5.9	5.4	6.3	6.6	7.5	6.8
			B1	X	6.7	6.3	7	7.3	8.1	6.6	8.7
			B2	X	5.2	7.2	6.5	7	7.9	6.8	7.6
			B3	X	6.5	6.3	6.5	7.4	5.7	6.7	7.3
IW939	*Cuora (“Cyclemys“) mouhotii GRAY*	SMF71599	L1	6.5	11.3	13.9	14.1	15	15	X	X
			L2	7	10.2	12.2	15.2	14.8	14.8	X	X
			H	8.4	7.8	8.4	8.3	9.1	9.1	X	X
			B1	4.9	7.3	8.3	8.4	9.1	9.3	X	X
			B2	4.5	6.2	7.4	8.1	7.9	8.5	X	X
			B3	8.5	6.7	7.5	7.4	7.7	6.9	X	X
IW934	*Melaclemys ("centrata“) terrapin*	SMF36419	L1	9.2	15	17.8	17.4	15.2	15	15.4	12.9
			L2	6.4	13.4	16	17.6	15.7	15.2	11.3	7.8
			H	8.7	9	10.3	10	11	10.5	11.5	9.7
			B1	6	10	9.8	14.4	9.9	9.3	9.5	11.1
			B2	5.4	6.2?	10.5	9.6	9.2	10.3	8.8	10.6
			B3	9.1	9.3	8.8	8.7	9.4	7.9	10.1	10.3
IW1033	*Pyxis (“Acinixys“) planicauda Grand.*	SMF7722	L1	7.4	X	14.8	18	17.7	15.5	14.7	13.9
			L2	?	X	13.5	14.4	15.3	15.6	13.5	9.5
			H	11.1	X	8.7	9.4	9.8	10.2	11.2	11.3
			B1	?	X	9	9.7	9.9	9.3	8.7	12.7
			B2	6.6	X	8.6	8.7	9.3	10.1	10.6	11.5
			B3	6.6	X	8	8.7	9.9	10.3	11.5	11.8
IW1034	*Indotestudo (“Testudo”) elongata*	SMF71585	L1	X	13.3	19.4	20.6	22.7	20	19.1	20.2
			L2	X	10.8	16.9	23.5	22	21.8	20.2	15.5
			H	X	14.6	11.6	13.2	12.3	14.7	14.8	16.9
			B1	X	9.9	11.6	13.1	13.7	14.1	13.5	17.7
			B2	X	9.3	12.2	12.2	12.4	12.6	14.2	14.1
			B3	X	10.9	10.6	10.4	11	12.4	12	16.8
IW1035	*Dermatemys mawii GRAY*	SMF59463	L1	7.5	22.3	30.4	31.3	27.1	25.9	30.7	27.3
			L2	?	23	24.3	27.1	27.1	28.9	26.8	18
			H	12.4	13.3	13.9	13.9	15.4	18.2	21.2	21.8
			B1	?	8.3	11.3	12.4	12.4	14.2	15.7	18.9
			B2	7.7	8.3	14	13	13.7	14.5	12.9	15.9
			B3	10.5	13	12	12.9	13	10.8	13.7	20
IW1043	*Testudo graeca*	SMF 67588	L1	X	12.4	15.6	16.5	16	15.2	15.3	19
			L2	X	9.4	14.4	18	15.9	14.5	13.1	11.5
			H	X	10.9	11.2	9.4	10.1	10.8	11.9	13
			B1	X	9.5	9.8	10.3	10.7	11.5	11.6	12.4
			B2	X	7.1	9.2	9.5	9.7	6.9	9.4	11
			B3	X	7.9	8.8	7.3	5.9	9.5	8.8	10.5
IW1044	*Kinixys erosa*	SMF40166	L1	9.3	15.4	18.5	20.9	21.3	19.8	X	17.9
			L2	8.7	13.1	20.7	20.8	21	20.1	X	15.5
			H	9.9	10.5	8.9	9	9.9	10.6	X	10.7
			B1	5.6	10	10.2	10.1	10.6	10.2	X	10.4
			B2	6.8	7.6	8.1	8.7	8.7	9	X	10.1
			B3	8.9	9.9	10.6	7.9	8.5	9.6	X	13.2
IW1045	*Testudo hermanni*	SMF71882	L1	X	8.5	10.6	11.3	11.4	11.2	12.6	12.3
			L2	X	8	9.9	11.9	10.8	10.8	9	6.7
			H	X	7.9	7.6	7.6	8.3	8.3	8.7	9.1
			B1	X	6	6.9	7.6	6.8	7.6	7.2	8.4
			B2	X	5.7	6.8	6.9	7.1	7.1	8.1	9
			B3	X	6.2	5.8	6.1	6.2	7.5	8.3	9.6
IW1113	*Macrochelys temminckii*	Teaching collection of Geowissenschaftliches Institut Tübingen	L1	X	28.7	35.2	35.9	36.3	36.6	38.9	39.7
			L2	X	32	37.2	36.7	38.2	36.7	33.6	22.5
			H	X	26.1	25.8	2.2	28.1	40.3	34.7	30.8
			B1	X	22.3	26.8	28.2	27.9	30.5	31.2	28.2
			B2	X	15.7	24.6	26.1	28.4	27.9	20	25.8
			B3	X	23.3	25.4	26.6	25.6	17.6	23.8	28.2

Table S2. Living specimens used for radiography and/or computed tomography (CT) scans. For specimens used for CT, weight was measured to calculate dosages of the anaesthetic. Euthanized specimens (*) were provided by the veterinary program of the University of Veterinary Medicine, Vienna and died of causes not related to this project.

ID	species	origin / literature reference	weight
	Pleurodira		
IW1121	*Phrynops hilarii*	Tiergarten Schönbrunn	X
IW1140	*Phrynops hilarii*	Tiergarten Schönbrunn	3.15kg
IW1141	*Podocnemis unifilis*	Pet trade.	0.35kg
	Cryptodira		
IW1114	*Astrochelys radiata*	Tiergarten Schönbrunn	X
IW1133	*Astrochelys radiata*	Tiergarten Schönbrunn	2.42kg
IW1115	*Chelydra serpentina*	Tiergarten Schönbrunn	5.22kg
IW1116	*Emys orbicularis*	Joseph Weisgram lab. Vienna / Austria	X
IW1135	*Emys orbicularis*	Tiergarten Schönbrunn	0.89kg
IW1137	*Graptemys pseudogeographica*	Tiergarten Schönbrunn	0.41kg
IW1138	*Graptemys pseudogeographica*	Tiergarten Schönbrunn	0.55kg
IW1117	*Heosemys grandis*	Tiergarten Schönbrunn	X
IW1118	*Heosemys grandis*	Tiergarten Schönbrunn	X
IW1139	*Heosemys grandis*	Tiergarten Schönbrunn	3.39kg
IW1119	*Malacochersus tornieri*	Tiergarten Schönbrunn	X
IW1142	*Malacochersus tornieri*	Tiergarten Schönbrunn	0.2kg
IW1120	*Pelodiscus sinensis*	private breeding by IW	X
IW1163	*Pelodiscus sinensis*	Michaela Gumpenberger Scan	X
IW1122	*Testudo graeca*	Tiergarten Schönbrunn	X
IW1123	*Testudo graeca*	Joseph Weisgram lab. Vienna / Austria	X
IW1124	*Testudo graeca*	Joseph Weisgram lab. Vienna / Austria	X
IW1143	*Testudo graeca*	Tiergarten Schönbrunn	0.18g
IW1130	*Testudo hermanni**	Patient of Michaela Gumpenberger. Vienna	X
IW1023	*Testudo hermanni*	Joseph Weisgram lab. Vienna / Austria	X
IW1024	*Testudo hermanni*	Joseph Weisgram lab. Vienna / Austria	X
IW1144	*Testudo hermanni*	Tiergarten Schönbrunn	0.14kg
IW1131	*Trachemys scripta elegans**	Michaela Gumpenberger Scan	X
IW1145	*Sternotherus carinatus*	private pet specimen of Ingmar Werneburg	0.26kg
	Outgroup taxa		
IW1134	*Pogona vitticeps*	Tiergarten Schönbrunn	0.29kg
IW1136	*Rhacodactylus ciliatus*	Tiergarten Schönbrunn	0.03kg

Table S3. Literature references used for angle measurement.

ID	taxon	origin / literature reference
	Stem Testudines	
IW924B	*† Meiolania platyceps*	AMNH No. 57984 ((Gaffney, 1985): figure 4)
IW921B	*† Proganochelys quenstedti*	SMNS 16980 (reconstruction by (Gaffney, 1990))
PQ	*† Proganochelys quenstedti*	MB 1910.45.2 (reconstruction by (Gaffney, 1990))
	Pleurodira	
CL	*Chelodina longicollis*	Herrel et al. ((Herrel et al., 2008): figure 7.21)
CN (IW1168)	*Chelodina novaeguineae*	6 specimens from (Weisgram and Splechtna, 1992)
PS (IW1167)	*Pelomedusa subrufa*	Original X-Rays of 8 specimens from (Weisgram and Splechtna, 1990)
	Cryptodira	
AS	*Apalone spinifera*	Herrel et al. ((Herrel, Van Damme and Aerts, 2008): figure 7.17)
CP	*Chrysemys picta belli*	Scanlon ((Scanlon, 1982): figure 5.1)
KS	*Kinosternon subrubrum*	Bramble et al. ((Bramble et al., 1984): figure 9). X-Ray?
TC	*Terrapene carolina*	(Landberg et al., 2003) (macerated + arranged)
TH	*Testudo hermanni hermanni*	Literature data of (Weisgram and Splechtna, 1990) – (10 individuals)
TR	Trionychidae indet.	(Dalrymple, 1979) (figure 1)
TS1	*Trachemys scripta*	(Callister et al., 1992)
TS2	*Trachemys scripta*	(Callister et al., 2005)

Table S4. Measurements of the amount of mobility in fossil and macerated bones. CV = cervical vertebrae. For specimen ID compare to Table S1-3. For the permissible amount of mobility compare with Fig. 2A-D.

A) neutral position (facets of zygapophyses of adjacent vertebrae fully overlap)								
ID	Species	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8
919	*Carettochelys insculpta*	+2.9	+6.3	+14	+25	+35.2	+28.4	+14.5
CP	*Chrysemys picta* (figure 1A)	-14.8	+10.4	+7.3	+11.1	+47.5	+15.9	-12.7
920	*Platysternon megacephalum*	-0.3	+9.1	+15.6	+36.6	+27.5	+30.2	-5.8
921A	*† Proganochelys quenstedti*	?	-0.2	+10.5	-1.6	-0.2	-6.9	+18
921B	*† Proganochelys quenstedti*	-3.9	-5.2	+4.7	+7.6	-7.3	0	+3.5
PQ-B	*† Proganochelys quenstedti*	+1.6	+2.5	+3.3	+10	+0.3	-0.1	0
922	*† Chisternon undatum*	X	-16.6	+6.6	+14.6	+4.1	+5.8	-7
924A	*† Meiolania platyceps*	+5.1	-1	+7.3	+2.4	-1.2	-5.2	-5.6
931	*† Naomichelys speciosa*	+1.1	+2.9	+4.5	-10.2	+11	-8.3	+3.2
932	*Podocnemis unifilis*	X	+6	-0.7	+12.5	+10.9	+7.6	-8.2
933	*Chelydra serpentina*	-8.5	-2.9	+14.3	+13.9	+28.6	+5.8	-5
934	*Melaclemys terrapin*	-8.7	+3.5	+12.6	+36.6	+48.6	-2.3	-16.6
935	*Phrynops geoffroanus*	+12	-3.1	+2	+12.4	+.2.2	-3.9	-11.6
936	*Kinosternon scorpioides*	x	+22.3	+12.9	+22.3	+51.9	+25.5	+25.6
937	*Emys orbicularis*	+21	-1.3	+23.8	+36.5	+36.8	+16.8	-21.5
939	*Cuora mouhotii*	X	+13.3	+15.7	+31.7	+45.9	X	X
1033	*Acinixys planicauda*	X	X	+6.4	+14.1	+35.6	+41.7	+8.7
1034	*Testudo elongata*	+2	+17.3	+2.5	+19	+29.4	+48.3	+22.6
1035	*Dermatemys mawii*	X	-5.9	+9.8	+11	+46.8	+11.4	+2.1
1040	*Hydromedusa tectifera*	+15.7	+4.2	+8.2	+15.3	+18.3	+12.1	+13.3
1043	*Testudo graeca*	+10.6	+2.4	+35.8	+30.7	+31.1	+30.7	+3.3
1044	*Kinixys erosa*	-6.5	+11.3	+17.1	+21.8	+47.7		
1045	*Testudo hermanni*	X	+3.3	+1.7	+30.4	+34	+11.3	-29.9
1048	*Erymnochelys madagascariensis*	?	+14.1	+4.1	+15	+26.4	-21.5	+8.7
1113	*Macrochelys temminckii*	X	-6.1	+12.8	+17.3	+30.7	+19.2	-12.5
TC	*Terrapene carolina* (figure: 1C)	-6.1	+7	+2.2	+32.7	+27.6	+15.3	+9.9
TS1	*Trachemys scripta* (figure 1A)	-10.1	0	+13.9	+20.3	+33.1	+26.1	+2.5
IW1166	*† Xinjiangchelys chowi*	A/B: -5.2			C/D: +13			
B) maximal dorsal flexion								
ID	species	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8
919	*Carettochelys insculpta*	+20.5	+51.5	+54.1	+56.4	+60.1	+46	+21.5
920	*Platysternon megacephalum*	+9.1	+59.1	+35.7	+39.3	+78.9	+24	+26.9
921A	*† Proganochelys quenstedti*	?	+7.9	+10.7	+7.2	+14.7	-4.7	+22.3
922	*† Chisternon undatum*	X	-4.3	+27.4	+45	+12.6	+18.6	+3.1
924A	*† Meiolania platyceps*	+5.9	+4.3	+12.5	+11.2	+14.1	+5.1	+5.1
931	*† Naomichelys speciosa*	+35	+19.5	+15	+4.8	+25.4	+6.7	-2.5
932	*Podocnemis unifilis*	X	+27	+25.2	+40.4	+30.9	+23.9	+9
933	*Chelydra serpentina*	+10.9	+51.7	+55.3	+45.9	+63.4	+53.4	+44.7
934	*Melaclemys terrapin*	+12.3	+64.6	+57.4	+77.2	+90	+26.9	+61.7
935	*Phrynops geoffroanus*	+14.8	+27.4	+31	+33.6	+16	+9	+15.4
936	*Kinosternon scorpioides*	x	+59.3	+49.7	+77	+107.4	+33.8	+49.4
937	*Emys orbicularis*	+23.1	+54	+58.4	+62.7	+82.6	+50.3	+13.6
939	*Cuora mouhotii*	X	+48	+53.9	+71.6	+84.7	X	X
1033	*Acinixys planicauda*	X	X	+49.1	+47.8	+74.1	+76.1	+47.7
1034	*Testudo elongata*	+4	+29.1	+58.1	+41.1	+59.4	+87.9	+45.9
1035	*Dermatemys mawii*	X	+44.9	+43.3	+59.4	+100.1	+46.6	+36.7
1040	*Hydromedusa tectifera*	+26.4	+37.1	+35.1	+34	+24.3	+26.5	+25.6
1043	*Testudo graeca*	x	+53.5	+53.6	+67.2	+67.9	+70.9	+27.6
1044	*Kinixys erosa*	+3.8	+57.2	+61.9	+68.1	+84.5	x	x
1045	*Testudo hermanni*	X	+56.6	+63.9	+67.5	+80.5	+46.5	+36
1048	*Erymnochelys madagascariensis*	?	?	?	?	?	+2.5	?
1113	*Macrochelys temminckii*	x	+33.2	+42.3	+51.3	+60.7	+46.7	+36
IW1166	*† Xinjiangchelys chowi*	A/B: +18.6			C/D: +46.8			
C) maximal ventral flexion								
ID	species	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8
919	*Carettochelys insculpta*	-36.8	-44.3	-20.2	-11.6	+6.2	-19.1	-21.6
920	*Platysternon megacephalum*	-25.4	-26.8	-26.3	-4.2	-6.3	-23.2	-56.4
921A	*† Proganochelys quenstedti*	?	-16.8	-9.9	-22	-14.3	-37.3	-15.1
922	*† Chisternon undatum*	X	-49.4	-17.8	?	-20.4	?	-26.2
924A	*† Meiolania platyceps*	-28.3	-14.8	-7.6	-12	-15.9	-10.4	-11.8
931	*† Naomichelys speciosa*	-15.3	-14.1	-18	-23	-7.8	-31.7	-41.1
932	*Podocnemis unifilis*	X	-25.4	-23.3	-12.4	-23.1	-17.8	-29
933	*Chelydra serpentina*	-10.2	-33.9	-19	-19.5	+6.9	-22.8	-48.3
934	*Melaclemys terrapin*	-79.5	-26.8	-23.9	+2	-0.8	-31.4	-48.8
935	*Phrynops geoffroanus*	-24.4	-35	-31.6	-17.2	-13.3	-21.8	-36.4
936	*Kinosternon scorpioides*	x	-9.4	-10.7	-20.4	+3.9	-5.9	-12.4
937	*Emys orbicularis*	-25.2	-32.4	-27.2	+26.4	+7	-20.8	-49.3
939	*Cuora mouhotii*	X	-17.9	-17.2	+2.3	+11.7	X	X
1033	*Acinixys planicauda*	X	X	-56.3	-39.9	-12.5	-11.5	-44.9
1034	*Testudo elongata*	-71.2	-36.7	-29	-21.2	-2.2	+17.1	-23.5
1035	*Dermatemys mawii*	X	-34.2	-27.8	-18.3	+21.1	-29.1	-45.5
1040	*Hydromedusa tectifera*	-27.1	-28.8	-20.8	-22.1	-11.6	-32.6	-13.6
1043	*Testudo graeca*	x	-29.4	-20.3	-13.9	-6.2	-6.9	-50.4
1044	*Kinixys erosa*	-42.3	-22.3	-18.2	-18	+4.1	x	x
1045	*Testudo hermanni*	X	-29.7	-32.9	0	0	-20.7	-43.5
1048	*Erymnochelys madagascariensis*	?	?	?	?	?	-42.5	?
1113	*Macrochelys temminckii*	x	-27	-22.9	-8.2	+6.3	-13.1	-35.1
IW1166	*† Xinjiangchelys chowi*	A/B: -46.9			C/D: -28.8			
D) maximal lateral flexion								
ID	species	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8
919	*Carettochelys insculpta*	15.7	28.3	26.6	25	19.1	24.5	19.1
920	*Platysternon megacephalum*	23.9	35.3	35.7	31.3	33.6	17	11.2
921A	*† Proganochelys quenstedti*	?	54.5	32.5	38.1	38.5	35.4	48.9
922	*† Chisternon undatum*	X	43.5	?	?	46.9	?	54.4
924A	*† Meiolania platyceps*	30.6	21	38.2	31	29	47.1	42.2
931	*† Naomichelys speciosa*	20	13.2	37.2	55	35.4	45.8	42.4
932	*Podocnemis unifilis*	X	53.8	55.9	65.2	60.6	71	68.1

933	*Chelydra serpentina*	40	28.5	24.6	31.3	39.8	26.6	43.7
934	*Melaclemys terrapin*	41.2	40.7	19	46.9	24.9	30	25.7
935	*Phrynops geoffroanus*	57	38	63.9	60.6	50.9	46.4	61.5
936	*Kinosternon scorpioides*	X	18.6	18.9	17.7	25.9	14.7	28.4
937	*Emys orbicularis*	6.7	40.3	38.1	32.6	26.8	33.7	34.3
939	*Cuora mouhotii*	X	35.3	21.8	46.6	27.4	X	X
1033	*Acinixys planicauda*	X	X	X	37	37.7	22.9	23.9
1034	*Testudo elongata*	22.4	27.9	33.5	37.2	25.9	21.6	27.2
1035	*Dermatemys mawii*	X	48.6	41.6	41.2	46.1	27.5	26.1
1040	*Hydromedusa tectifera*	29.2	48.6	85	42.3	65.5	57.1	35.7
1043	*Testudo graeca*	X	36.5	43.5	40.3	24	13.1	20.4
1044	*Kinixys erosa*	27.7	37	32.5	42.2	28.7	X	x
1045	*Testudo hermanni*	X	39.7	39.9	41.4	38.9	38.8	21.5
1048	*Erymnochelys madagascariensis*	?	?	?	?	?	41.7	?
1113	*Macrochelys temminckii*	X	33.4	37.1	35.3	34.9	36	35.2
IW1166	*† Xinjiangchelys chowi*	A/B: 66.8				C/D: 27.3		
		E) maximal dorsoventral flexion of the neck (dorsal + ventral) in lateral view						
ID	species	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8
919	*Carettochelys insculpta*	57.30	95.80	74.30	68.00	53.90	65.10	43.10
920	*Platysternon megacephalum*	34.50	85.90	62.00	43.50	85.20	47.20	83.30
921A	*† Proganochelys quenstedti*	-	24.70	20.60	29.20	29.00	32.60	37.40
922	*† Chisternon undatum*	-	45.10	45.20	-	33.00	-	29.30
924A	*† Meiolania platyceps*	34.20	19.10	20.10	23.20	30.00	15.50	16.90
931	*† Naomichelys speciosa*	50.30	33.60	33.00	27.80	33.20	38.40	38.60
932	*Podocnemis unifilis*	-	52.40	48.50	52.80	54.00	41.70	38.00
933	*Chelydra serpentina*	21.10	85.60	74.30	65.40	56.50	76.20	93.00
934	*Melaclemys terrapin*	91.80	91.40	81.30	75.20	90.80	58.30	110.50
935	*Phrynops geoffroanus*	39.20	62.40	62.60	50.80	29.30	30.80	51.80
936	*Kinosternon scorpioides*	-	68.70	60.40	97.40	103.50	39.70	61.80
937	*Emys orbicularis*	48.30	86.40	85.60	36.30	75.60	71.10	62.90
939	*Cuora mouhotii*	-	65.90	71.10	69.30	73.00	-	-
1033	*Acinixys planicauda*	-	-	105.40	87.70	86.60	87.60	92.60
1034	*Testudo elongata*	75.20	65.80	87.10	62.30	61.60	70.80	69.40
1035	*Dermatemys mawii*	-	79.10	71.10	77.70	79.00	75.70	82.20
1040	*Hydromedusa tectifera*	53.50	65.90	55.90	56.10	35.90	59.10	39.20
1043	*Testudo graeca*	-	82.90	73.90	81.10	74.10	77.80	78.00
1044	*Kinixys erosa*	46.10	79.50	80.10	86.10	80.40	-	-
1045	*Testudo hermanni*	-	86.30	96.80	67.50	80.50	67.20	79.50
1048	*Erymnochelys madagascariensis*	-	-	-	-	-	45.00	-
1113	*Macrochelys temminckii*	-	60.20	65.20	59.50	54.40	59.80	71.10
IW1166	*† Xinjiangchelys chowi*	A/B: 65.5				C/D: 75.6		

Table S5. Angle measurements between the zygapophyses. A = anterior face. P = posterior face. *= estimated measurement for off broken zygapophyses. Compare to Fig. 2E.

ID	species	CV1A	CV1P	CV2A	CV 2P	CV 3A	CV 3P	CV 4A	CV 4P	CV 5A	CV 5P	CV 6A	CV 6P	CV 7A	CV 7P	CV8A	CV 8P
919	*Carettochelys insculpta*	153.4	149.6	130.6	99.6	109.8	96	103.7	102.3	112	111.9	130	93.5	98.9	93.8	101.7	119.7
920	*Platysternon megacephalum*	?	136.5	123.4	76.8	80.3	71.4	77.5	83.4	85	133.6	103.6	96.5	129.6	111.2	108.4	153.1
921B	*† Proganochelys quenstedti*	55.4	56.5	88.5	44.1	50.5	46.6	50.6	46.2	46.7	39.9	51.8	40.7	44.6	37.7	32.9	37.9
PQ	*† Proganochelys quenstedti*	?	72.8	94.6	57.5	73.1	52.5	60.5	50.2	68.3	55.7	64.1	45.1	48.5	49	62.2	49.5
922	*† Chisternon undatum*	X	X	?	72.3	72.7	68	?	?	65.3	62.9	69.5	60.4	?	54.8	53.9	?
923	*† Meiolania platyceps*	X	X	X	X	X	X	X	X	X	X	X	X	51.9	40.3	X	X
924A	*† Meiolania platyceps*	?	70.3	37	44.2	58.4	38.3	43.4	37.2	44.6	39.6	41.4	32.4	34.2	25.2	31.2	?
931	*† Naomichelys speciosa*	115.3	130.9	93.9	57.1	81.2	46	67.3	82.6*	59.6	66.3	66	52	70	51.4	55.3	56.2
932	*Podocnemis unifilis*	X	X	67.9	57.5	63.4	51.5	60.1	52.6	61.7	56.3	60.6	53.4	57.2	50.5	57.1	40.4
933	*Chelydra serpentina*	113.9	85	144.1	77.5	91.8	74.7	78.5	78.3	77.3	81	73.9	86.6	87.7	73.7	77.9	116.8
934	*Melaclemys terrapin*	114.4	167	91	74.2	99.9	73.1	78.9	69.7	66.6	88.4	86.4	68.6	76.3	95.7	89.3	125.9
935	*Phrynops geoffroanus*	53.8	64.6	51.2	45.9	54.5	49.7	56.8	46.8	50.3	46.4	58.7	49.6	55.5	42.7	46.9	25.4
936	*Kinosternon scorpioides*	x	x	122.4	92.9	104.3	87.7	108.6	85	91.9	96.2	105.8	70.1	75	80.2	89.5	134.9
937	*Emys orbicularis*	?	118.7	142.5	95.8	121.6	100.5	98.1	76.1	80.4	77.5	70.6	63.7	65.1	93.1	85.5	124.1
939	*Cuora mouhotii*	?	X	X	72.8	87.2	75.6	91.2	77.5	79.2	74	77.7	79.1	X	X	X	X
1033	*Acinixys planicauda*	129.4	90.4	105.7	80.3	94.8	84.6	85.2	77.5	82.7	98.8	91.8	98.3	90.6	106.9	122.5	137.7
1034	*Testudo elongata*	?	107.8	123.1	70.9	81.7	66.8	77.1	66	67.5	64.8	65.8	65.5	86.5	72.8	79.9	106.4
1035	*Dermatemys mawii*	X	X	110.8	81.4	99.3	64.9	72.5	71.3	71.5	65.3	68.2	67.5	66.6	84	91.6	118.6
1040	*Hydromedusa tectifera*	79.1	60.8	63	46.4	53.1	47.4	51.9	52.5	61.6	51.8	59.9	51.4	67.1	40.6	54.5	31.9
1043	*Testudo graeca*	X	X	130.3	66.8	77.8	65.6	89	56.5	57.5	48.5	47.8	60.1	53.8	63.6	69.6	97
1044	*Kinixys erosa*	?	121.1	119.6	82.2	94	73.8	72.9	66.4	62.6	88.3	67.8	73.1	X	X	77.8	121.4
1045	*Testudo hermanni*	X	X	115.7	71.1	109.8	63.4	79.3	62.3	66.6	65.3	70.3	81.1	83.4	80	X	X
1048	*Erymnochelys madagascariensis*	83.9	?	?	?	?	?	?	?	?	?	?	44.6	46.7	?	?	35.9
1113	*Macrochelys temminckii*	x	x	106.6	79.1	96.7	89.1	86.3	96.9	94	110	81.7	72.5	61.5	71	72.6	106.1
1166	*Xinjiangchelys chowi*	A-A	117.1	A-P	77.6	B-A	76.2	B-P	72.3	C-P	61	D-A	93.8	D-P	68.2	E-A	51.7

Table S6 Linear regressions of the linear measurements of the vertebrae and the related angles of movement and the zygapophyseal angles. Ant = angles at the anterior facets of the vertebrae; post = angles at the posterior facets of the vertebrae; ant+post = absolute values of the angles of the anterior plus posterior facets of the vertebrae; neutral, dorsal, ventral, lateral = directions of movements (angles), zygapo = angles of the zygapophyses. Correlations larger than $R^2 = 0.5$ are highlighted. Compare to Fig. 2.

Linear regressions	L1	L2	H	B1	B2	B3	Ant-neutral	Ant-dorsal
L1								
L2	y = 0,8286x + 1,3172 R^2 = 0,8225							
H	y = 0,2082x + 32,015 R^2 = 0,0211	y = -0,7783x + 90,637 R^2 = 0,0797						
B1	y = 0,9372x - 4,0957 R^2 = 0,6297	y = 0,9953x - 2,7549 R^2 = 0,5928	y = 0,7923x + 2,8617 R^2 = 0,827					
B2	y = 0,5283x + 0,957 R^2 = 0,5493	y = 0,571x + 1,5055 R^2 = 0,5356	y = 0,3756x + 6,2352 R^2 = 0,5102	y = 0,4862x + 4,6601 R^2 = 0,6489				
B3	y = 0,5369x + 0,4121 R^2 = 0,6604	y = 0,5448x + 1,6975 R^2 = 0,5689	y = 0,3127x + 7,0582 R^2 = 0,4159	y = 0,3925x + 5,9475 R^2 = 0,5153	y = 0,7511x + 2,4657 R^2 = 0,6617			
Ant-neutral	y = -0,512x + 23,946 R^2 = 0,1128	y = -0,2576x + 17,186 R^2 = 0,0239	y = -0,3571x + 18,654 R^2 = 0,1052	y = -0,3603x + 19,343 R^2 = 0,0834	y = -0,5547x + 19,927 R^2 = 0,0639	y = -0,6704x + 20,839 R^2 = 0,0763		
Ant-dorsal	y = -0,9266x + 62,835 R^2 = 0,1561	y = -0,6011x + 53,693 R^2 = 0,0569	y = -0,8416x + 56,981 R^2 = 0,2501	y = -0,9111x + 57,498 R^2 = 0,2219	y = -1,0827x + 56,63 R^2 = 0,1032	y = -1,2451x + 57,548 R^2 = 0,112	y = 0,9662x + 29,134 R^2 = 0,3984	
Ant-ventral								
Ant-lateral								
Ant-zygapo								
Post-neutral								
Post -dorsal								
Post -ventral								
Post-lateral								
Post -zygapo								
Ant+post neutral								
Ant+post dorsal								
Ant+post ventral								
Ant+post lateral								
Ant+post zygapo								

Ant+post neutral	Post -zygapo	Post-lateral	Post -ventral	Post -dorsal	Post-neutral	Ant-zygapo	Ant-lateral	Ant-ventral
y = -0,983x + 54,827 R² = 0,1928	y = -0,6147x + 88,857 R² = 0,0588	y = 0,2082x + 32,015 R² = 0,0211	y = -0,0306x - 18,504 R² = 0,0004	y = -1,0149x + 65,974 R² = 0,172	y = 0,1204x + 33,053 R² = 0,0085	y = -0,6468x + 94,427 R² = 0,0921	y = 0,1503x + 32,652 R² = 0,0139	y = -0,0901x - 18,912 R² = 0,0032
y = -0,6642x + 45,969 R² = 0,0803	y = 1,0382x - 2,5463 R² = 0,4896	y = 0,1069x + 34,553 R² = 0,0052	y = 0,1316x - 22,002 R² = 0,0064	y = -0,6845x + 57,064 R² = 0,0721	y = -0,2591x + 18,362 R² = 0,0232	y = -0,6367x + 92,468 R² = 0,0739	y = 0,087x + 34,378 R² = 0,004	y = 0,2134x - 25,602 R² = 0,0153
y = -0,7346x + 45,444 R² = 0,2173	y = -0,6652x + 86,971 R² = 0,1286	y = 0,0706x + 35,522 R² = 0,0047	y = -0,0275x - 18,705 R² = 0,0006	y = -1,0373x + 61,778 R² = 0,3512	y = -0,4274x + 20,76 R² = 0,1326	y = -0,6201x + 91,016 R² = 0,1563	y = 0,0702x + 34,859 R² = 0,006	y = 0,0328x - 21,698 R² = 0,0008
y = -0,6909x + 44,416 R² = 0,1721	y = -0,6566x + 86,202 R² = 0,0995	y = 0,0742x + 35,498 R² = 0,0045	y = 0,0636x - 20,349 R² = 0,0028	y = -0,99x + 60,405 R² = 0,2833	y = -0,99x + 60,405 R² = 0,2833	y = -0,7052x + 91,868 R² = 0,1534	y = 0,0447x + 35,393 R² = 0,0018	y = 0,0441x - 21,878 R² = 0,0011
y = -0,8927x + 45,065 R² = 0,0963	y = -0,2374x + 78,32 R² = 0,0045	y = -0,1118x + 38,37 R² = 0,0035	y = 0,1459x - 21,228 R² = 0,0047	y = -1,2332x + 60,224 R² = 0,1525	y = -0,4086x + 18,887 R² = 0,036	y = -0,4425x + 84,923 R² = 0,0201	y = -0,1022x + 37,98 R² = 0,0032	y = 0,0351x - 21,176 R² = 0,0003
y = -1,0829x + 46,502 R² = 0,1111	y = 0,4059x + 69,568 R² = 0,011	y = -0,2723x + 40,329 R² = 0,0158	y = 0,0348x - 19,684 R² = 0,0002	y = -1,2742x + 59,816 R² = 0,1261	y = -0,5499x + 20,309 R² = 0,0513	y = 0,035x + 79,258 R² = 0,0001	y = -0,3198x + 40,394 R² = 0,0246	y = -0,2248x - 18,269 R² = 0,0078
y = 1,2063x + 15,681 R² = 0,6523	y = 0,1717x + 71,116 R² = 0,0119	y = -0,4067x + 42,067 R² = 0,1863	y = 0,1991x - 20,904 R² = 0,0345	y = 0,6055x + 35,302 R² = 0,1309	y = 0,4358x + 7,9617 R² = 0,1516	y = 0,1586x + 74,922 R² = 0,0145	y = -0,1822x + 38,386 R² = 0,0486	y = 0,777x - 30,135 R² = 0,5637
y = 0,5643x + 8,6224 R² = 0,3961	y = 0,208x + 64,857 R² = 0,0418	y = -0,1649x + 43,37 R² = 0,0863	y = 0,1457x - 24,267 R² = 0,0506	y = 0,542x + 21,085 R² = 0,2951	y = 0,2861x + 2,0272 R² = 0,179	y = 0,2012x + 68,578 R² = 0,0584	y = -0,1222x + 41,04 R² = 0,0506	y = 0,3045x - 33,221 R² = 0,199
y = 0,7654x + 46,62 R² = 0,297	y = -0,2584x + 67,921 R² = 0,0308	y = -0,2469x + 31,79 R² = 0,0753	y = 0,1962x - 14,474 R² = 0,0371	y = 0,1014x + 45,7 R² = 0,0041	y = 0,221x + 18,119 R² = 0,0431	y = -0,1685x + 73,41 R² = 0,0183	y = -0,0481x + 35,236 R² = 0,0035	
y = -0,3381x + 44,353 R² = 0,0415	y = -0,8616x + 104,44 R² = 0,214	y = 0,5876x + 14,921 R² = 0,3381	y = 0,0124x - 18,682 R² = 0,0001	y = -0,4395x + 59,744 R² = 0,0564	y = -0,1482x + 19,338 R² = 0,0141	y = -0,7619x + 104,56 R² = 0,2371		
y = 0,1765x + 13,953 R² = 0,0259	y = -0,2279x + 92,736 R² = 0,0406	y = -0,2433x + 56,277 R² = 0,1563	y = -0,0807x - 12,737 R² = 0,0139	y = 0,3469x + 14,879 R² = 0,1054	y = 0,0727x + 7,0235 R² = 0,0105			
y = 1,0023x + 16,626 R² = 0,5483	y = -0,2105x + 76,433 R² = 0,0182	y = -0,1987x + 39,128 R² = 0,0543	y = 0,7446x - 28,825 R² = 0,5937	y = 1,0873x + 28,418 R² = 0,5259				
y = 0,596x + 4,7265 R² = 0,4649	y = -0,1562x + 80,542 R² = 0,022	y = -0,1674x + 43,439 R² = 0,0888	y = 0,3055x - 32,031 R² = 0,227					
y = 0,7643x + 44,082 R² = 0,2839	y = -0,1355x + 71,162 R² = 0,007	y = -0,0912x + 34,804 R² = 0,0105						
y = -0,6164x + 52,655 R² = 0,1609	y = 0,1328x + 68,65 R² = 0,0056							
y = -0,1096x + 35,071 R² = 0,012								

Ant+post zygapo	Ant+post lateral	Ant+post ventral	Ant+post dorsal
y = -1,1751x + 181,56 R² = 0,0739	y = 0,192x + 68,019 R² = 0,0058	y = 0,0454x + 40,266 R² = 0,0005	y = -2,0067x + 133,25 R² = 0,2113
y = -1,3207x + 181,52 R² = 0,079	y = 0,004x + 72,395 R² = 2E-06	y = -0,223x + 46,173 R² = 0,0119	y = -1,4188x + 117,41 R² = 0,0991
y = -1,2383x + 177,34 R² = 0,1534	y = 0,0314x + 71,901 R² = 0,0003	y = -0,0882x + 42,963 R² = 0,0041	y = -1,8385x + 120,52 R² = 0,3692
y = -1,3093x + 177,45 R² = 0,1363	y = 0,0326x + 71,885 R² = 0,0003	y = -0,176x + 44,57 R² = 0,0145	y = -1,8877x + 121,18 R² = 0,345
y = -0,6032x + 162,7 R² = 0,0099	y = -0,3351x + 77,729 R² = 0,0107	y = -0,2191x + 43,979 R² = 0,0082	y = -2,3116x + 120,23 R² = 0,169
y = 0,4514x + 148,89 R² = 0,0047	y = -0,7163x + 81,719 R² = 0,0364	y = -0,0944x + 42,708 R² = 0,001	y = -2,6062x + 121,23 R² = 0,1654
y = 0,291x + 147,05 R² = 0,0123	y = -0,6939x + 82,243 R² = 0,1762	y = -0,6199x + 49,75 R² = 0,2229	y = 1,7252x + 62,281 R² = 0,3438
y = 0,3893x + 134,59 R² = 0,0535	y = -0,3038x + 85,545 R² = 0,0934	y = -0,2296x + 50,682 R² = 0,0852	y = 1,5209x + 22,364 R² = 0,7697
y = -0,4186x + 142,08 R² = 0,0291	y = -0,4365x + 64,632 R² = 0,0709	y = -0,841x + 25,459 R² = 0,4537	y = 0,7915x + 101,25 R² = 0,0811
y = -1,6035x + 208,71 R² = 0,2675	y = 1,6028x + 14,054 R² = 0,78	y = 0,0904x + 37,768 R² = 0,0039	y = -0,7748x + 114,78 R² = 0,0579
y = 0,7721x + 92,736 R² = 0,3271	y = -0,7511x + 119,98 R² = 0,1865	y = 0,1451x + 27,845 R² = 0,0164	y = 1,0807x - 6,9657 R² = 0,1559
y = -0,0589x + 154,42 R² = 0,0009	y = -0,1818x + 73,276 R² = 0,0133	y = -0,5774x + 47,62 R² = 0,226	y = 1,7506x + 57,872 R² = 0,3736
y = 0,1612x + 146,57 R² = 0,0154	y = -0,2478x + 81,179 R² = 0,0584	y = -0,107x + 44,55 R² = 0,0185	y = 1,6533x + 11,172 R² = 0,7864
y = -0,3125x + 147,79 R² = 0,0247	y = -0,0126x + 70,942 R² = 5E-05	y = -0,8109x + 25,395 R² = 0,3693	y = 1,1441x + 102,72 R² = 0,1338
y = -0,5305x + 172,75 R² = 0,057	y = 1,3895x + 20,827 R² = 0,6006	y = 0,2264x + 31,333 R² = 0,0267	y = -1,4526x + 136 R² = 0,1799
y = 0,8382x + 90,624 R² = 0,4595	y = 0,1554x + 53,581 R² = 0,0114	y = 0,0486x + 35,197 R² = 0,0026	y = -0,4434x + 104,5 R² = 0,0374
y = 0,0375x + 145,56 R² = 0,001	y = -0,0196x + 65,691 R² = 0,0002	y = -0,3587x + 48,433 R² = 0,1571	y = 1,6577x + 27,672 R² = 0,587
y = 0,06x + 140,07 R² = 0,0177	y = 0,0296x + 61,792 R² = 0,0024	y = -0,0337x + 40,993 R² = 0,0065	
y = 0,1654x + 137,98 R² = 0,0234	y = 0,3325x + 52,383 R² = 0,0482		
y = -0,1747x + 155,1 R² = 0,0642			

Table S7. Measurements of the degrees of freedom between vertebrae using radiographic studies of living specimens. # = image in publication. * measured on original image of publication. § measured along the lines indicated by the floor of the neural canal. ** angle between 8th and 9th vertebrae; "+" = dorsal orientation or direction of head; "-" ventral direction or head averted direction; ~ measured from maximum left to maximum right position in literature

A) **maximal extended neck** in lateral view											
ID	species	#	S/CV1	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	CV8/DV1
CL	*Chelodina longicollis*	*7.19A middle*	-3.2	+1.6	-7.5	-1.5	+11.9	+12.7	+4	+9.8	-18.1
1116	*Emys orbicularis*		-19.6	+4.7	+2.9	+24.8	+13	?	?	?	?
1121	*Phrynops hilarii*		-4.1	-4.2	-7.9	-1	+14	+15	?	?	?
1140	*Phrynops hilarii*		+13.3	+2.6	+7.1	-9	+10.6	+14.4	+0.1	-6.2	-24.7
TH	*Testudo hermanni*		?	0	0	+5	+17	+39	+40	+10	-44.8*
1124	*Testudo hermanni*		-7.2	+0.8	?	?	?	-5.8	+22.8	+15.8	-77.8
1137	*Graptemys pseudogeographica*		+1.7	-7	+6.8	-1	+18.8	+25.7	+4.5	+4.5	-42
1145	*Sternotherus carinatus*		-13.6	-8.6	+6.3	+6.7	+28.2	+44.5	+12.4	-1.5	-57.2
B) **Maximal lateral flexion** in dorsal view											
ID	species	#	S/CV1	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	CV8/DV1
CL	*Chelodina longicollis ~*	*7.21*	+/-10	+/-12	+/-10.5	+/-40	+/-31.5	+/-22.2	+/-29.5	+/-11.8	+/-10
CN (IW1168)	*Chelodina novaeguineae ~*		?	+/-60	+/-65	+/-65	+/-60	+/-70	+/-55	+/-55	?
1116	*Emys orbicularis*		+17.3	+6.9	+21.3	+26.1	+0.5	0	0	0	0
PS (IW1167)	*Pelomedusa subrufa ~*	*X*	?	+/-50	+/-45	+/-65	+/-57	+/-57	+/-56	+/-64	?
1121	*Phrynops hilarii*		+13.1	-5.1	+14.5	+25	+43.1	+8.2	+14.3	-4	0
1135	*Emys orbicularis*		0	+1.6	+8.1	+7	+14.5	+9.8	+16.9	+11.6	-10.1
1137	*Graptemys pseudogeographica*		+1	+32.4	+10.3	+10.3	+17.6	+13.4	0	0	0
1138	*Graptemys pseudogeographica*		+5.5	+22.5	+13.8	+16.1	+9.9	+13.1	+2.2	0	0
1141	*Podocnemis unifilis*		+16.1	+29.9	+25.8	-25	-62.7	+50.4	68.3	0	0
C) **maximal dorsal flexion** in lateral view											
ID	species	#	S/CV1	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	CV8/DV1
CL	*Chelodina longicollis*	*7.19A top*	-6.8	+8.7	-2.9	+20.6	+25.3	+21.8	+9.9	+8.4	-6.7
CP	*Chrysemys picta*	*5.1j*	0**	-18.8	+37	+37.5	+36.7	0	+27	-39.5	?
1121	*Phrynops hilarii*		+20.1	+2	+9.5	+36.3	+16.6	?	?	?	?
1140	*Phrynops hilarii*		+10.3	+2.4	+6.2	+16.2	+28	+27.6	?	?	?
1134	*Pogona vitticeps*		-14.3	+6	+14.4	+14.5	+22.2	+9.1	+12.1	+9.1	+3.9**
1137	*Graptemys pseudogeographica*		+11.5	-1.3	+13.9	+9.3	+32	+37.9	+27.7	-28.7	-23.8
1145	*Sternotherus carinatus*		+12	+5.4	+8.2	+17.5	+40	+52.7	+17	+4.6	-60.8
D) **maximal ventral flexion** in lateral view											
ID	species	#	S/CV1	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	CV8/DV1
CL	*Chelodina longicollis*	*7.19A down*	-4.5	-4.5	+0.5	-2.4	+6.7	+1	+1.8	+1.7	24.4
1116	*Emys orbicularis*		-2.1	+9	-11.7	-6.2	?	?	?	?	?
1140	*Phrynops hilarii*		+8.9	+1.2	-5.5	-7.4	-5.4	+0.9	?	?	?
1135	*Emys orbicularis*		+9.2	-0.8	-5.2	-7.4	+4	+35.5	+12.7	-16.2	-52.6
1137	*Graptemys pseudogeographica*		+6.5	-7.9	-6.2	+2.8	+14.4	+34.8	-4.1	-24.4	-31
1145	*Sternotherus carinatus*		+5.3	-1.2	+2	-3.1	+21.9	+35.3	+22.2	-6.5	-67.1
E) **maximal retracted neck in Pleurodira** in dorsal view											
ID	species	#	S/CV1	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	CV8/DV1
PS (IW1167)	*Pelomedusa subrufa ~*		?	0	+17	+62	+42	+53	+12	-62	?
IW1167	*Pelomedusa subrufa*		-4.1	+39.1	+31.5	+34.3	+54	+55.8	+19.3	-53.8	-36
IW1168	*Chelodina novaeguineae ~*		-13.9	+32.8	+24.3	+37.4	+52	+46.8	+51.5	-60.1	-48.8
1121	*Phrynops hilarii*		-11.4	+33	+26.7	+30.7	+46.6	+62.1	+24.6	-35.2	-51.7 ?
1141	*Podocnemis unifilis*		+3.8	+20.4	+31.8	+41.1	+55.4	+25.9	-53-6	-43.8	0
F) **maximal retracted neck in Cryptodira** in lateral view											
ID	species	#	S/CV1	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	CV8/DV1
CP	*Chrysemys picta*	*5.1a*	?	?	+34.7	+40.7	+59.1	+69.4	-4.1	-56.4	-114.4
1113	*Heosemys grandis*		?	+6.7	+37.3	+57.9	+48.5	-2	-46.4	-107.4	-24.3
1114	*Astrochelys radiata*		?	?	?	?	?	?	?	+54.6	-154.7
1115	*Chelydra serpentina*		?	?	+39.1	+52.5	+58.3	+17.1	-17.8	-145	-9.7
1116	*Emys orbicularis*		?	?	?	?	?	?	+6.9	?	?
1123	*Testudo hermanni*		?	?	?	?	?	+47.1	+46.8	-81.1 (?)	-78.1 (?)
1124	*Testudo hermanni*		?	?	?	?	?	+60.3	+28.4	-96.6 (?)	-86.3 (?)
1133	*Astrochelys radiata*		?	?	?	?	+52	+54.5	+3.5	-19.8	-134 ?
1135	*Emys orbicularis*		?	?	?	?	+29	+6	-7.1	-24.4	-131.1
1137	*Graptemys pseudogeographica*		?	?	?	?	+52.8	+21	+1.5	-20.1	-121.2
1142	*Malacochersis tornieri*		+11 ?	+34.7	+58.9	+56.9	+23.6	-8.3	-46.6	-132	-121.5
1143	*Testudo graeca*		+11.3	+36.1	+41.6	+38.4	+31.7	+15.4	+4	-85.1	-74.3
1144	*Testudo hermanni*		?	?	?	?	?	+34	+17.6	-29.9	-135.4
1145	*Sternotherus carinatus*		+4.5	+12.7	+31	+36.7	+53.1	+47	-9.1	-35.5	-108.4
KS	*Kinosternon subrubum*		+15.9	-1.2	+42.3	+52.6	+51.9	+31	+6.7	-26.9	-131.6
TC	*Terrapene carolina*	*1C*	+43.2	+10	+47.2	+48.3	+43.3	+43.5	-57.9	-7.9	-137.3
TS1	*Trachemys scripta* (Callister 1992)	*1top*	-20	+17.3	+32.8	+40.4	+61.1	+63.3	-12	-43	-97.4
TR	*trionychid*	*1*	-2.6	+13.5	+14.4	+78.9	+68	+23.9	+5.6	+8.7	-172
TH	*Testudo hermanni*		?	0	+52	+38	+46	+28	+20	-35	-119*
G) **maximal dorsoventral flexion of the neck (C: dorsal + D: ventral)** in lateral view											
ID	species	#	S/CV1	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	CV8/DV1
TH §	*Testudo hermanni*		?	10	65	61	55	53	55	63	?
1140	*Phrynops hilarii*		1.4	1.2	11.7	23.6	33.4	26.7	?	?	?
1137	*Graptemys pseudogeographica*		5	6.6	20.1	6.5	17.6	3.1	31.8	4.3	7.2
1145	*Sternotherus carinatus*		6.7	6.6	6.2	20.6	18.1	17.4	5.2	11.1	6.3

Table S8. Angle measurements between vertebrae using computed tomography scans of anesthetized specimens. Legend: * Still a small tonus; ° only neck retraction could be measured for this species; ** estimated angle; dorsal/ventral view: + = clockwise, - = anti-clockwise; lateral flexion = to the right side; (X) = partly retracted; ^ = the centra of the 7th and 8th CV completely detach; R = slight rotation

A) maximal extended neck										
ID	species	S/CV1	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	CV8/DV1
AS	*Apalone spinifera*	+5.2	-3.4	+2.9	+6.3	+6.3	+16.2	+69.4	+72.8	-149.2
1130	*Testudo hermanni*	0	+2	-1	+4	+11.4	+26.9	+33.5	+10.8	-70.3
1131	*Trachemys scripta elegans*	?	?	-5.5	-15.6	+22.5	+53.6	+17.9	-4.6	-73.9
1134	*Pogona vitticeps*	+21.7	-5.2	+2.6	0	+3.7	+2.4	-1.5	-3.8	-2.7
1136	*Rhacodactylus ciliatus*	?	-15.7	-3.8	0	+11	+22.4	0	+5.9	+7
1137	*Graptemys pseudogeographica*	+6.5	+10	+9.4	+2.8	+22.8	+39.4	+8.2	-10.2	-46.3
1138	*Graptemys pseudogeographica*	-24.8	+34.6	-0.1	+4.5	+22.9	+22.5	+12.2	-1.9	-68.5
1140	*Phrynops hilarii*	+13	+11.2	+4	+7.1	+5	+9	-3.6	-0.8	-1
1141	*Podocnemis unifilis*	+17	+4	+5.8	+7.3	+5.3	+11.8	-4.5	-8.2	-10
1142	*Malacochersus tornieri*	+1.9	+12.9	+2.2	0	+9.7	+31	+12.9	+31.6	-101.5
1143	*Testudo graca**	+6.9	+9.7	-10.4	+1.5	+13.1	+28.3	+18.1	+13.7	-78.1
1144	*Testudo hermanni*	-6.8	-9.7	+1.5	+5.6	+17.8	+36.8	+37.5	-9.2	-106.4
1145	*Sternotherus carinatus*	-8	+6.7	+10.3	+6.1	+23	+42.6	+15.3	+10	-78.2
B) maximal retracted neck in lateral view										
ID	species	S/CV1	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	CV8/DV1
AS	*Apalone spinifera*	-24.6	-10.2	+22.7	+68.3	+101.2	+7.9	+6.9	-7.2	-167.4
1115	*Chelydra serpentina*°*	-15	+0.8	+27.6	+33.9	+38.9	+60.2	+38.6	-15.9	-155.6
1133	*Astrochelys radiata*	-2	+5.4	+50.4	+28.1	+41	+44.4	+12.3	+25.3	-109.7
1135	*Emys orbicularis*	-6.5	+8.8	+46.1	+57.4	+41.8	+43.5	+4.9	-41.8	-111.8
1137	*Graptemys pseudogeographica*	+22	+19.2	+43.1	+48.4	+64.6	+24.6	-11	-45.3	-128.4
1138	*Graptemys pseudogeographica*	+30.2	-3.8	+30.9	+54.9	+58.9	+40.1	0	-19.9	-153.5
1139	*Heosemys grandis*	+8	+10.3	+34.8	+53.6	+43.8	+51.8	+3.5	-45.7	-125.1
1140	*Phrynops hilarii (right side)*	-18	+12.3	+8	+13.4	+21.2	-3.4	+3.6	-4	-16.8
1141	*Podocnemis unifilis (left side)*	+12	-15.7	+13.4	+17.1	+27.1	-23.5	+11.3	+9.1	-22.5
1142	*Malacochersus tornieri*	+4.1	+15.4	+26.2	+52.8	+51.1	+43	+16.8	-9.6	-168.8
1143	*Testudo graca**	+16.4	+21.7	+10.5	+53.2	+52.7	+26.4	+3.4	+2.3	-172.7
1144	*Testudo hermanni*	+8.7	+22.6	+50.5	+38.3	+40.4	+22.4	+20.2	+18.7	-163.8
1131	*Trachemys scripta elegans*	-31.2	-5.4	+36.4	+46.7	+61.3	+49.8	+25.6	-17.8	-132.9
1145	*Sternotherus carinatus*	0	+30.4	+39.8	+40.5	+46.1	+47.8	-6.6	-12.6	-154.1
1162	*Stigmochelys nigra (X)*	-12.8	+13.3	+9.3	+10.9	+9.8	+32.8	+56.8	-15-6	-157.3
1163	*Pelodiscus sinensis (X)*	-19.7	+14.1	+10.3	+29.9	+81.3	+64.1	0	-0.9	-177.1
1164	*Geochelone pardalis (X)*	-0.7	-0.2	+1.2	+22	+37.8	+60.1	+45	-79.7	-76
1165	*Platysternon megacephalum (X)*	-47.1	+4.9	0	+41.6	+43.6	+45.8	+6.9	?	-145.3**
C) maximal retracted neck in dorsal/ventral view										
ID	species	S/CV1	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	CV8/DV1
1140	*Phrynops hilarii (right side)*	+0.5	+8.8	-32.8	-50.3	-58.8	-51.9	0	+24.3	+41.8
1141	*Podocnemis unifilis (left side)*	-17.4	-16.9	+27.3	+59.1	+54.5	+41.1	+23.4	-41.6	-47.8
D) maximal lateral flexion in dorsal/ventral view										
ID	species	S/CV1	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	CV8/DV1
1130	*Testudo hermanni*	-19.5	-20.5	-13.3	-2.8	-2	0	0	0	0
1131	*Trachemys scripta elegans*	-12.5	-2.1	-21.4	-37.4	-29.2	-4.8	-1	0	0
1134	*Pogona vitticeps*	+7.5	+1.7	+11.5	+6.5	+4	+0.7	+2.4	+5.8	5.8
1136	*Rhacodactylus ciliatus*	+13.2	11.1	-1.8	+3.7	0	+2.8	+15	+8.5	+10.3
1137	*Graptemys pseudogeographica*	-8	-18.5	-15.3	-15.7	-21.1	0 **	0 **	0 **	-9.2
1138	*Graptemys pseudogeographica*	-6.6	-5.8	-7.2	-17.8	-25.6	+2.6	0 **	0 **	-21.5
1140	*Phrynops hilarii*	+10.6	+4	+9.5	-13.2	-43.6	-48.9	-37.4	+18.4	-17-2
1141	*Podocnemis unifilis*	-6.8	+14	-1	+4.6	-47.6	-39.5	-21.9	+33.9	-12.2
1142	*Malacochersus tornieri*	-10.5	-4.5	-17.3	-7.5	-3.9	0 **	0 **	0 **	-9.6
1143	*Testudo graca**	-6.3	-6.5	-9	-13.1	-8.9	-5.5	-4	0 **	-7.1
1144	*Testudo hermanni*	-63.8	+38.3	-8.2	+4.4	+7.8	+20.2	0**	0**	-60
1145	*Sternotherus carinatus*	-49.6R	-9.5	-6.4	-20.2	-34.5	-1	0**	0**	-13.8
E) maximal lateral flexion in lateral view (torsion of the dorsal/ventral axis)										
ID	species	S/CV1	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	CV8/DV1
1130	*Testudo hermanni*	-6.9	-5.2	-1.3	+3.2	+16	+33.3	+26.9	-8.1	-17.2
1131	*Trachemys scripta elegans*	-3.6	-1.8	-1.5	+1.2	+17	+26.9	+19	+10.9	-108.5
1134	*Pogona vitticeps*	+7.9	+1.9	+3.7	-1.2	-1.8	+1.8	-4.3	-3.3	-3.5
1136	*Rhacodactylus ciliatus*	+11.7	-2.7	-8.7	+16.5	+3.5	-7.8	+6.8	+8	+4.6
1137	*Graptemys pseudogeographica*	-25.5	-21.8	+4.1	+10.4	+44.3	+72.3	+6.4	-32.9	-67.2
1138	*Graptemys pseudogeographica*	-11.9	-15.6	+4.3	+12.7	+33.6	+51.1	+16.1	+2	-118.9
1140	*Phrynops hilarii*	-6.4	-2	0	-4.2	+26.8	+26.4	-3	+4.4	-12.5
1141	*Podocnemis unifilis*	+24.6	-23	+4.7	+9.8	+25.8	+3.1	-21.2	+5.4	-15.1
1142	*Malacochersus tornieri*	-11.9	0	-3.4	+4.1	15.7	+41.6	+37.4	+30.1	-121.1
1143	*Testudo graca**	-14.2	+2	-5.5	+9	+22.7	+31.8	+28	+10.9	-91.2
1144	*Testudo hermanni*	-15.2	+32.6	+6.8	+14.4	+19.1	+35.1	+15.6	-58.2^	-13.6^
1145	*Sternotherus carinatus*	-53.2	-23.9	-33	-19.4	+14	+73	+5.6	-28.7	-74.7
F) maximal dorsal flexion										
ID	species	S/CV1	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	CV8/DV1
1130	*Testudo hermanni*	+8.4	+8.6	+12.3	+10	+7.2	+19.3	+13.5	+6.2	-90.7
1131	*Trachemys scripta elegans*	+11.5	+21.6	+20.4	+23.3	+22.5	+49.4	+43.2	-1.1	-77.2
1134	*Pogona vitticeps*	+23	+8.5	+4	+2.6	+13.2	+20.4	+5.8	+10.4	+12.6
1136	*Rhacodactylus ciliatus*	?	0	+2	+12	+2	+20.2	+10.5	+4	+1.5
1137	*Graptemys pseudogeographica*	-4	+3.8	+27.1	+32.3	+47.1	+61.4	+6.4	-15.7	-42.1
1138	*Graptemys pseudogeographica*	-32.3	-9.6	+20.5	+20.2	+44.7	+54	+16.8	+11.4	-60.6
1141	*Podocnemis unifilis*	-42	+65.3	+22.3	+23.6	+34.3	+22.5	+17.7	-10.2	-3.9
1142	*Malacochersus tornieri*	+14	+15.7	+16.6	+14	+15.5	+29.3	+28.3	+38.2	-93.6
1143	*Testudo graca**	-11	+30.7	+20.1	+14.5	+13.6	+57.1	+18.3	+19.7	-95.5
1144	*Testudo hermanni*	0	+47.4	+15.2	+15.5	+21.8	+42.6	+4	-58.4^	-13^
1145	*Sternotherus carinatus*	-21.6	-0.5	+22.4	+37.2	+37	+80.7	+20	+23.6^	-61^
G) maximal ventral flexion										
ID	species	S/CV1	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	CV8/DV1
1134	*Pogona vitticeps*	+5.4	-8.5	-0.8	-0.4	-1	-1.7	-7.4	-6.1	-3.3
1136	*Rhacodactylus ciliatus*	?	+1.5	-8.1	0	0	+6.2	+7.7	-8.5	-18
1137	*Graptemys pseudogeographica*	-12.8	-17.3	-10.8	-15.3	+20	+58.8	0	-20.7	-57.3
1138	*Graptemys pseudogeographica*	+12.9	-35.5	-7.6	-10.3	+13	+38.6	+14.3	-13.3	-59.7
1141	*Podocnemis unifilis*	-20.7	-22.9	+1.6	-6.4	+1	+1.9	-4	-5.2	-4.3
1142	*Malacochersus tornieri*	-26.2	+4.3	-20.9	-6.3	+2.4	+23.6	+29.9	+48.3	-113.1

1143	*Testudo graca**	-6.3	-8	-13.1	+1.2	+22.4	+60.3	+26.1	+10	-118.7
1144	*Testudo hermanni*	-51.8	+6.7	+9.1	-5.1	+8	+35	+4.3	-43	-46.7
1145	*Sternotherus carinatus*	-2.9	0	-13.1	-20.9	-13.3	+13.7	+0.7	+8.1	-56.9

Table S9. Taphonomic distance calculation A: raw data summary. Angles measured on macerated bones and those measured in the live CTs were plotted against each other in each taxon pair for each neck position. The regression curves can be found in Table S10. ps. = *pseudogeographica*

Taxon	Movement (method)	S/CV1	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	CV8/DV1
Phrynops										
Phrynops geoffroanus	lateral (macerated)	-	57,00	38,00	63,90	60,60	50,90	46,40	61,50	-
Phrynops hilarii	lateral (live CT)	10,6	4	9,5	13,2	43,6	48,9	37,4	18,4	19
Podocnemis unifilis										
Podocnemis unifilis	lateral (macerated)	-	-	53,80	55,90	65,20	60,60	71,00	68,10	-
Podocnemis unifilis	lateral (live CT)	-6,8	14	1	4,6	47,6	39,5	21,9	33,9	12,2
Podocnemis unifilis	ventral (macerated)	-	-	-25,40	-23,30	-12,40	-23,10	-17,80	-29,00	-
Podocnemis unifilis	ventral (live CT)	-20,7	-22,9	+1,6	-6,4	1	+1,9	-4	-5,2	4,3
Podocnemis unifilis	dorsal (macerated)	-	-	27,00	25,20	40,40	30,90	23,90	9,00	-
Podocnemis unifilis	dorsal (live CT)	-42	65,3	22,3	23,6	34,3	22,5	17,7	-10,2	-3,9
Kinosternidae										
Kinosternon scorpioides	lateral (macerated)	-	-	18,60	18,90	17,70	25,90	14,70	28,40	-
Sternotherus carinatus	lateral (live CT)	49,6	9,5	6,4	20,2	34,5	1	0	0	13,8
Kinosternon scorpioides	ventral (macerated)	-	-	-9,40	-10,70	-20,40	3,90	-5,90	-12,40	-
Sternotherus carinatus	ventral (live CT)	-2,9	0	-13,1	-20,9	-13,3	13,7	+0,7	+8,1	-56,9
Kinosternon scorpioides	dorsal (macerated)	-	-	59,30	49,70	77,00	107,40	33,80	49,40	-
Sternotherus carinatus	dorsal (live CT)	-21,6	-0,5	22,4	37,2	37	80,7	20	23,6	-61
Emydidae										
Melaclemys terrapin	lateral (macerated)	-	41,20	40,70	19,00	46,90	24,90	30,00	25,70	-
Graptemys (IW 1137)	lateral (live CT)	8	18,5	15,3	15,7	21,1	0	0	0	9,2
Graptemys ps. (IW 1138)	lateral (live CT)	6,6	5,8	7,2	17,8	25,6	2,6	0	0	21,5
Melaclemys terrapin	ventral (macerated)	-	-79,50	-26,80	-23,90	2,00	-0,80	-31,40	-48,80	-
Graptemys ps. (IW 1137)	ventral (live CT)	-12,8	-17,3	-10,8	-15,3	20	+58,8	0	-20,7	-57,3
Graptemys ps. (IW1138)	ventral (live CT)	+12,9	-35,5	-7,6	-10,3	13	+38,6	+14,3	-13,3	-59,7
Melaclemys terrapin	dorsal (macerated)	-	12,30	64,60	57,40	77,20	90,00	26,90	61,70	-
Graptemys ps. (IW1137)	dorsal (live CT)	-4	+3,8	+27,1	+32,3	+47,1	+61,4	+6,4	-15,7	-42,1
Graptemys ps. (IW1138)	dorsal (live CT)	-32,3	-9,6	+20,5	+20,2	+44,7	54	+16,8	+11,4	-60,6
Testudo graeca										
Testudo graeca	lateral (macerated)	-	-	36,50	43,50	40,30	24,00	13,10	20,40	-
Testudo graeca	lateral (live CT)	6,3	6,5	9	13,1	8,9	5,5	4	0	7,1
Testudo graeca	ventral (macerated)	-	-	-29,40	-20,30	-13,90	-6,20	-6,90	-50,40	-
Testudo graeca	ventral (live CT)	-6,3	-8	-13,1	+1,2	+22,4	+60,3	+26,1	10	-118,7
Testudo graeca	dorsal (macerated)	-	-	53,50	53,60	67,20	67,90	70,90	27,60	-
Testudo graeca	dorsal (live CT)	-11	+30,7	+20,1	+14,5	+13,6	+57,1	+18,3	+19,7	-95,5
Testudo hermanni										
Testudo hermanni	lateral (macerated)	-	-	39,70	39,90	41,40	38,90	38,80	21,50	x
Testudo hermanni (IW1130)	lateral (live CT)	19,5	20,5	13,3	2,8	2	0	0	0	0
Testudo hermanni (1144)	lateral (live CT)	63,8	38,3	8,2	4,4	7,8	20,2	0	0	-60
Testudo hermanni (1130)	ventral (macerated)	-	-	-29,70	-32,90	0,00	0,00	-20,70	-43,50	-
Testudo hermanni (1144)	ventral (live CT)	-51,8	+6,7	+9,1	-5,1	8	35	+4,3	-43	-46,7
Testudo hermanni	dorsal (macerated)	-	-	56,60	63,90	67,50	80,50	46,50	36,00	-
Testudo hermanni (IW1130)	dorsal (live CT)	+8,4	+8,6	+12,3	10	+7,2	+19,3	+13,5	+6,2	-90,7
Testudo hermanni (IW1144)	dorsal (live CT)	0	+47,4	+15,2	+15,5	+21,8	+42,6	4	-58,4^	-13^

Table S10. Taphonomic distance calculation B: regressions for each neck flexion. For each taxon, the regressions and the variance (R^2) are listed for each movement.

taxon	Movement	regression	R^2
Testudines	Lateral	$y = 0{,}0142x^2 - 0{,}6908x + 14{,}542$	0,3224
	Ventral	$y = 0{,}0081x^2 + 1{,}2285x + 22{,}893$	0,4367
	Dorsal	$y = -0{,}0323x^2 + 1{,}0194x + 19{,}6$	0,1256
Pleurodira	Lateral	$y = -0{,}002x^2 + 0{,}593x - 2{,}4929$	0,0364
	Ventral (= *Podocnemis unifilis*)	$y = -0{,}0006x^2 + 0{,}1594x + 1{,}9342$	0,0829
	Dorsal (= *Podocnemis unifilis*)	$y = 0{,}0303x^2 + 2{,}8686x - 33{,}153$	0,9721
Phrynops	Lateral	$y = 0{,}0679x^2 - 0{,}0607x + 52{,}379$	0,0209
Podocnemis unifilis	Lateral	$y = -0{,}4568x^2 + 58{,}562x - 1833{,}1$	0,9271
	Ventral	$y = -0{,}0006x^2 + 0{,}1594x + 1{,}9342$	0,0829
	Dorsal	$y = 0{,}0303x^2 + 2{,}8686x - 33{,}153$	0,9721
Cryptodira	Lateral	$y = 0{,}0588x^2 - 3{,}4417x + 51{,}832$	0,2735
	Ventral	$y = 0{,}0069x^2 + 1{,}1203x + 22{,}903$	0,3993
	Dorsal	$y = 0{,}0107x^2 - 0{,}4552x + 6{,}8036$	0,5103
Kinosternidae	Lateral	$y = -0{,}4019x^2 + 16{,}555x - 150{,}81$	0,4185
	Ventral	$y = 0{,}0448x^2 + 1{,}7703x + 5{,}9171$	0,4414
	Dorsal	$y = 0{,}0127x^2 - 1{,}0423x + 45{,}037$	0,9155
Emydidae + Testudo	Lateral	$y = 0{,}0555x^2 - 3{,}1398x + 45{,}075$	0,4199
	Ventral	$y = 0{,}0092x^2 + 1{,}4517x + 31{,}715$	0,5833
	Dorsal	$y = 0{,}0138x^2 - 0{,}7238x + 8{,}7164$	0,4631
Emydidae	Lateral	$y = 0{,}1039x^2 - 6{,}444x + 99{,}386$	0,8355
	Ventral	$y = 0{,}0093x^2 + 1{,}4287x + 29{,}083$	0,6786
	Dorsal	$y = 0{,}0127x^2 - 0{,}5866x + 8{,}1292$	0,6823
Testudo	Lateral	$y = 0{,}018x^2 - 0{,}8139x + 10{,}737$	0,1842
	Ventral	$y = 0{,}015x^2 + 1{,}7326x + 35{,}808$	0,464
	Dorsal	$y = 0{,}0151x^2 - 1{,}2995x + 39{,}313$	0,2463
Testudo graeca	Lateral	$y = 0{,}0152x^2 - 0{,}5513x + 7{,}8361$	0,838
	Ventral	$y = 0{,}0791x^2 + 5{,}3074x + 76{,}247$	0,8377
	Dorsal	$y = 0{,}0159x^2 - 1{,}3x + 42{,}98$	0,108
Testudo hermanni	Lateral	$y = -0{,}0225x^2 + 1{,}7044x - 26{,}238$	0,1266
	Ventral	$y = -0{,}048x^2 - 0{,}7115x + 20{,}63$	0,8181
	Dorsal	$y = -0{,}0196x^2 + 3{,}3353x - 114{,}98$	0,5022

Table S11. Calculation of mobility of the neck in fossil taxa using the polynomic regressions of the taphonomic distance in extant turtle taxa (see Table S9). For measured raw-data compare also to Table S4. For every species, movements were calculated with the taphonomic distance formula for Testudines, Pleurodira, and Cryptodira. With the assumption that the measured angles are usually larger than the calculated life-angles (almost no overstretching of adjacent vertebrae) and with the assumption that the fossil neck vertebrae had the same relationship to each other as those of extant taxa (meaning the same formula), plausible (green and orange) and non-plausible (red) calculations are highlighted. In the case of two or three plausible movements, the largest differences to the meassured value are presumed to be less plausible (orange) than the smaller difference (green). The most plausible live angles for each fossil and movement are marked (for a summary see Table S12).

ID	species		Vertebra	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	Most plausible
921A	*† Proganochelys quenstedti*	*Dorsal*	Measured	?	7,9	10,7	7,2	14,7	-4,7	22,3	
			Calculated (Testudines)	-	25,637417	26,809553	25,265248	27,605473	14,095313	26,270153	
			Calculated (Pleurodira)	-	-8,600037	1,010067	-10,928328	15,562947	-45,966093	45,884667	
			Calculated (Cryptodira)	-	3,875307	3,158003	4,080848	2,424323	9,179403	1,973643	X
		Ventral	Measured	?	-16,8	-9,9	-22	-14,3	-37,3	-15,1	
			Calculated (Testudines)	-	4,540344	11,524731	-0,2136	6,981819	-11,660601	6,189531	
			Calculated (Pleurodira)	-	-0,913064	0,297334	-1,863	-0,467914	-4,846194	-0,609546	X
			Calculated (Cryptodira)	-	6,029416	12,488299	1,596	8,293691	-9,284289	7,559739	
		Lateral	Measured	?	54,5	32,5	38,1	38,5	35,4	48,9	
			Calculated (Testudines)	-	19,07095	7,08975	8,835382	8,99415	7,882552	14,717062	
			Calculated (Pleurodira)	-	23,8851	14,6671	17,19718	17,3731	15,99298	21,72238	X
			Calculated (Cryptodira)	-	38,91005	2,08425	6,057898	6,48285	3,681628	24,136018	
922	*† Chisternon undatum*	*Dorsal*	Measured	X	-4,3	27,4	45	12,6	18,6	3,1	
			Calculated (Testudines)	-	14,619353	23,282012	0,0655	27,316492	27,386332	22,449737	
			Calculated (Pleurodira)	-	-44,927733	68,194668	157,2915	7,801788	30,685548	-23,969157	X
			Calculated (Cryptodira)	-	8,958803	2,364252	7,9871	2,766812	2,038652	5,495307	
		Ventral	Measured	X	-49,4	-17,8	?	-20,4	?	-26,2	
			Calculated (Testudines)	-	-18,027984	3,592104	-	1,202496	-	-3,733536	X
			Calculated (Pleurodira)	-	-7,404376	-1,093224	-	-1,567256	-	-2,653944	X
			Calculated (Cryptodira)	-	-15,601336	5,147856	-	2,920384	-	-1,712424	
		Lateral	Measured	X	43,5	?	?	46,9	?	54,4	
			Calculated (Testudines)	-	11,36215	-	-	13,377942	-	18,985392	
			Calculated (Pleurodira)	-	19,5181	-	-	20,91958	-	23,84758	X
			Calculated (Cryptodira)	-	13,38235	-	-	19,753338	-	38,613888	
924A	*† Meiolania platyceps*	*Dorsal*	Measured	5,9	4,3	12,5	11,2	14,1	5,1	5,1	
			Calculated (Testudines)	24,490097	23,386193	27,295625	26,965568	27,551977	23,958817	23,958817	
			Calculated (Pleurodira)	-15,173517	-20,257773	7,438875	2,776152	13,318203	-17,735037	-17,735037	
			Calculated (Cryptodira)	4,490387	5,044083	2,785475	3,047568	2,512547	4,760387	4,760387	X
		Ventral	Measured	-28,3	-14,8	-7,6	-12	-15,9	-10,4	-11,8	
			Calculated (Testudines)	-5,386341	6,485424	14,024256	9,3174	5,407611	10,992696	9,524544	
			Calculated (Pleurodira)	-3,057354	-0,556344	0,688104	-0,065	-0,751946	0,211544	-0,030264	X
			Calculated (Cryptodira)	-3,275349	7,833936	14,787264	10,453	6,834619	11,998184	10,644216	
		Lateral	Measured	30,60	21	38,2	31	29	47,1	42,2	
			Calculated (Testudines)	6,699832	6,2974	8,874648	6,7734	6,451	13,506742	10,678168	
			Calculated (Pleurodira)	13,78018	9,0781	17,24122	13,9681	13,0221	21,00058	18,97002	X
			Calculated (Cryptodira)	1,573948	5,4871	6,162372	1,6461	1,4735	20,170438	11,305652	
931	*† Naomichelys speciosa*	*Dorsal*	Measured	35	19,5	15	4,8	25,4	6,7	-2,5	
			Calculated (Testudines)	15,7115	27,196225	27,6235	23,748928	24,654092	24,980033	16,849625	
			Calculated (Pleurodira)	104,3655	34,306275	16,6935	-18,685608	59,257788	-12,573213	-40,135125	
			Calculated (Cryptodira)	3,9791	1,995875	2,3831	4,865168	2,144732	4,234083	8,008475	X
		Ventral	Measured	-15,3	-14,1	-18	-23	-7,8	-31,7	-41,1	
			Calculated (Testudines)	5,993079	7,181511	3,4044	-1,0776	13,803504	-7,910841	-13,915749	
			Calculated (Pleurodira)	-0,645074	-0,432626	-1,1294	-2,0494	0,654376	-3,721714	-5,630666	X
			Calculated (Cryptodira)	7,377631	8,478559	4,9732	0,7862	14,584456	-5,676769	-11,485781	
		Lateral	Measured	20	13,20	37,2	55	35,4	45,8	42,4	
			Calculated (Testudines)	6,406	7,897648	8,494768	19,503	7,882552	12,689848	10,780272	
			Calculated (Pleurodira)	8,5671	4,98622	16,79902	24,0721	15,99298	20,47122	19,05478	X
			Calculated (Cryptodira)	6,518	16,646872	5,170552	40,4085	3,681628	17,543372	11,612208	
IW1166	*† Xinjiangchelys chowi (A/B and C/D)*		Vertebra	A/B	C/D						
		Dorsal	Measured	18,6	46,8						
			Calculated (Testudines)	27,386332	-3,436832	-	-	-	-	-	
			Calculated (Pleurodira)	30,685548	167,46175	-	-	-	-	-	
			Calculated (Cryptodira)	2,038652	8,935808	-	-	-	-	-	X
		Ventral	Measured	-46,9	-28,8						
			Calculated (Testudines)	-16,906809	-5,769336	-	-	-	-	-	X
			Calculated (Pleurodira)	-6,861426	-3,154184	-	-	-	-	-	
			Calculated (Cryptodira)	-18,860981	-5,297384	-	-	-	-	-	X
		Lateral	Measured	66,8	27,3						
			Calculated (Testudines)	31,760368	6,266278	-	-	-	-	-	X
			Calculated (Pleurodira)	28,19502	12,20542	-	-	-	-	-	X
			Calculated (Cryptodira)	544,117272	189,61346	-	-	-	-	-	

Table S12. Summary of the most plausible calculated live neck performances in the fossils (Table S10-11). For Cryptodira, the maximal and minimal dorsal and ventral mobility, which was measured during neck retraction using CT (compare to Table S7B), and for Pleurodira, the maximal and minimal lateral mobility, which was measured during neck retraction using CT (compare to Table S7C), are listed (compare to Fig. 4). Overstretched vertebrae are highlighted. The calculations for *Chisternon undatum* lie largely over the allowed range of motion, which indicates to a completely different relationship of its vertebrae to each other than to all other crown Testudines.

Taxon	Movement (mode)	S/CV1	CV1/CV2	CV2/CV3	CV3/CV4	CV4/CV5	CV5/CV6	CV6/CV7	CV7/CV8	CV8/DV1
A) Dorsal-ventral movement										
† Proganochelys quenstedti	Dorsal (cryptodiran)	-	-	3,875307	3,158003	4,080848	2,424323	9,179403	1,973643	-
† Proganochelys quenstedti	Ventral (pleurodiran)	-	-	-0,913064	0,297334	-1,863	-0,467914	-4,846194	-0,609546	-
† Chisternon undatum	Dorsal (pleurodiran)	-	-	-44,927733	68,194668	157,2915	7,801788	30,685548	-23,969157	-
† Chisternon undatum	Ventral (Testudines-like)	-	-	-18,027984	3,592104	-	1,202496	-	-3,733536	-
	Ventral (pleurodiran)	-	-	-7,404376	-1,093224	-	-1,567256	-	-2,653944	
† Meiolania platyceps	Dorsal (cryptodiran)	-	4,490387	5,044083	2,785475	3,047568	2,512547	4,760387	4,760387	-
† Meiolania platyceps	Ventral (pleurodiran)	-	-3,057354	-0,556344	0,688104	-0,065	-0,751946	0,211544	-0,030264	-
† Naomichelys speciosa	Dorsal (cryptodiran)	-	3,9791	1,995875	2,3831	4,865168	2,144732	4,234083	8,008475	-
† Naomichelys speciosa	Ventral (pleurodiran)	-	-0,645074	-0,432626	-1,1294	-2,0494	0,654376	-3,721714	-5,630666	-
Cryptodira	minimal ventral movement during retraction	-47,1	-15,7	1,2	13,4	9,8	-23,5	-11	-79,7	-177,1
Cryptodira	maximal dorsal movement during retraction	30,2	30,4	50,5	68,3	101,2	64,1	56,8	25,3	-16,8
A) Lateral movement										
† Proganochelys quenstedti	Lateral (pleurodiran)	-	-	23,8851	14,6671	17,19718	17,3731	15,99298	21,72238	-
† Chisternon undatum	Lateral (pleurodiran)	-	-	19,5181	-	-	20,91958	-	23,84758	-
† Meiolania platyceps	Lateral (pleurodiran)	-	13,78018	9,0781	17,24122	13,9681	13,0221	21,00058	18,97002	-
† Naomichelys speciosa	Lateral (pleurodiran)	-	8,5671	4,98622	16,79902	24,0721	15,99298	20,47122	19,05478	-
Pleurodira	minimal lateral movement during retraction	0,50	8,80	27,30	50,30	54,50	41,10	0,00	24,30	41,80
Pleurodira	maximal lateral movement during retraction	17,40	16,90	32,80	59,10	58,80	51,90	23,40	41,60	47,80

Table S13. Calculation of CV8-DV1 mobility. 1) derived from the curve of macerated bones (data from Table S4) assuming an expected correlated mobility as the first vertebrae. 2) calculated life performance using the regressions of Table S9. Non-plausible movement angles are highlighted.

	dorsal	*† Chisternon undatum*	*† Meiolania sp,*	*† Naomichelys speciosa*	*† Proganochelys quenstedti*
CV1/CV2	x=1		5,9	35	?
CV2/CV3	x=2	-4,3	4,3	19,5	7,9
CV3/CV4	x=3	27,4	12,5	15	10,7
CV4/CV5	x=4	45	11,2	4,8	7,2
CV5/CV6	x=5	12,6	14,1	25,4	14,7
CV6/CV7	x=6	18,6	5,1	6,7	-4,7
CV7/CV8	x=7	3,1	5,1	-2,5	22,3
1a	Regression of fossil bone curve in dorsal movement	$y = -5{,}0429x^2 + 44{,}763x - 67{,}54$	$y = -0{,}8286x^2 + 6{,}6571x - 1{,}7429$	$y = 0{,}2631x^2 - 6{,}6655x + 36{,}243$	$y = 0{,}0774x^2 + 1{,}0131x + 2{,}7$
1b	R^2 of fossil bone curve in dorsal movement	0,6126	0,566	0,5839	0,1558
1c	Calculation of CV8-DV1 in dorsal movability in between fossil bones (with x=8)	-32,1816	-1,5165	-0,2426	15,7584
2a	Calculation of CV8-DV1 in dorsal position between bones in living animal (Testudines-formula: y=-0,0323x2 + 1,0194x + 19,6) (see Table S12)	-46,6575918	17,9797973	19,35079255	27,64314535
2b	(Pleurodira-formula: y= 0,0303x2 + 2,8686x - 33,153) (see Table 12)	-94,0887798	-37,4335488	-33,8471391	19,57585951
2c	(Cryptodira-formula: y= 0,0107x2 - 0,4552x + 6,8036) (see Table S12)	32,53417687	7,51851836	6,914661266	2,287477045
	Ventral	*† Chisternon undatum*	*† Meiolania sp,*	*† Naomichelys speciosa*	*† Proganochelys quenstedti*
CV1/CV2	x=1		-28,3	-15,3	?
CV2/CV3	x=2	-49,4	-14,8	-14,1	-16,8
CV3/CV4	x=3	-17,8	-7,6	-18	-9,9
CV4/CV5	x=4	?	-12	-23	-22
CV5/CV6	x=5	-20,4	-15,9	-7,8	-14,3
CV6/CV7	x=6	?	-10,4	-31,7	-37,3
CV7/CV8	x=7	-26,2	-11,8	-41,1	-15,1
1a	Regression of fossil bone curve in ventral movement	$y = -4{,}975x^2 + 49{,}032x - 124{,}36$	$y = -0{,}9762x^2 + 9{,}5952x - 33{,}257$	$y = -1{,}3405x^2 + 7{,}0667x - 23{,}029$	$y = 1{,}0131x^2 - 11{,}344x + 8{,}6286$
1b	R^2 of fossil bone curve in ventral movement	0,7295	0,6263	0,6706	0,4837
1c	Calculation of CV8-DV1 in ventral movability in between fossil bones (with x=8)	-50,504	-18,9722	-52,2874	-17,285
2a	Calculation of CV8-DV1 in ventral position between bones in living animal (Testudines-formula: y=0,0081x2 + 1,2285x + 22,893) (see Table S12)	-18,4908665	2,50120172	-19,1968961	4,078424423
2b	(Pleurodira-formula: y= -0,0006x2 + 0,1594x + 1,9342) (see Table S12)	-7,64653001	-1,3059353	-8,04079488	-1,00029174
2c	(Cryptodira-formula: y= 0,0069x2 + 1,1203x + 22,903) (see Table S12)	-16,0771185	4,13206051	-16,810166	5,600135953
	lateral	*† Chisternon undatum*	*† Meiolania sp,*	*† Naomichelys speciosa*	*† Proganochelys quenstedti*
CV1/CV2	x=1	-	30,6	20	-
CV2/CV3	x=2	43,5	21	13,2	54,5
CV3/CV4	x=3	?	38,2	37,2	32,5
CV4/CV5	x=4	?	31	55	38,1
CV5/CV6	x=5	46,9	29	35,4	38,5
CV6/CV7	x=6	?	47,1	45,8	35,4
CV7/CV8	x=7	54,4	42,2	42,4	48,9
1a	Regression of fossil bone curve in lateral movement	$y = 5{,}3911x^2 - 45{,}623x + 104{,}54$	$y = -1{,}3643x^2 + 16{,}971x - 10{,}814$	$y = -1{,}4976x^2 + 17{,}588x - 6{,}7143$	$y = 2{,}5482x^2 - 23{,}474x + 87{,}916$
1b	R^2 of fossil bone curve in lateral movement	0,3464	0,7938	0,5306	0,6831
1c	Calculation of CV8-DV1 in lateral movability in between fossil bones (with x=8)	84,5864	37,6388	38,1433	63,2088
2a	Calculation of CV8-DV1 in lateral position between bones in living animal (Testudines-formula: y=0,0142x2 - 0,6908x + 14,542) (see Table S12)	57,7087136	8,65796253	8,852349315	27,611365
2b	(Pleurodira-formula: y=-0,002x2 + 0,593x - 2,4929) (see Table S12)	33,357117	16,99355	17,216254	26,999214
2c	(Cryptodira-formula: y= 0,0588x2 - 3,4417x + 51,832) (see Table S12)	181,4167	5,5912828	137,29056	69,212994

References to the Supplementary data file

Bramble DM, Hutchison JH, Legler JM. 1984. Kinosternid shell kinesis: structure, function and evolution. Copeia 1984:456-475.

Callister RJ, Callister R, Peterson EH. 1992. Design and control of the head retractor muscle in a turtle, Pseudemys (Trachemys) scripta: I. Architecture and histochemistry of single muscle fibers. The Journal of Comparative Neurology 325:405-421.

Callister RJ, Pierce PA, McDonagh JC, Stuart DG. 2005. Slow-tonic muscle fibers and their potential innervation in the turtle, Pseudemys (Trachemys) scripta elegans. Journal of Morphology 264:62-74.

Dalrymple GH. 1979. Packaging problems of head retraction in trionychid turtles. Copeia:655-660.

Gaffney ES. 1985. The cervical and caudal vertebrae of the cryptodiran turtle, *Meiolania platyceps*, from the Pleistocene of Lord Howe Island, Australia. American Museum Novitates 2805:1-29.

Gaffney ES. 1990. The comparative osteology of the Triassic turtle *Proganochelys*. Bulletin of the American Museum of Natural History 194:1-263.

Herrel A, Van Damme J, Aerts P. 2008. Cervical anatomy and function in turtles. In: Wyneken J, Godfrey MH, Bels V editor^editors. Biology of Turtles. Boca Raton, London, New York: CRC Press. p. 163-185.

Jaekel O. 1915. Die Wirbeltiere aus dem Keuper von Halberstadt, Q8 Serie II, Testudinata. . Paleontologische Zeitschrift 2:88-214.

Landberg T, Mailhot JD, Brainerd EL. 2003. Lung ventilation during treadmill locomotion in a terrestrial turtle, Terrapene carolina. Journal of Experimental Biology 206:3391-3404.

Scanlon TC. 1982. Anatomy of the neck of the western painted turtle (Chrysemys picta belli Gray; Reptilia, Testudinata) from the perspective of possible movements in the region. In: Guthe K, Faulkner J, Nussbaum R editor^editors. Michigan: The University of Michigan. p. 283.

Weisgram J, Splechtna H. 1990. Intervertebral movability in the neck of two turtle species (*Testudo hermanni hermanni*, *Pelomedusa subrufa*). Zoologische Jahrbücher Abteilung für Anatomie und Ontogenie der Tiere 120:425-431.

Weisgram J, Splechtna H. 1992. Cervical movement during feeding in *Chelodina novaeguinaeae*. Zoologische Jahrbücher Abteilung für Anatomie und Ontogenie der Tiere 122:331-337.

Werneburg I. 2011. The cranial musculature in turtles. Palaeontologia Electronica 14:15a:99 pages.