Regionalization and morphological integration in the vertebral column of Eurasian small-bodied newts (Salamandridae: *Lissotriton*)

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Abstract

Serially homologous structures may have complex patterns of regionalization and morphological integration, influenced by developmental *Hox* gene expression and functional constraints. The vertebral column, consisting of a number of repeated, developmentally constrained and highly integrated units – vertebrae – is such a complex serially homologous structure. Functional diversification increases regionalization and modularity of the vertebral column, particularly in mammals. For salamanders, three concepts of regionalization of the vertebral column have been proposed, recognizing one, two or three presacral regions. Using 3D geometric morphometrics on vertebra models acquired with micro-CT scanning we explored the covariation of vertebrae in four closely related taxa of small-bodied newts in the genus *Lissotriton.* The data were analyzed by segmented linear regression to explore patterns of vertebral regionalization and by a two-block partial least squares method to test for morphological integration. All taxa show a morphological shift posterior to the 5^{th} trunk vertebra, which corresponds to the two-region concept. However, morphological integration is found to be strongest in the mid-trunk. Taken jointly, these results indicate highly integrated presacral vertebral column with a subtle two-region differentiation. The results are discussed in relation to specific functional requirements, developmental and phylogenetic constraints, and specific requirements posed by a biphasic life cycle and different locomotor modes (swimming vs. walking). Further research should be conducted on different ontogenetic stages and closely related but ecologically differentiated species.

Keywords: axial skeleton, geometric morphometrics, micro-CT scanning, modularity, regional differentiation, serial homology, tailed amphibians

Introduction

Morphological integration is defined as the covariation of morphological traits as a result of developmental and functional interactions (Olson & Miller, 1958), but may also be shaped by selective pressures (Cheverud, 1996; Wagner & Altenberg, 1996; Klingenberg, 2008; Zelditch & Goswami, 2021). Modularity implies variation in integration within an organism and some parts can be more integrated than others. Accordingly, morphological modules are interpreted as units with strong covariation within and minor covariation among units.

Serially homologous structures such as vertebrae, teeth and ribs provide worthwhile model systems for the study of regionalization, modularity and morphological integration, because they share a common structural plan with variation throughout the series (Gómez-Robles & Polly, 2012; Jones et al., 2018; Urošević et al., 2020). Elements within serially homologous structures tend to be developmentally constrained and strongly integrated (Cowley & Atchley, 1990; Carroll, 2001; Young & Hallgrímsson, 2005; Asher et al., 2011; Jones et al., 2018, 2020). In some cases, different functional demands and selection pressures may lead to the "parcellation" of regional differentiation (Wagner & Altenberg, 1996), such as in the limb skeleton (Young & Hallgrímsson, 2005), the feeding apparatus (Wainwright, 2007) and the vertebral column (Randau & Goswami, 2017; Jones et al., 2020). For example, the mammalian presacral vertebral column is markedly regionalized and can be divided into several developmental and functional modules (Randau & Goswami, 2017).

The evolution of vertebral modularity appears largely driven by locomotion and ecology (Galis et al., 2014; Jones et al., 2018) and is also under developmental constraints (Galis, 1999). The vertebral column can be viewed as an integrated structure because it derives entirely from the somites (the presomitic mesoderm) and it has independent developmental and evolutionary

patterns derived from the abaxial domain of the mesoderm (Shearman & Burke, 2009). The shape of vertebrae and regionalization of the vertebral column are determined throughout the early ontogenetic stages by spatial and temporal expression of the *Hox* genes during somitogenesis (Krumlauf, 1994; Aulehla & Pourguié, 2010; Mallo et al., 2010). The boundaries in *Hox* genes expression correspond to the boundaries of the vertebral regions. In mammals, the expression boundary of the *Hox*6 gene determines the cervico-thoracic transition, *Hox*10 the thoraco-lumbar and *Hox*11 the lumbar-sacral transition (Burke et al., 1995; Wellik, 2007; Kuratani, 2009). This tetrapod-like organization of *Hox* genes expression has presumably a deep evolutionary origin and may have arisen in the first jawed vertebrates (Criswell et al., 2021). Some well-preserved fossil skeletons of the early tetrapod *Ichthyostega* had recognizable thoracic, lumbar, sacral and caudal vertebral regions (Ahlberg et al., 2005), suggesting that the regionalization of the vertebral column was, be it only subtly expressed, present in the stem tetrapod lineage (Head & Polly, 2015; Jones et al., 2018).

In extant amphibians the vertebral column encompasses three distinctive body plans as found in the tailless frogs and toads (Anura), the elongated, limbless caecilians (Gymnophiona) and the tailed amphibians or salamanders (Caudata). Salamanders have a cylindrical body with a poorly differentiated vertebral column, four relatively short appendages and a tail (Mivart, 1870; Duellman & Trueb, 1994). They have widely been used as morphological analogues to the early terrestrial vertebrates that presumably possessed the same general body plan and similar modes of locomotion. Their presacral vertebral column consists of a single cervical vertebra (the atlas) which articulates to the skull and lack ribs, and a series of rib-bearing trunk vertebrae. They also have a single sacral vertebra, several postsacral and numerous caudal vertebrae, depending on the species (Duellman & Trueb, 1994; Litvinchuk & Borkin, 2003; Lanza et al., 2010) (Fig. 1A).

Recent studies on vertebral regionalization (Jones et al., 2018) and morphological differentiation (Scholtes et al., 2021) indicate that the trunk region in salamanders is not as uniform as previously thought. A three-region pattern of the presacral vertebral column was found in *Ambystoma* (Jones et al., 2018). In small-bodied newts of the genus *Lissotriton* substantial morphological differentiation in the vertebrae shape along the trunk region was documented (Fig 1A; Scholtes et al., 2021). We here provide a brief description of three alternative concepts of the salamander's presacral vertebral column regionalization (see Table 1).

The vertebral column of tailed amphibians has traditionally been regarded as not, or poorly differentiated (Mivart, 1870; Duelman & Trueb, 1994, Slijepčević et al., 2015). The presacral vertebral column was in its entirety (minus the atlas) designated as the 'trunk region', due to a shared gross morphology of rib-bearing vertebrae. Subsequently Jones et al. (2018), using *Ambystoma* as model species, proposed a three-region differentiation of the salamander presacral vertebral column. The first region associates with the posterior branch of the brachial plexus, implying homology of the anterior trunk vertebrae with the cervical region, whereas the middle and posterior region correspond to regions of short and long ribs in the Amniotes (Jones et al., 2018). Alternatively, studies on morphometric variation in vertebrae size (Worthington & Wake, 1972; Govedarica et al., 2017) and shape (Scholtes et al., 2021) revealed morphological differentiation (substantial disparity in size and shape) of the presacral vertebral column in salamanders, particularly in the anterior trunk vertebrae. A similar heterogeneity among short and bulky anterior and elongated posterior vertebrae was documented in caecilians (Lowie et al., 2022). The morphological differentiation and disparity of anterior trunk vertebrae have been explained by different functional demands upon anterior vertebrae compared to the subsequent, posterior ones (Worthington & Wake, 1972; Scholtes et al., 2021).

We gathered data on *Lissotriton* vertebrae size and shape to analyze patterns of covariation (allometric variation, regionalization and integration), and we discuss our findings relative to three concepts of differentiation of the vertebral column in salamanders. Allometric variation is analysed because it is generated by variation in developmental processes that affect multiple traits, resulting in overall patterns of covariation, and it contributes to morphological integration and modularity (Mitteroecker & Bookstein, 2007; Klingenberg, 2013, 2016; Hallgrímsson et al., 2019). To explore regionalization, we used segmented linear regression (SLR) (Head & Polly, 2015; Jones et al., 2018) which provides information on the most probable changes in the pattern of covariation and suggests possible regions. Morphological integration was quantified as the strength of covariation among vertebrae using two-block partial least squares (PLS) (e.g., Bastir & Rosas, 2005; Klingenberg, 2009). We expected to observe higher integration within regions and lower integration among vertebrae from different regions.

Material and Methods

The studied material consists of 74 adult male specimens belonging to two closely related species *Lissotriton schmidtleri* (Raxworthy, 1988) and *L. vulgaris*, the latter being represented by the subspecies *L. v. vulgaris* (Linnaeus, 1758), *L. v. ampelensis* (Fuhn, 1951) and *L. v. meridionalis* (Boulenger, 1882). These taxa were chosen because they are phylogenetically close (Pabijan et al., 2017) and show similar patterns of morphological differentiation of the trunk region (Scholtes et al., 2021).

The material was either ethanol preserved as is, or prepared as cleared and stained skeletons preserved in glycerin. Detailed sample data on taxonomy, geographical origin, type of preservation and collection details are provided in Appendix I. For each specimen the atlas, the

158 1st to 12th or 13th trunk vertebrae and the sacral vertebrae were scanned with a SkyScan 1172
159 micro-CT scanner (Bruker Corporation) at a resolution of 26.33 µM (32 kV, 0.5 µM aluminium
160 filter, 0.7 degrees rotation steps, 175 ms exposure time, 180 degrees object scanning and a
161 manual flat field correction set at 35 kV). The data were processed into 3D models with Avizo
162 9.5 software (FEI, Thermo Fisher Scientific) (Figure 1A). The configurations of 14 landmarks
163 for the atlas and 18 landmarks for the trunk and sacral vertebrae (Figure 1B) were digitized using
164 the Landmark IDAV 141 v.3.6 software (https://landmark2.software.informer.com/3.6/) by a
165 single observer (MA). A morphological description of the landmarks is provided in Appendix II.
166 Raw morphometric data is provided in a supplementary file (Supplementary data S1).
167
168 *Shape variables*
169 We generated the matrix of shape coordinates for each vertebra using a generalized Procrustes
170 analysis (GPA) (Rohlf & Slice, 1990; Dryden & Mardia, 1998), that accounts for object
171 symmetry and quantifies the symmetric components of shape variation (Klingenberg et al.,
172 2002). The principal components (PC scores) from principal component analysis were used as
173 shape variables and centroid size (CS) was used as a measure of general size (Zelditch et al.,
174 2012). CS values are provided in a supplementary file (Supplementary data S1). For the subset of
175 individuals (N = 12, 7 *L. v. meridionalis* and 5 *L. v. vulgaris*) for which standard length (Snout-
176 vent length, SVL) was available, we found a strong correlation between CS and standard body
177 length ($r = 0.88$, $p < 0.05$ and $r = 0.99$, $p < 0.05$, respectively).
178
179 *Analyses of allometric variation*

For each vertebra the divergence in allometric slopes among taxa was tested for homogeneity of regression slopes with a multivariate analysis of covariance (MANCOVA), with shape variables (PC scores) as the dependent variables, (sub)species as a factor and log-transformed CS (logCS) as a covariate. For the comparisons of allometric variation among vertebrae within the vertebral column, the subset of *T. v. vulgaris* with the largest sample size (n = 47, Appendix I) was used. The homogeneity of slopes was similarly tested with vertebra as a factor. The differences in allometric slopes between vertebrae were further explored by comparisons of allometric regression slopes among vertebrae. At statistical evaluation the Bonferroni correction for multiple comparisons was applied. The PCAs were done with MorphoJ software v. 1.06 (Klingenberg, 2011) and MANCOVAs were done with the Statistica 10 software package (Statistica for Windows; StatSoft, Inc., Tulsa, USA).

Trunk regionalization

Principal component analysis on the mean shape values of the individual trunk vertebrae for each (sub)species was used to explore patterns of shape variation and for SLR analyses. The series of continuous regression lines was fit to the slopes of the PC scores, and boundaries of regions were determined from the transition points that minimized the sum of squares (Head & Polly, 2015). The Akaike information criterion (AIC) weighted average of the relative fit was calculated to represent the amount of regionalization for each of the region models (Jones et al., 2018) with a maximum of three, for the cervical, thoracic and lumbar region. The SLR- and AIC-fittings were calculated with the *Regions* package (Jones, 2018) in R version 4.1.1. (R core team, 2021).

Morphological integration

To estimate the strength of covariation between vertebrae we employed a two-block PLS analysis, based on a singular value decomposition of the matrix of covariances between the two sets of variables (Bookstein, 1991; Rohlf & Corti, 2000; Young & Hallgrímsson, 2005). This approach is suitable for testing covariation between the two separate sets of landmarks, with separate Procrustes superimpositions (Bastir & Rosas, 2005; Klingenberg, 2009; McCane & Kean, 2011; Neaux et al., 2013; Urošević et al., 2020). The measures of covariation between the vertebrae were the RV coefficient (Klingenberg, 2009, 2011) and z-scores (Adams & Collyer, 2016). The RV coefficient is a generalization of Pearson's correlation coefficient (Escoufier, 1973). Statistical significance of the RV coefficients was assessed via a permutation test against a null hypothesis of total independence (Good, 2000; Manly, 2007; Klingenberg, 2009, 2011) under Bonferroni correction for multiple comparisons. Because the use of the RV coefficient has been criticized on the ground that it is sensitive to sample size and other variables (Adams, 2016; Adams & Collyer, 2016) we repeated analyses corrected for the effect of (sub)species by applying multivariate regression, with shape as the dependent variable and (sub)species numerically coded and used as an independent variable. Two-block PLS was then done on the regression residuals. For the quantification of the covariation strength we used z-scores, centered on their estimated empirically expected values, with statistical significance estimated by a randomization test with 999 permutations (Adams & Collyer, 2016).

Morphological integration was tested between structures (atlas, trunk and sacral vertebrae) in pairwise manner on the covariance matrices pooled within taxa. RV coefficients were calculated with MorphoJ software v. 1.06 (Klingenberg, 2011) and z-scores were calculated with *Geomorph 4.0.0.* package (Adams et al., 2021). A heat map visualization of the results was

produced with the *Lattice* and *LatticeExtra* packages (Sarkar, 2008; Sarkar & Andrews, 2019) in R. All R scripts used are provided as a supplementary file (Supplementary data S2).

Results

Analyses of allometric variation

The MANCOVA analysis testing for homogeneity of allometric slopes between sub(species) over individual vertebrae (Supplementary Table S3) showed that allometry was not statistically significant, except for the 10th and 11th trunk vertebrae ($F_{26,42}$ = 2.85, P = 0.0012 and $F_{26,39}$ = 3.06, P = 0.0008, respectively). A significant (sub)species × logCS interaction ($F_{78,117.49}$ = 1.87, P = 0.001) was found only for the 7th trunk vertebra which also diverged in shape among taxa ($F_{78,117.49}$ = 1.81, P = 0.002).

A statistically significant difference of allometric slopes of vertebrae was found within the vertebral column (Table 2). Pairwise comparisons revealed highly significant slope differences between the 3th and 5th and 6th and 12th trunk vertebrae (Table 3). Because of the absence of statistically significant allometry at the sub(species) level and statistically significant differences in allometric slopes between vertebrae along the vertebral column, we did not apply a correction for allometry in subsequent analyses.

Trunk regionalization

Similar patterns of variation in vertebrae shape were found across the four (sub)species (Figure 2). In all taxa the first and second PC axes together explained >90% of the total shape variation. The first axis explained a shape gradient from the shortened and widened anterior vertebrae with increased height to the elongated, narrower posterior vertebrae with reduced height. The second

axis explained a shift from the mid-trunk vertebrae which were shorter, with a higher neural arch to the posterior-most vertebrae that were elongated, with a reduced neural arch (Figure 2). The SLR analyses yielded the best fit for the two-region model (Table 1). The transition point corresponded to the 5th trunk vertebra in all taxa (Table 4, Figure 3).

Morphological integration

The estimation of morphological integration ranged from moderate (0.3<RV<0.5) to strong (RV>0.5) and was statistically significant for all pairs of vertebrae, except for the atlas and all other vertebrae, excluding the 1st, 2nd and 5th trunk vertebrae. The strongest morphological integration was detected at the 6th and 7th trunk vertebrae (Figure 4; Supplementary table S2). Integration levels estimated from z-scores varies from weak (z<2) to moderate (2<z<4) and strong (z>4) and was the highest between the 3rd and 7th trunk vertebrae. The strongest integration between adjacent vertebrae was between the 1st and 2nd, 2nd and 3rd, 5th and 6th and 8th and 9th trunk vertebrae. Among the adjacent trunk vertebrae, there was no significant integration between the 9th and 10th and the 11th and 12th (Figure 4, Supplementary table S4).

Discussion

The tetrapod body plan is determined by *Hox* genes and is largely developmentally constrained. The regionalization of the vertebral column in tetrapods, which is most pronounced in mammals, is largely driven by various functional demands (Carroll, 1997; Jones et al., 2018). Based on morphological, developmental and functional criteria and the literature we considered three concepts of vertebral column regionalization in salamanders, in which one, two or three presacral regions are recognized (Table 1). Considering the results for both analytical methods separately,

271 our data support the traditional concept of regionalization with a single, highly integrated trunk,
272 and the two regions concept, which recognizes an anterior and a posterior trunk region.

273 The results are not unequivocal because the differentiation into an anterior and a posterior
274 region with a break between the 5th and 6th trunk vertebrae recognized by the SLR analysis is not
275 supported by the pattern of morphological integration observed by the PLS analysis. The
276 vertebrae within regions should, by definition, be more integrated than between regions (Wagner
277 & Altenberg, 1996; Klingenberg, 2008). However, the morphological integration is found to be
278 strongest in the mid-trunk (Figure 4) where the break point between the regions is detected
279 (Figure 3). The strong individual integration between the adjacent 1st, 2nd and 3rd vertebrae could
280 be related to the center of the anterior region whereas the atlas, sacral vertebra and 12th trunk
281 vertebra tend to have some autonomy from the remaining trunk vertebrae.

282 In summary, our results suggest a subtle pattern of regionalization, corresponding to a
283 functionally-based, two-region concept, despite a high level of integration that was observed in
284 the anterior and middle parts of the presacral vertebral column. The marked morphological
285 integration could be explained by the homogeneity of the whole vertebral column as possibly
286 required for its functional stability (Arlegi et al., 2020). In salamanders the vertebral column,
287 together with the axial musculature, provides support and locomotion in aquatic as well as
288 terrestrial environments (Duellman & Trueb, 1994). The axial musculoskeletal system in
289 salamanders has been described in detail for the fire salamander, *Salamandra salamandra*
290 (Linnaeus, 1758) (Francis, 1934). The dorsal musculature arrangement is more or less uniform,
291 with a main function in the bending and flexion of the spine. The first to fifth trunk vertebrae are
292 involved in movements of the pectoral girdle and the front limbs. The first and second trunk
293 vertebrae are connected with the cranial skeleton with the muscles involved in the coordinated

head movement and spine flection (Francis, 1934). This could explain the covariation between the 1st to 5th trunk vertebrae, notwithstanding their differences in shape (Scholtes et al., 2021). The posterior region (from the 6th to the 11th or the 12th vertebra) consists of vertebrae with similar shape and the same arrangement of muscles driving the lateral bending of the trunk during swimming and walking.

In salamanders, the axial skeleton forms during early development and remains largely unchanged during the metamorphosis. It has been proposed that the complex life cycle, with opposing functional requirements upon the axial skeleton during the larval and adult phases, constrain evolutionary changes in the vertebral column (Bonett & Blair, 2017). Therefore, changes in the pattern of regionalization might be expected in non-metamorphic taxa, including paedomorphic lineages (e.g., Sirenidae, Proteidae) and in lineages with direct development (Plethodontidae). However, a different regionalization pattern was found in *Ambystoma* with three regions (Jones et al., 2018) and *Lissotriton* with two regions (this study), that both have a complex life cycle and similar requirements for locomotory performance (swimming vs. walking). Compared to the three-region hypothesis of differentiation described for *Ambystoma* (Jones et al., 2018), the anterior trunk region in *Lissotriton* coincides with the "cervical" region whereas the posterior trunk region is uniform, without detectable differentiation in the subsequent anterior and posterior "dorsal" region (Jones et al., 2018). As clades *Ambystoma* and *Lissotriton* are unrelated. It is possible that *Ambystoma* kept the ancestral condition of regionalization including an ancestral amphicoelous morphology of the vertebrae, compared to the derived condition of ophisthocoelous vertebrae found in the family Salamandridae (Worthington & Wake, 1972; Duelman & Trueb, 1994). The morphometric study of Worthington & Wake (1972) also found that species belonging to different lineages of tailed

amphibians (namely Ambystomatidae, Salamandridae and Plethodontidae) have different patterns of morphometric variation along the vertebral column.

To further explore patterns of vertebral regionalization, modularity and morphological integration in salamanders, it would be beneficial to include different life stages (e.g., larvae vs. metamorphs), or closely related, but ecologically differentiated forms. For the genus *Lissotriton*, this points to paedomorphic populations such as found in *L. vulgaris* (Toli et al., 2022) and to the frequently stream-dwelling *L. boscai* (Lataste, 1879) from the Iberian Peninsula. Related species with different numbers of presacral vertebrae such as found within the genera *Triturus* and *Tylototriton* warrant attention (Arntzen et al., 2015), as does the genus *Salamandra* for which larviparous, pueriparous and viviparous lineages can be compared (Buckley et al., 2007). Ideally, these studies would be accompanied by data on *Hox* gene expression.

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Tables

Table 1. Concepts of regional differentiation of the presacral vertebral column in tailed amphibians.

Concept	Traditional, one region
Regions recognized	Trunk
Source	Mivart (1870), Duelman & Trueb (1994), Slijepčević et al. (2015)
Concept	A three-regions pattern conserved across the Tetrapods
Regions recognized	Cervical, anterior dorsal and posterior dorsal
Source	Jones et al. (2018)
Concept	A two-regions pattern based on morphological disparity and functional differentiation
Regions recognized	Anterior trunk and posterior trunk
Source	Worthington & Wake (1972), Govedarica et al. (2017), Scholtes, et al. (2021), present study

Table 2. Homogeneity of slopes in *Lissotriton v. vulgaris*, with the effect of vertebrae, size (logCS) and vertebra × logCS interaction, tested by a multivariate analysis of covariance. Statistically significant interaction indicates heterogenous regression slopes.

Effect	Wilks' Lambda	F	Effect df	Error df	P
Vertebra	0.836	1.74	55	2429.06	0.0007
LogCS	0.524	95.26	5	524.00	<0.0001
Vertebra × logCS	0.837	1.73	55	2429.06	0.0008

Table 3. Results of MANCOVA tests for differences in allometric slopes among vertebrae. Vertebrae are numbered from 1 to 12. Wilk's lambda values in boldface type denote statistical significance for pairwise comparisons at $P < 0.05$ after Bonferroni correction, with an adjusted alpha value of 0.0008.

	1	2	3	4	5	6	7	8	9	10	11
2	0.892										
3	0.852	0.981									
4	0.845	0.915	0.865								
5	0.828	0.829	**0.713**	0.961							
6	0.906	0.888	0.842	0.931	0.932						
7	0.871	0.899	0.803	0.968	0.965	0.949					
8	0.846	0.966	0.953	0.936	0.833	0.919	0.868				
9	0.910	0.933	0.892	0.961	0.960	0.975	0.974	0.952			
10	0.928	0.984	0.944	0.925	0.841	0.927	0.904	0.954	0.951		
11	0.874	0.975	0.957	0.963	0.869	0.912	0.888	0.984	0.946	0.966	
12	0.873	0.933	0.883	0.848	0.798	**0.775**	0.808	0.875	0.836	0.925	0.907

Table 4. Results of a segmented linear regression analysis on vertebrae shape averaged for *Lissotriton* (sub)species. The most likely regionalization models are shown in boldface type.

(Sub)species	Regions	T1	T2	sumRSS	AICc	deltaAIC	model_lik	Ak_weight
Lissotriton schmidtleri	**2**	**5**	**0**	**2.75**	**-21.19**	**0.00**	**1.0000**	**0.9937**
	3	3	5	0.68	-10.92	10.26	0.0059	0.0059
	1	0	0	12.35	-5.85	15.34	0.0005	0.0005
Lissotriton v. ampelensis	**2**	**5**	**0**	**3.02**	**-18.86**	**0.00**	**1.0000**	**0.8253**
	3	4	7	0.55	-15.74	3.12	0.2102	0.1735
	1	0	0	12.35	-5.84	13.03	0.0015	0.0012
Lissotriton v. meridionalis	**2**	**5**	**0**	**2.28**	**-25.61**	**0.00**	**1.0000**	**0.9998**
	3	3	9	0.78	-7.71	17.90	0.0001	0.0001
	1	0	0	11.91	-6.71	18.89	0.0001	0.0001
Lissotriton v. vulgaris	**2**	**5**	**0**	**1.81**	**-40.06**	**0.00**	**1.0000**	**0.9654**
	3	4	9	0.56	-33.40	6.66	0.0359	0.0346
	1	0	0	12.99	-8.14	31.93	0.0000	0.0000

Figures

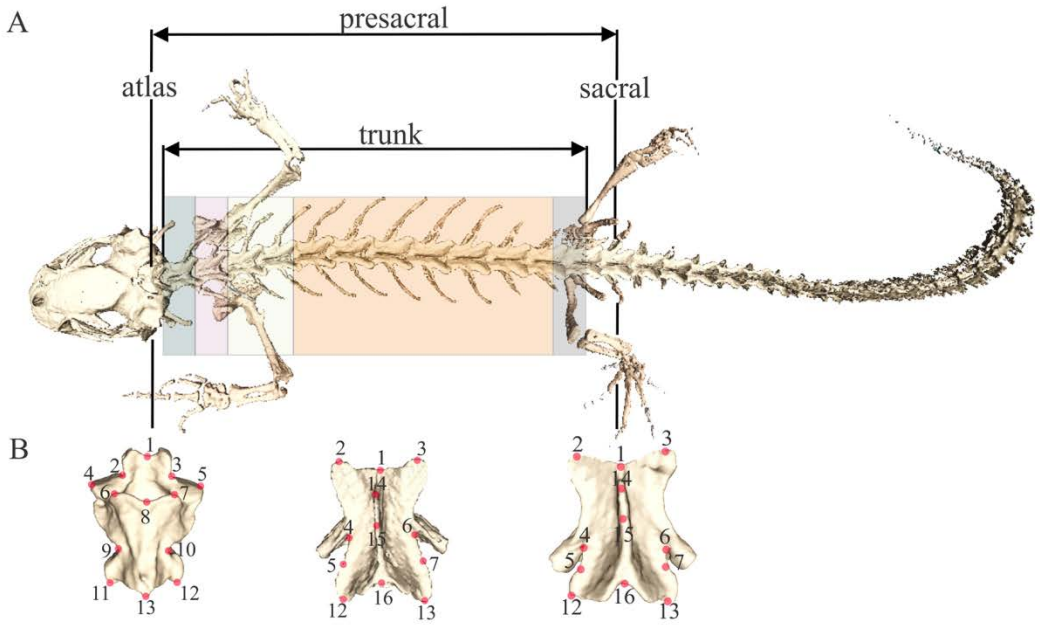
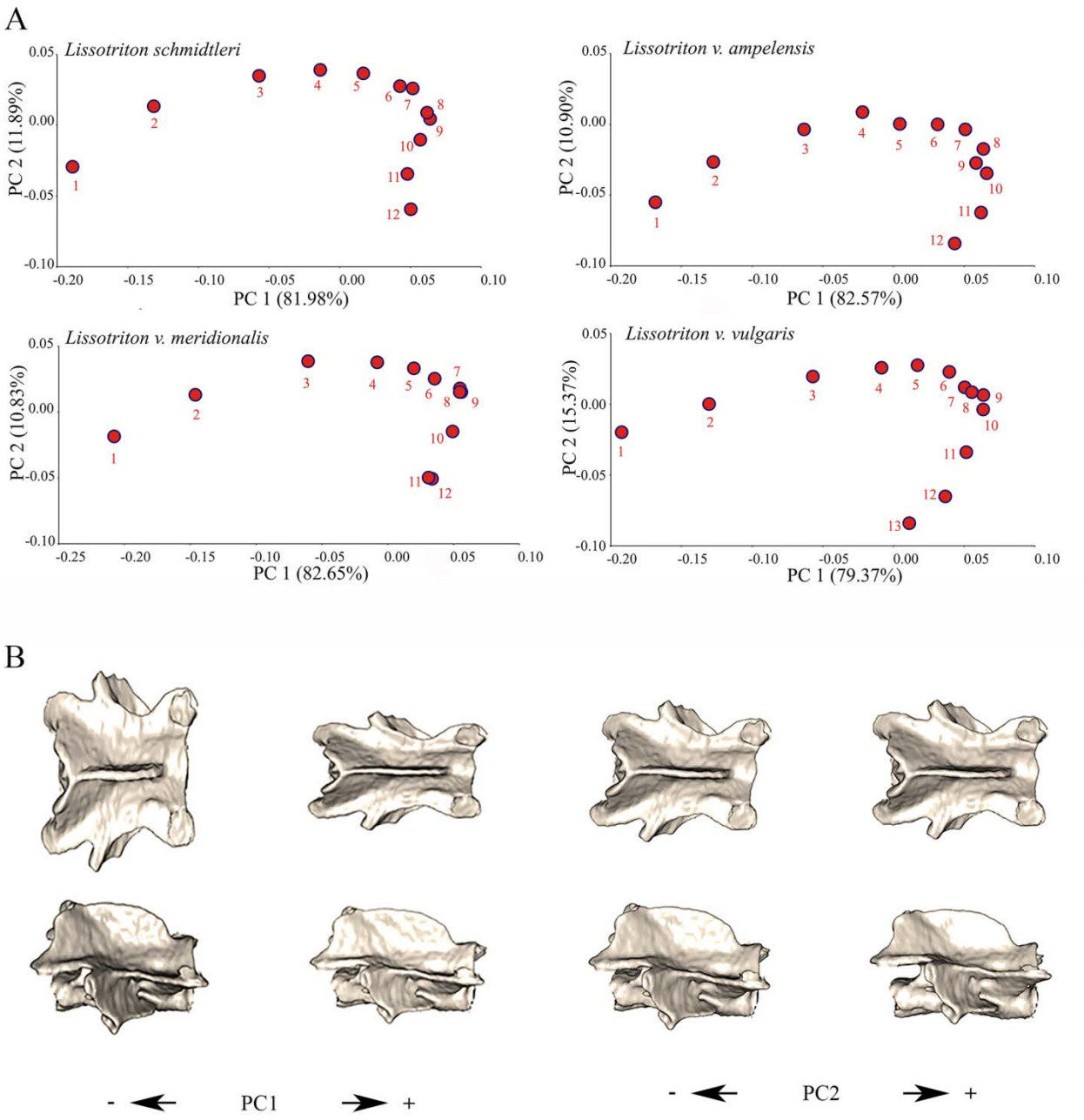


Figure 1. Morphological differentiation and regionalization of the presacral vertebral column in *Lissotriton* newts showing (A) different morphologies of trunk vertebrae, indicated by different color shadings, and (B) the configuration of the landmarks used to describe the shape of the atlas and the trunk and sacral vertebrae.



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587 **Figure 2.** Shape changes of trunk vertebrae in four *Lissotriton* taxa with (A) the position of the

588 trunk vertebrae over numbers 1 to 12 or 13, and (B) the gradient of shape changes over the first

589 and second principal component axis.

590

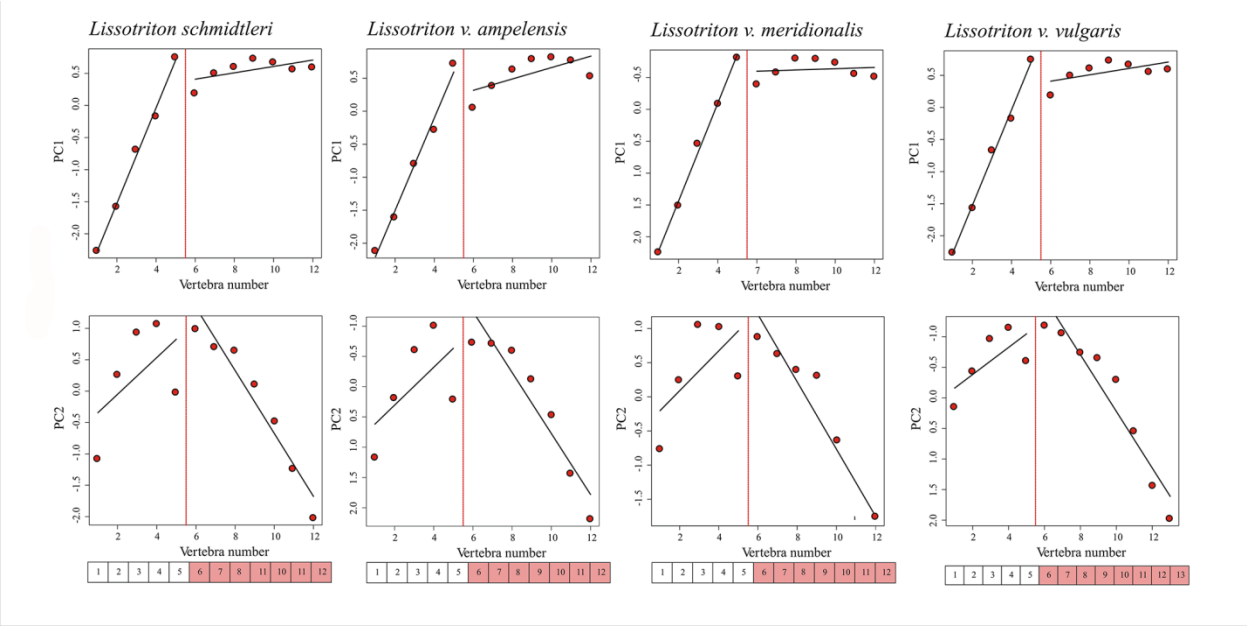

Figure 3. Results of segmented linear regression analysis of the trunk vertebrae in four *Lissotriton* taxa. Dots show the scores along the first (top panel) and second (bottom panel) axis of a principal component analysis for vertebrae 1-12. Region models are shown in bars below each of the graphs.

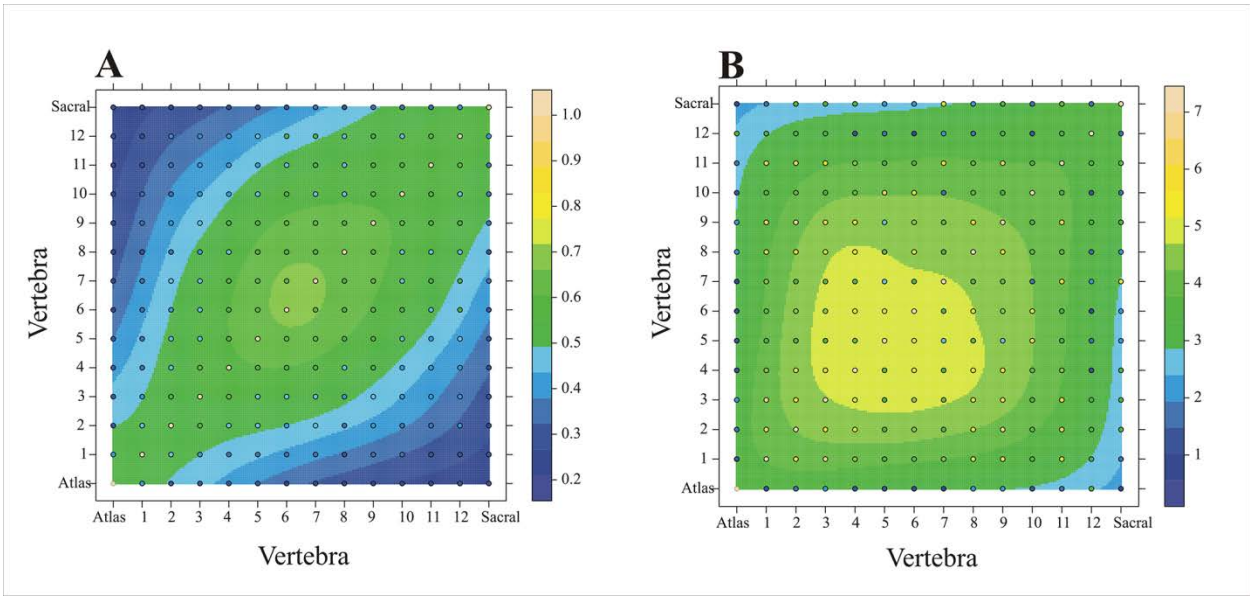

Figure 4. Heat maps presenting patterns of morphological integration of the presacral vertebral column in *Lissotriton* newts. Dots represent individual pairwise correlations corrected for (sub)species for (A) RV scores on the symmetric component of the shape variation, and (B) z-scores on total shape. For actual values see color bars.

Appendices

Appendix I. Analyzed material with scientific name, taxonomic authority, sample size (N), collection identification numbers (ID), locality of origin and type of preservation (ethanol preserved whole animals and glycerin stored skeletons).

Species and (sub)species	N	Collection	ID	Locality	Preservation
Lissotriton schmidtleri (Raxworthy, 1988)	13	IBISS	OZ 58 G21921; OZ 58 G21932; OZ 58 G21934; OZ 58 G2193235; OZ 58 G21937-40; OZ 58 G21948-50; OZ 58 G21952; OZ 58 G21953	Efes, Turkey	Glycerin
L. v. meridionalis (Boulenger, 1882)	8	IBISS	2373 15625; 2373 15629; 2373 15633; 2373 15641-44; 2373 15646	Podstrmec, Slovenia	Ethanol
L. v. ampelensis (Fuhn,1951)	6	IBISS	OZ 62 G22595; OZ 62 G22598; OZ 62 G22600-03	Garda de Sus, Romania	Glycerin
L. v. vulgaris (Linnaeus, 1758)	5	IBISS	2579 17780; 2579 17788; 2579 17795; 2579 17797; 2579 17813	Valjevo, Serbia	Glycerin
L. v. vulgaris (Linnaeus, 1758)	20	ZMA.RENA	9270 (1-20)	Marcillé-la-Ville, France	Ethanol
L. v. vulgaris (Linnaeus, 1758)	22	RMNH.RENA	9521 (1-14); (G, H, J-M, O, P)	Hoensbroek, The Netherlands	Ethanol

IBISS – University of Belgrade, Institute for Biological Research "Siniša Stanković" – National Institute of the Republic of Serbia, RMNH.RENA and ZMA.RENA – Naturalis Biodiversity Center, Leiden, The Netherlands.

Appendix II. The configuration of 14 three-dimensional landmarks identified on the atlas and 18 three-dimensional landmarks on the trunk and sacral vertebrae of *Lissotriton* newts. For a visualization see Figure 1B.

Structures	Number	Description
Atlas	1	Tip of processus odontoideus
	2,3	Maximal constriction of processus odontoideus
	4,5	Most lateral point of occipital joint
	6,7	Tip of the lamina
	8	Tip of the vertebra on the dorsal side
	9,10	Maximal constriction of vertebra
	11,12	Maximal curvature of the postzygapophysis
	13	The end of vertebra on the dorsal side
	14	Tip of the cotylus
Trunk and sacral vertebrae	1	Neural arch – anterior, above vertebral foramen
	2,3	Prezygapophysae – antero-lateral margins
	4,6	Neural arch – lateral margin at the level of rib-bearers
	5,7	Maximal constriction of the postzygapophysis
	8,10	Parapophyses – articulation point
	9,11	Diapophyses – articulation point
	12,13	Postzygapophysae – posterio-lateral margins
	14	Neural spine – the most anterior part
	15	Neural spine – the midle part
	16	Neural spine – the most posterior part
	17	The anterior tip of the condylus
	18	Tip of the cotylus

Supporting information

Supplementary data S1. Raw morphometric data and Centroid Size values for the atlas, 1st to 12th (or 13th) trunk and sacral vertebra of *Lissotriton* (sub)species. Information is given on the individual (ID), the (sub)species (Taxon) and the raw coordinates for altogether 32 landmarks (RawCoord1 - RawCoord42 for atlas) or (RawCoord1 - RawCoord54 for trunk and sacral vertebrae).

Supplementary file S2. R scripts used in the study for the packages *Regions* (Jones, 2018), *Geomorph* (Adams et al., 2021), *Lattice* (Sarkar, 2008) and *Lattice Extra* (Sarkar & Andrews, 2019).

Supplementary table S3. Homogeneity of slopes for vertebrae allometry, with the effect of (sub)species, size (logCS) and (sub)species x logCS interaction, tested by multivariate analysis of covariance. Statistically significant (sub)species x logCS interactions indicate heterogenous regression slopes. The Bonferroni adjusted alpha 0.05 value is 0.0036. Comparisons that are statistically significant are in boldface type.

Supplementary table S4. Generalized Pearson correlation coefficients among vertebrae in *Lissotriton* newts with RV values in the top panel and z-score in the bottom panel. The Bonferroni adjusted value for alpha 0.05 is 0.00055. Data in boldface statistical significance of the pairwise comparisons.