Rise of dinosaurs reveals major body-size transitions are driven by passive processes of trait evolution

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A major macroevolutionary question concerns how long-term patterns of body-size evolution are underpinned by smaller scale processes along lineages. One outstanding long-term transition is the replacement of basal therapsids (stem-group mammals) by archosauriaomorphs, including dinosaurs, as the dominant large-bodied terrestrial fauna during the Triassic (approx. 252–201 million years ago). This landmark event preceded more than 150 million years of archosauriaomorph dominance. We analyse a new body-size dataset of more than 400 therapsid and archosauriaomorph species spanning the Late Permian–Middle Jurassic. Maximum-likelihood analyses indicate that Cope’s rule (an active within-lineage trend of body-size increase) is extremely rare, despite conspicuous patterns of body-size turnover, and contrary to proposals that Cope’s rule is central to vertebrate evolution. Instead, passive processes predominate in taxonomically and ecologically more inclusive clades, with stasis common in less inclusive clades. Body-size limits are clade-dependent, suggesting intrinsic, biological factors are more important than the external environment. This clade-dependence is exemplified by maximum size of Middle–early Late Triassic archosauriaomorph predators exceeding that of contemporary herbivores, breaking a widely-accepted ‘rule’ that herbivore maximum size greatly exceeds carnivore maximum size. Archosauriaomorph and dinosaur dominance occurred via opportunistic replacement of therapsids following extinction, but were facilitated by higher archosauriaomorph growth rates.

Keywords: evolutionary trends; body size; Cope’s rule; Archosauriaomorpha; Therapsida; Permo-Triassic

1. INTRODUCTION

Body size is a trait that is fundamental to the biology of all animals [1–3] and covaries with key ecological, physiological and life-history traits such as range size, fecundity, metabolic efficiency and thermal physiology [4]. Body size has a complex interaction with individual fitness [5]; larger animals are often more successful in obtaining food, territory and mates [6,7], but are more susceptible to extinction, and in some cases predation, having lower fecundity, and requiring more resources per individual [7]. One of the longest noted trends in vertebrate evolution is a perceived tendency towards larger body sizes during the evolution of a clade: Cope’s rule [8–10]. Cope’s rule denotes an ‘active’ within-lineage directional trend of increase, generally held to be driven by selection for larger body size [7,11]. This results in increasing maximum and minimum body size through time within a clade [9]. In contrast, ‘passive diffusion’ denotes an increase in trait variance over evolutionary time without unidirectional selection, yielding an increase in maximum body size, but unaltered or decreasing minimum size [12,13]. Whether ‘active’ within-lineage processes, or ‘passive’ processes resulting from differential among-lineage effects are responsible for large-scale patterns of body-size evolution in deep time is an enduring question in evolutionary biology and palaeontology [9,14,15].

The effects of trophic interactions on body size are also of great interest to biologists [16]. In terrestrial faunas, the largest herbivores tend to be an order of magnitude larger than the largest closely related carnivores [17], and body size in carnivores and herbivores tends to correlate in time and space [18]. However, these ecological ‘rules’ are derived almost exclusively from the mammal-dominated fauna of the past 65 million years (Myr), and their general applicability has not been extensively tested. The ca 100 Myr time span from the Late Permian (approx. 260 million years ago (Ma)) to the Middle Jurassic (approx. 160 Ma) provides an excellent case study of terrestrial vertebrate body-size evolution. This interval witnessed the ‘rise’ of dinosaurs and other archosauriaomorphs (birds, crocodiles and their extinct relatives including dinosaurs and pterosaurs, [19–21]) to more than 150 Myr of dominance as large-bodied terrestrial vertebrates, coincident with the ‘fall’ of the previously dominant therapsids (stem-group mammals; [22]). This landmark transition is bracketed by two of the largest mass extinctions in Earth’s history, at the Permo-Triassic (approx. 252.2 Ma, [23,24]) and Triassic–Jurassic (approx. 201.5 Ma, [23,25]) boundaries [26,27]; it may be causally linked to these events, and to smaller extinction events within the Triassic [20,28,29]. Ornithodiran archosauriaomorphs included the largest land animals (saurapod dinosaurs) and the largest flying organisms (azhdarchid pterosaurs) ever to exist, and

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dinosaurs especially have long been icons of Cope’s rule [30]. However, other analyses of body-size evolution in dinosaurs suggest a more complex situation [31], or the absence of selection-driven trends [32].

We examine body-size evolution in multiple clades over an extended time interval. Non-phylogenetic (time series) and phylogenetically informed modelling approaches are used to analyse more than 400 species from the two dominant clades of Late Permian–Middle Jurassic terrestrial vertebrates (Archosauromorpha and Therapsida). We test whether the major patterns in body-size evolution that accompanied the rise and decline of these clades (figure 1) are the result of clade-wide, ‘active’ within-lineage, directional trends towards increased or decreased body size (Cope’s rule and its inverse). Moreover, we investigate the relationship between carnivore and herbivore body size within the time interval, and discuss its implications for the role of intrinsic, biological factors in body-size evolution.

2. MATERIAL AND METHODS

(a) Body mass proxy data

Femoral length was used as a body size proxy because it shows a consistent relationship with body mass in terrestrial vertebrates [33], and has been used in previous studies of archosauromorphs [31,32]. Femora have not been described for 77 per cent of the therapsids sampled, but use of femoral length was required to yield absolute values comparable with those of Archosauromorpha. Thus, for many therapsids, femoral length was estimated based on basal skull length using regression equations (see the electronic supplementary material). This is justified because basal skull length is tightly correlated ($R^2 = 0.903$, $p < 0.001$, $n = 26$) with femoral length for therapsids in which both were described from the same individual.

(b) Dating

Taxa were dated to geological stage (see the electronic supplementary material), with ranges representing either stratigraphic uncertainty or genuine observed ranges. Most taxa were assigned ranges based on age and formation assignments in the Paleobiology Database (http://paleodb.org), updated with more recent information where appropriate. Absolute ages for stages were based on Walker & Geissman [23].

(c) Phylogenies

Phylogenies were compiled for Archosauromorpha and Therapsida using an informal supertree approach ([20,32,34], see the electronic supplementary material, figures S1 and S2 and table S1). Source phylogenies were chosen for their recentness and comprehensiveness of taxon and/or character sampling. The phylogenies were calibrated against time (see the electronic supplementary material), with taxa assigned absolute ages by taking the range midpoint. Unconstrained/zero length nodes/branches were given a date/length by setting a root length and sharing this time equally between unconstrained branches [19], using the date.phylo() function of Graeme Lloyd (http://www.graemetlloyd.com/methdpf.html).

(d) Time-series model fitting

Time-series models provide an approximation of the trajectory of mean body size within clades without reference to phylogeny or individual evolutionary lineages. Time-series analyses were carried out in R v. 2.13.1 [35] using the paleoTS package [36]. Data were binned by stage, with...
taxa placed in each bin that their stratigraphic range overlapped. Four models—generalized random walk (GRW), unbiased random walk (URW), an Ornstein–Uhlenbeck (OU) process and stasis—were fitted to mean body size and variance for each stage for 12 different clades (Gorgonopsia was not analysed alone owing to small sample sizes). GRW is a random walk with a non-zero step mean, corresponding to a directional evolutionary trend. URW is a random walk with a zero step mean corresponding to noticeable trait variation through time, but no consistent directional trend. An OU process is evolution towards an optimum, which becomes exponentially less attractive as the optimal value is neared. The Akaike information criterion (AICc) with correction for finite sample sizes was used to calculate Akaike weights and thus compare models (see the electronic supplementary material). To make assumptions more realistic for populations related by cladogenesis, and because variances showed significant heteroskedasticity, variances were not pooled between bins. Joint parameterization was used for all tests. Binning with uniform 5 Myr bins was carried out to assess sensitivity to the timescale used. Analyses were also repeated with binned means and variances for only the taxa present in the phylogenies to allow comparison with phylogenetic models (see the electronic supplementary material).

(c) Phylogenetic model fitting
Maximum-likelihood models were used to investigate body-size evolution ([32,37]). Five models—Brownian motion (BM) with trend, BM, stasis, OU and early burst (EB)—were fitted to 13 clades. BM with trend is equivalent to a GRW (see §2d) and thus approximates directional within-lineage evolution (see [38]), BM is equivalent to an URW (see §2d), and EB is an exponentially decreasing rate of evolution through time. Model fitting was carried out in R using the package GEIGER [39]). The five models listed above were fitted for 13 clades. AICc was used to compare models. Analyses were also carried out in which species were dated using the lower bound of their stratigraphic range rather than the midpoint to assess the sensitivity of results to inaccuracies in dating (see the electronic supplementary material).

(f) Generalized least-squares regression of carnivore and herbivore size
Generalized least-squares regression models were analysed in R using the gls() function from the nlme package [40] with herbivore size as a predictor of carnivore size, and compared with a null model using AICc and Akaike weights, both with no autoregressive model (AR0, equivalent to ordinary least-squares regression) and with a first-order autoregressive (AR1) model. Data were again binned by stage.

3. RESULTS
(a) Large-scale patterns of body-size evolution
Our body-size data clearly show a sustained increase in archosauromorph size and decrease in therapsid size over the study interval (figure 1a). Archosauromorphs attained large sizes only after extinction or decimation of therapsids of the same trophic guild. Thus, archosauromorph carnivores increased in size after the Permain–Triassic boundary extinction of gorgonopsians (hypercarnivorous therapsids), and archosauromorph herbivores increased in size during the Triassic following extinction of most anomodonts (large herbivorous therapsids; see electronic supplementary material, figure S3). From the Anisian to the early Norian (245–216 Ma), carnivore maximum body size is larger than herbivore maximum body size (figure 1b), with archosauromorphs being the largest carnivores and therapsids the largest herbivores during this interval.

(b) Time-series model fitting
An URW model recorded the best AICc score for both Archosauromorpha and Therapsida. The fit of GRW models was non-negligible, with positive (Archosauromorpha) and negative (Therapsida) step means (μ), reflecting long-term body-size differentiation (figure 1a). For Dinosauria and Theropoda (predatory dinosaurs), the GRW model fitted best, and μ was higher than for other archosauromorphs, reflecting more rapidly increasing mean body size than witnessed in non-dinosaurian archosauromorphs. An URW model fitted best for ornithischian dinosaurs, Pterosauria, Pseudosuchia (crocodilians and their stem group) and Cynodontia (the derived therapsid clade including mammals). An OU model fitted best for sauropodomorphs, aetosaurs (herbivorous/ omnivorous Triassic pseudosuchians) and anomodonts, with a higher optimum body size (θ) in sauropodomorphs (3.031 log10 mm) than anomodonts (2.484 log10 mm) or aetosaurs (2.266 log10 mm). At least one other model was non-negligible for all clades except Aetosauria and Pseudosuchia (table 1). Results using uniform 5 Myr time binning were similar but favoured more directional models (see the electronic supplementary material).

(c) Phylogenetic model fitting
Maximum-likelihood models of body-size evolution demonstrate that active trends fit the phylogeny poorly compared with other models (figure 2 and table 2; modelled as BM with trend). BM, stasis and EB models provided the best fit (lowest AICc scores) for most clades (BM in Archosauromorpha, Dinosauromorpha, Theropoda and Anomodontia; stasis in Sauropodomorpha, Ornithischia, Aetosauria, Pterosauria and Theropoda; EB in Pseudosuchia, Therapsida and Cynodontia), and an OU model fitted best for Gorgonopsia. At least one other model was non-negligible (Akaike weight greater than 1/8 that of the best model) for most clades (figure 2 and table 2). Results when lower range bounds were used as taxon ages were qualitatively similar to those based on range midpoints (see the electronic supplementary material).

(d) Regression of carnivore and herbivore size
A generalized least-squares regression model using herbivore maximum and mean body size to predict carnivore size substantially outperformed a null model when Therapsida and Archosauromorpha were examined together with no autoregressive model (AR0, equivalent to ordinary least-squares regression, table 3). However, the null model (though worse) was non-negligible for Archosauromorpha analysed alone, and outperformed the herbivore model for Therapsida analysed alone, suggesting inconsistent within-clade relationships through the study interval. When an autoregressive model (AR1) was implemented, the null model was best supported for most comparisons. Under this model, a strong, significant relationship, with substantially better (lower) AICc than
Table 1. Summary of results for time-series model fitting for archosauromorph and therapsid clades. Higher Akaike weight (A.W.) indicates a better model fit. | Generalized random walk indicates an evolutionary trend, unbiased random walk indicates significant variation but no trend and OU indicates evolution towards an optimum. No shading and bold text, best model; light shading, non-negligible models (A.W./C21/8 best model), dark shading, negligible models (A.W./C21/8 best model). |

<table>
<thead>
<tr>
<th>clade</th>
<th>n</th>
<th>A.W.</th>
<th>$\sigma^2$ (log mm)</th>
<th>A.W.</th>
<th>$\sigma^2$ (log mm)</th>
<th>A.W.</th>
<th>$\sigma^2$ (log mm)</th>
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<th>$\sigma^2$ (log mm)</th>
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<tr>
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<td>0.001</td>
<td>0.266</td>
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<tr>
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<td>0.128</td>
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<td>0.001</td>
<td>0.266</td>
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Indeed, archosauromorphs exhibited repeated episodes of secondary size reduction, e.g. in drepanosauromorphs (small, superficially lizard-like archosauromorphs), basal pterosaurs and coelurosaurian theropod dinosaurs. Four large and ecomorphologically varied subclades of Archosauromorpha (Dinosauria, Theropoda and Pseudosuchia) and Therapsida (Anomodontia) favour a BM model, reflecting passive expansion into a range of niches. An EB model favoured for Cynodontia reflects their early ecological diversification into larger ('non-probainognathan') and smaller bodied ('probainognathan') subclades. The subclades best modelled by stasis or the null model was only recovered for maximum body size, and only when considering Archosauromorpha and Therapsida together.

4. DISCUSSION

Our phylogenetic results demonstrate that passive processes governed body-size evolution during a major reorganization of dominance in the terrestrial environment. Though Cope’s rule has been supported for fossil mammals [10,42] and some dinosaurian clades [30,37], it did not occur in all dinosaurs [31,32], including Mesozoic birds [43], and no neontological studies support its occurrence [3,44]). The results of our phylogenetic models provide little evidence for active trends towards higher (or lower) body sizes during the Late Permian–Middle Jurassic interval (approx. 260–160 Ma, figure 2 and table 2), despite overall increasing mean size in archosauromorphs, and decrease in therapsids (figure 1, and demonstrated by step means in non-phylogenetic random walk models, table 1). Within-lineage processes do not follow Cope’s rule, or its inverse (a selection-driven decrease in body size). Instead, large-scale patterns are underlain by passive expansion of clades into smaller and larger body-size niches, with relative stasis within these niches (i.e. in less inclusive, less ecomorphologically varied clades). Thus, apparent ‘trends’ in body-size evolution resulted from changes in niche diversity, mediated by differential among-lineage processes such as origination followed by radiations of smaller- or larger-bodied subclades, and size-selective extinction. This agrees with previous work finding passive trends in size in more inclusive clades and longer time intervals and lack of trends at smaller scales and when phylogeny is taken into account [14,15,45].
OU models have a limited ecomorphological variation (Sauropodomorpha, Ornithischia, Pterosauria, Aetosauria, Theropoda and Gorgonopsia) during the study interval, and include the least inclusive clades examined. These clades thus exhibit the patterns expected of groups constrained within particular niche optima by selection.

The lack of evidence for within-lineage active trends of size increase among archosauromorphs and therapsids sheds new light on the enduring topic of reasons for archosaur and dinosaur ascent and therapsid downfall [19,20,28,29,32,46]. A major question is whether this shift followed Liu et al. [41] (see the electronic supplementary material, table S1). Full phylogenies are given in the electronic supplementary material, figures S1 and S2 and stage abbreviations in the electronic supplementary material, table S2.

Figure 2. Simplified archosauromorph (top) and therapsid (bottom) phylogenies calibrated against time from the Permian to Jurassic with Akaike weights of phylogenetic models of body-size evolution displayed as pie charts next to clades for which analyses were carried out. Thick lines indicate observed stratigraphic range, thin lines indicate inferred range based on phylogeny, and thick lines with diagonal striping indicate uncertainty in observed range. Relationship between therapsid clades follows Liu et al. [41] (see the electronic supplementary material, table S1). Full phylogenies are given in the electronic supplementary material, figures S1 and S2 and stage abbreviations in the electronic supplementary material, table S2.

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Table 2. Summary of results for phylogenetic model fitting for archosauromorph and therapsid clades. Key as for table 1 except:

- $r$, decay rate for exponentially changing rate of evolution.
- Brownian motion (BM) with trend indicates an evolutionary trend, BM indicates significant variation but no trend, OU indicates evolution towards an optimum and early burst indicates Ornstein–Uhlenbeck (OU) early burst (EB).

<table>
<thead>
<tr>
<th>Clade</th>
<th>Brownian motion (BM) with trend</th>
<th>Brownian motion (BM)</th>
<th>n</th>
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<th>$\rho$ (log mm) A.W.</th>
<th>$\Delta$ (log mm) A.W.</th>
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The authors thank A. B. Smith (Natural History Museum, London) for continued advice and discussions, G. Lloyd (Natural History Museum, London) and P. D. Mannion (University College London) for comments on the manuscript and methodological advice, G. Hunt (Smithsonian Institution), L. J. Harmon (University of Idaho), and F. Marx (University of Otago) for methodological advice, F. Abdala (University of the Witwatersrand) and P. Galton (University of Bridgeport) for discussion and direction towards occurrence and size data, and K. Tang (University College London) for assistance with Chinese language literature. S. Brusatte and an anonymous reviewer provided useful comments that improved the final version of this manuscript. Animal silhouettes in figures are from Wikipedia. R.J.B. is supported by an Emmy Noether Programme Award from the German Research Foundation.
the DFG (BU 2587/3-1). R.B.J.B. is supported by a Title A research fellowship at Trinity College, Cambridge, UK.

REFERENCES

Table 3. Summary of results for generalized least-squares regression models of carnivore maximum and mean size for both null models and models using herbivore size to predict carnivore size. The only model robustly better than null was maximum herbivore and carnivore size for both therapsid and archosauromorph taxa analysed together. AR1, first-order autoregressive model implemented to remove serial correlation. Bold Aikake weight (A.W.), herbivore models of carnivore size where null model was negligible (A.W. < 1/8 best model), bold model name, null model negligible under ordinary least squares, bold and italicized model name, null model negligible under ordinary least squares and generalized least squares with AR1.

<table>
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<tr>
<th>carnivore clade(s)</th>
<th>ordinary least squares</th>
<th>generalized least squares (AR1)</th>
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<tbody>
<tr>
<td></td>
<td>null model</td>
<td>herbivore model</td>
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<td>maximum size</td>
<td>Therapsida+Archosauromorpha</td>
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<td>Archosauromorpha</td>
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<tr>
<td>mean size</td>
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<tr>
<td></td>
<td>Archosauromorpha</td>
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