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Supplementary Information

Part A. Acknowledgments

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Part B. Systematic Paleontology of *Maiopatagium furculiferum*

Clade Mammaliaformes (1 - Rowe 1988)

Clade Haramiyida (51 - Hahn et al. 1989)

Clade (Order) Eleutherodontida (21 - Kermack et al. 1998)

Maiopatagium furculiferum Genus et Species. Nov.

Etymology: "*Maio*-," meaning "mother" in Latin, "*-patagium,*" meaning "skin membrane" in Latin, in reference of the preservation of skin membrane in the fossil; "*furculiferum*" – "furcula," meaning "fork" in Latin, "*-ferum*", meaning "similar" in Latin, in reference to the fused interclavicle and clavicles that are morphologically convergent to the wishbone of birds.

Holotype specimen: Beijing Museum of Natural History PM002940 (BMNH PM002940; hereafter abbreviated as BMNH2940, or BM2940), with almost all bones and the halo of integumentary tissues preserved on the single shale slab (designated as the main slab) (Fig. 1 and extended data Fig. S1). A thin sheet of shale covering the fossil represents a counter-layer on top of the fossil. The fragments of this counter-layer, although not complete, have preserved impression and a halo of integuments. The parts of the counter-layer are still associated the slab. The furs and soft-tissue on the intact main slab and the fractured counter-layer show a similar pattern of preserved integumentary tissues, observed using ultraviolet (UV) fluorescent.

Life Science Identifier (LSID) for the new taxon: urn:lsid:zoobank.org:pub:68A81281-1BA0-4B7B-9B25-F067F5FFF47B (ZooBank online registration for the International Code of Zoological Nomenclature [ICZN] LSID).

Type Locality and Geological Age: The Daxishan Fossil Site, Linglongta Township, Jianchang County, Liaoning Province. The vertebrate-bearing stratigraphic level of this site of the Tiaojishan Formation was reviewed by Liu et al. 2012 (23) and Huang 2015 (22). The fossil site belongs to the Linglongta Fossiliferous Bed of Tiaojishan Formation and can be correlated by the conchostracan arthropod (jumping shrimp) index fossil *Qaidamestheria sp.* (*sensu* Liao and Huang 2014, Huang 2015; Huang et al. 2015) (="*Euestheria luanpingensis*" of Duan et al. 2009) (52-54). The shale slab of the holotype specimen (BMNH2940) has preserved several specimens of *Qaidamestheria sp.* that are the index fossil for the upper fossiliferous stratigraphic level of Tiaojishan Formation (21). The Daxishan Site was dated to be 158.5±1.6 million years ago (Ma) to 161.0±1.44 Ma (22), and these dates have been corroborated by an independent study (54). The referred juvenile specimen BMNH3258 (Fig. S4) is also from Daxishan site of Jianchang County. The Daxishan site has also yielded several other mammaliaforms, as summarized elsewhere (16; 24).

Differential Diagnosis: Dental formula I1, P2, M2. Similar to all eleutherodonts in having a reduced post-incisor tooth count, and in having four upper premolars and molars. Similar to eleutherodonts in showing a down-turned rostrum at the long post-incisor

diastema, and in having a subtemporal angle on the maxilla near the maxillary-jugal junction. Among all eleutherodonts, *M. furculiferum* is most similar to *Shenshou lui* (16) in having a diastema between the penultimate and ultimate upper premolars, upper molars with coalescence of cusps of the lingual cusp row or a crest-like lingual cusp row, and a straight and median occlusal furrow that is open at both ends. In these features it differs from all other eleutherodonts in which the penultimate upper premolar abuts the ultimate premolar, upper molars are characterized by distinctive cusps on the cusp rows, and a fusiform median furrow is closed at both mesial and distal ends to form a mortar-like basin. The upper incisor of *M. furculiferum* has a single cusp, while the upper incisor is bicuspid in *S. lui*. The premolars and molars have simple cusps on the labial cusp row (Fig. 2 and Fig. S2) and lack the fluting ornamentation of the labial cusps of *S. lui* (16). The lingual cusp row is crest-like and lacks the weak division of cusps on the lingual cusp row of *S. lui* (16). Lengths of M1 and M2 of *Maiopatagium* are only 70% of the lengths of the same teeth of *Shenshou lui* holotype (Ref. 16; Supplementary Information). *Maiopatagium furculiferum* is different from the paulchoffatiid multituberculates from the Late Jurassic (including *Rugosodon*) in lacking the lingual offset of the ultimate upper molar to penultimate upper molar (2; 24). More detailed information on dental, skeletal and soft-tissue features of this fossil is provided below in "Part D" of the Supplementary Information.

Note on Fossil Authentication: The fossil was acquired from a third party by the Beijing Museum of Natural History from the Daxishan Site. Thus, we are here addressing how we independently authenticated its provenance. The fossil is preserved on a shale slab (designated to be the main slab BMNH2940) that is about 5 mm thick. The skeletal fossil and its soft-tissue halo on the slab were originally covered by a paper-thin shale sheet (<1 mm thick), which is designated here as the counter-layer. The counter-layer was already broken when the fossil was found. Parts of the fractured counter-layer were lost but several local areas of the counter-layer are conserved with the fossil slab. One preserved area of the counter-layer can be matched with the intact furs and the skin membrane (using the outline of the soft tissue halo and hair-filament pattern) on the right side of the skeleton between the right forelimb and the hindlimb. Another preserved area of the counter-layer can be matched to the skin membrane between the left knee and the lumbar region. A third area of preserved counter-layer can be matched, by fur pattern and skin membrane outline, to the edge of the skin membrane and fur between the left elbow and knee. The furs and soft tissue on the intact main slab and the fractured counter-layer shows similar preserved integumentary tissues under UV fluorescence (Fig. S1).

During the preparation, fossil preparator Akiko Shinya of our research team removed the rock matrix from the underside of the shale slab to expose the intact ventral aspect of the skull. The anterior part of cranium is undistorted and is preserved with full dentition (Figs. 2 and S2). During the study, systematic and comprehensive preparation was carried out on the manus, pes, pelvis, vertebrae (along the entire vertebral column), and shoulder girdle region. The matching of the counter-layer (although now fragmentary) with the main fossil slab and our firsthand preparation of the fossil has authenticated the intact nature of the fossil.

We can also authenticate the provenance of the fossil to the Daxishan site by fossils of *Qaidamestheria* identified on the BMNH2940 slab. This index invertebrate fossil (52) suggests that this mammal fossil slab is from the main fossiliferous layers typically preserved with a modest abundance of individuals of *Qaidamestheria* at the Daxishan site. This fossil is also an index fossil for the nearby Bawanggou and Nanshimen Sites of the Qinglong County, Hebei Province of the upper fossiliferous level of the Tiaojishan Formation (52; 55). Because *Qaidamestheria sp*. of the Daxishan/Nanshimen/Bawanggou localities of the upper part of Tiaojishan Formation (159-161 Ma) can be distinguished from *Euestheria "luanpingensis*," the index fossil of the Daohugou Site in the lower part of Tiaojishan Formation (165-164 Ma), fossil slabs can be distinguished by the estheriid taxa, between these localities, and between specimens from the Tiaojishan Formation and those from the Early Cretaceous Yixian Formation (52; 55). Thus, the distinctive, small conchostracan *Qaidamestheria sp*. (*sensu* 52 and 55) on the mammal fossil slab corroborates the provenance at the Daxishan Site.

Part C. Notes on Dental and Skeletal Features of *Maiopatagium*

Incisor Morphology. The only upper incisor (I1) has a single cusp, and its crown is peg-like and slightly compressed bilaterally. The medial side of its crown has an extensive wear facet that extends from the apex down the crown height, and we infer that this facet would contact the lateral aspect of the lower incisor apex (not preserved). The I1 root is long, penetrating the depth of the premaxillary. Its closed root-tip is visible from its exposure on the dorsal aspect of the premaxillary (Fig. S2).

Alternative designation of premolars and molars (Fig. S3). To facilitate comparative discussion, we follow the designation of the two premolars for *Shenshou lui* by Bi and colleagues (16). The penultimate upper premolar is designated as P3 and the ultimate upper premolar designated as P4. Thus, we label the dentition as I1, P3-4, and M1-2.

However, there is some uncertainty in how the P4-M1 sequence of *Maiopatagium* can be compared to the teeth of *Shenshou lui*. We note that the P4 identified here for *Maiopatagium* is somewhat similar to the left upper M1 identified for the *S. lui* type specimen (16). The *Maiopatagium* P4-M1 size difference is similar to the size difference of M1-M2 in *S. lui* type specimen (Ref. 16: fig. 2). There is a possibility that the upper premolar and molar loci of *Maiopatagium*, as identified here, may be similar to the dental loci identified for the *Shenshou* type specimen by Bi et al. (2014) (16). If so, the upper dentition of *Maiopatagium* holotype would be I1, P4, M1-3. We do not have a preference for how these tooth positions should be identified in *Shenshou* and *Maiopatagium*. Both schemes of tooth positions need to be tested when the *Shenshou* paratype specimens are prepared so their dentitions can be examined, or additional (as yet un-described) taxa can provide further comparative information.

Premolar and Molar Morphology. With the above clarification of the alternative interpretation of dental formula, we tentatively designate the penultimate upper premolar to be P3. P3 has a sub-circular outline, a single taller cusp on the labial side, and a lower cingular shelf on the lingual side. P3 bears an extensive lingual (medial) wear

facet that extends the entire crown height. The intact labial aspect of P3 has no sign of any wear. A small diastema separates P3 from the ultimate premolar (P4) and molars.

We also identify the ultimate upper premolar as P4 (following Ref. 16). P4 is narrower along its anterior width, and shows a bulging lingual side that protrudes medially beyond the imaginary line of the lingual borders of M1-M2. Its posterior end protrudes beyond the labial cusp row to interlock with the first molar (M1). This contact relationship between the ultimate upper premolar and the first upper molar is also present in other eleutherodonts (25 - Luo et al. Manuscript in review).

The median furrow of P4 extends the entire tooth length and is open on both ends. The lingual cusp row is crest-like and shows no sign of any cusp division. This lingual crest shows a continuous wear facet along the entire tooth length, and it is much lower than the labial cusp row. The labial cusp row has two unworn cusps, and each cusp is triangular and pyramidal in shape. The anterior cusp is longer and extends anteriorly as a faint crest. The posterior cusp is the wider of the two cusps. A common and extensive lingual wear facet extends across both cusps along the median furrow for the entire tooth length. Due to wear, it is not possible to know if the P4 lingual row had been formed by discrete cusp(s) or a simple crest.

M1 is nearly rectangular in outline in occlusal view. Its labial cusp row has two crescent cusps that are coalesced at their bases. The labial cusp row is much higher than the crest-like lingual cusp row. The labial cusp row and lingual crest are separated by a shallow median occlusal furrow with open mesial and distal ends. The cusps of the labial row have no wear pattern of the buccal side. However, along the furrow side (i.e., lingual side) of the cusp row, there is an extensive and almost vertically oriented wear facet that extends for the entire tooth length. The lingual cusp row shows extensive wear on both its furrow (labial) side and on the lingual side, and it is more deeply worn than the labial cusp row. It is not possible to infer whether the M1 lingual row had been formed by a simple crest or by coalesced cusps, due to the strong wear.

M2 is also rectangular in outline. Its labial cusp row shows three crescentic cusps that are coalesced longitudinally. These cusps have well-developed wear on the lingual side of the cusp row but no sign of wear on the labial side. The lingual cusp row is lower and crest-like, and it bears strong wear on both its furrow (labial) side and on the lingual side. It is more strongly worn than the labial cusp row. It is not clear whether the M2 lingual row was formed by a simple crest or by coalesced cusps, due to the strong wear.

The contiguous P4 and M2 are mesio-distally aligned in a straight line, notwithstanding a slight bulging of P4 to the medial side. The median occluding furrows of upper P4-M2 are also aligned in a straight line. There is no lingual offset of the upper molar M2 from the upper molar M1, as seen in multituberculates.

On the palate and medial to the P4-M2 tooth row, there is an occluding grove on the surface of the maxilla along the medial side of the entire upper tooth row (Figs. 2 and S3). The groove extends from the P3-P4 diastema to the level of mid-tooth length of M2, with a deeper and larger pit near the P3-P4 diastema. We interpret that the maxillary occluding groove accommodated the lingual cusp row of the lower molars. The larger and deeper

pit in the anterior end of the occluding groove accommodated the larger main cusp of the lower premolar.

The upper dentition shows five unambiguous features that are significant for dental occlusion and their chewing function: (A) the strongest wear of molars are on their lingual cusp rows, and the labial cusp rows show no wear on their labial sides; (B) the labial cusp row has distinctive cusps and is significantly taller than the crest-like lingual cusp row; (C) the tooth series shows a mesio-distally straight alignment by the tooth positions; (D) the median occlusal furrow of P2-M2 are aligned mesio-distally in a straight line; and (E) the maxillary surface shows an occluding groove to receive the large lower premolar cusp and lingual cusps of the lower molars. These features suggest that the lingual-most cusp row of lower molars occluded lingual (medial) to the upper molars, and the labial cusp row of upper molars occludes outside the lower molars. The lower teeth had strong palinal occlusal movement relative to the upper molars. This is distinctly different from the ortho-palinal occlusion limited by the en echelon (step-like) pattern in *Haramiyavia* (12, 13, 56) and the dual-mortar-pestle occlusion of eleutherodontids (25 - Luo et al. Manuscript in review), which also includes *Xianshou* (16).

Comparison to Other Mammaliamorphs with Multi-rowed Postcanines. A more extensive wear pattern on the lingual side (or along lingual cusp row) than on the labial side of P4-M2, as seen in *Maiopatagium* (Fig. 2) and *Shenshou* (16), is also present in paulchoffatiid and plagiaulacid multituberculates. In these multituberculate clades, the posterior upper premolars can develop extensive wear on the lingual aspect of teeth, much more so than the labial part of the same teeth (56; 57; 58). On the multituberculate first upper molars (M1s) that have two cusp rows, the lingual row is worn more extensively and faster than the labial row (57; 59). The stronger and deeper lingual wear on upper premolars and molars, however, is a shared primitive feature typical of the occlusion in most mammaliaforms (including morganucodonts and docodonts). This wear pattern is due to the lower premolars and molars occluding medial to the opposite upper premolars and molars.

On the second upper molar (M2), the median occlusal furrow is aligned mesio-distally in a straight line with the rest of the tooth row in *Maiopatagium*. It completely lacks the more lingual off-set of the M2 position, and the lingual off-set of the cusp row on M2, as seen in multituberculates (2; 56; 58).

An additional feature of note is that the median furrow of the upper premolars and molars of *Maiopatagium* is open at both mesial and distal ends. To some extent this resembles the furrows between the cusp rows on the multi-row upper molars of tritylodontids and multituberculates, and can be plesiomorphic dependent on optimization of the phylogenetic characters. *Maiopatagium* lacks the derived features of other haramiyidans, such as a saddle-like transverse ridge between the lingual and labial cusp rows as in *Haramiyavia* and *Thomasia* (12). It lacks the encircled mesial basin of the upper molars of *Xianshou* and *Arboroharamiya* (16). The encircled mesial basins of the latter forms are apomorphic (25 - Luo et al. Manuscript in review), but the thoroughfare median furrow with open ends of *Maiopatagium* (possibly also in *Shenshou*) is likely plesiomorphic.

Inference of molar function and diet. Among extant mammals, the upper dentition of *Maiopatagium* is most similar and functionally analogous to the molars of extant megachiropteran fruit bats (47), such as *Hypsignathus* (Fig. S3). Fruit bats have bi-serial cusp rows on their molars, which are evolutionarily transformed from the tribosphenic molar morphology that is ancestral for the chiropteran clade. This molar type of megachiropterans is primarily adapted to feeding on fruits and to a lesser extent on flowers, although megachiropteran diets can be supplemented with pollens, nectar, leaves, and even insects (60; 61). The lingual crest and median furrow form a continuous grinding surface on the molars of *Maiopatagium* that is functionally analogous to the bi-serial cusp rows of megachiropteran bats (e.g., *Hypsignathus*) (47). The grinding surfaces along the lingual crests of molars of *Maiopatagium* are also similar to those of some phyllostomid bats (e.g., *Sturnira* and *Artibeus*) (48).

Thus, based on the close similarity in dental morphologies of *Maiopatagium* and extant megachiropteran bats and some phyllostomid fruit bats, we infer that *Maiopatagium* was phytophagous and had a primarily herbivorous component in its diet. The comparable tooth crown morphologies of *Maiopatagium* and *Hypsignathus* should be placed in broader context of mandibular function: jaws of bats have orthal occlusion, while jaws of eleutherodonts, such as *Maiopatagium*, have ortho-palinal occlusion. The similarity of occlusal surface (and the inferred dietary similarity) is functionally analogous, as the mechanics for orthal and ortho-palinal chewing are different in these comparative groups with analogous molar crown structures.

Maiopatagium would have consumed plant foods from the Jurassic flora of ferns and gymnosperm plants. Analogous to extant phytophagous bats feeding on soft fruits of angiosperm plants, in the pre-angiosperm ecosystem of the Jurassic, eleutherodonts would probably feed on soft plant parts of young leaves, tender meristem tissues, exposed tissues of stroboli, and cones and tender tissues of the recessed ovulates. Seed ferns and various gymnosperm plants that were common for animal herbivory would have supplied these plant products (49; 62; 63).

It should be noted that in the Tiaojishan Formation, the fossil flora consists of (in rank of diversity and abundance): bennettitales, seed ferns, ginkgoaleans, cycadalesan and coniferales (64; 65), which is consistent with broader flora of Eurasia during the Middle-Late Jurassic (49). Although some researchers have proposed putative angiosperm plants from Middle-Late Jurassic (66), the overall flora is pre-angiosperm and dominated by seed ferns and gymnosperm plants. Thus, *Maiopatagium* was certainly not a frugivore that consumed angiosperm products such as fleshy fruits. Rather, it likely had some soft plant food material in its herbivorous diet, analogous to the soft plant materials in the phytophagous diet of extant bats that feed on fruits.

Vertebral Column. The vertebral column has seven cervical vertebrae and a total of 21 dorsal vertebrae. Fifteen of the dorsal vertebrae bear mobile ribs. Changes in the orientation of the pre-zygapophyses and post-zygapophyses, which is a characteristic of the thoraco-lumbar transition, occur on dorsal vertebrae 12-13. The base of the transverse process of dorsal vertebrae on the posterior part of the centrum appears first in dorsal vertebrae 15-16. By traditional characters that diagnose the thoracic versus lumbar vertebrae, there can be two sets of characters: one based on vertebral body and

neural arch/lamina characteristics; the other based on presence or absence of mobile ribs. Based on vertebral body and neural arch features (*sensu stricto*), the thoraco-lumbar transition occurs in thoracic vertebra 13 rather than lumbar vertebra 14. However, this position for the thoraco-lumbar transition is not based on the presence or absence of mobile ribs.

The anticlinal vertebra is located either at the penultimate lumbar vertebra or at the vertebra immediately anterior to the penultimate lumbar. The features on new specimens corroborate that the diaphragmatic vertebra is dorsal vertebra 13 and the anticlinal vertebra is within the last three lumbar vertebrae, as originally recognized for *Shenshou* (16). There are 3 sacral vertebrae. A total of 14 caudal vertebrae are preserved on the distally incomplete tail, with three caudals within the pelvic region and 11 post-pelvic caudals. Nine caudal vertebrae are elongate, and five mid-caudals are longer than 1 cm.

The transition from presence to absence of mobile ribs through the thoraco-lumbar region occurs at lumbar vertebra 15 (rib present) and lumbar vertebra 16 (rib-less). All dorsal ribs appear to be single-headed as in extant monotremes. *Maiopatagium* lacks the two-headed ribs with differentiated capitulum and tuberculum as in extant therians and a number of Mesozoic theriimorph mammals.

Shoulder Girdle and Forelimb. The clavicles and interclavicle are fused, or suturally joined together, to form a Y-shaped structure. The fused structure is very similar to the avian furcula (Figs. 3, S4 and S5; Video S1). The interclavicle medial process is proximodistally short and overlaps on the ventral surface of the manubrium of the sternal series. The manubria are paired and separated by a mid-line suture in the juvenile BMNH3258, but they are fused in the adult holotype of *Maiopatagium* and in the additional eleutherodont specimens (e.g. BMNH2942) (Figs. S4, S5). The two clavicles are rod-like, slightly bowed, abutting and sutured with each other at the mid-line. The two clavicles form a clavicular angle that ranges from 85 degrees in the unnamed eleutherodont BMNH2942 to 90 degrees in *Maiopatagium* (BMNH2940). However, in BMNH3258, the clavicular angle is smaller and has only about 70 degrees as preserved *in situ*, which may be a juvenile condition of the latter specimen. Alternatively, the smaller angle may be due to a slight distortion if the clavicles were moved *post mortem* in this juvenile and the interclavicle was not yet fully ossified to consolidate a furcula-like claviculo-interclavicle structure.

The proximal one-fourth of the clavicle is rugose on the dorsal (internal) side, and it has parallel thin ridges and grooves in BMNH3258 and additional eleutherodonts (e.g., *Arboroharamiya*: Luo personal observation). The rugose parts of clavicles overlap and form a rigid suture junction with the interclavicle. The lateral processes of the interclavicle are twice as long as the posterior (median) process. The extensive overlapping and rigid suturing of the clavicles and interclavicle of eleutherodonts (BMNH2940 and BMNH2942) are similar to the claviculo-interclavicular structure of tritylodonts (a pre-mammalian cynodont group), the mammaliaform *Sinoconodon*, and extant monotremes (35; 36; 67; 68; 69). The short posterior (median) process of the interclavicle is represented by a blunt end that fits in a V-shaped, shallow midline depression on the anterior aspect of the manubrium, which is also demonstrated in *Shenshou* (16).

Eleutherodonts differ from tritylodontids and other mammaliaforms in several claviculo-interclavicle features. The clavicles are distinctively angled. The claviculo-interclavicle structure is Y-shaped, differing from the T-shaped structure of cynodonts, *Sinoconodon* and *Ornithorhynchus*. The clavicles are only slightly and uniformly curved, unlike the more bent (i.e., "boomerang-shaped") clavicles of tritylodontids and other cynodonts (35; 70). Eleutherodonts are different in having a much shorter median (posterior) process of the interclavicle than those in tritylodontids, *Sinoconodon,* and monotremes (35; 36; 67; 70), and in the overlapping contact between the interclavicle and the manubrium rather than an abutting contact of these bones as in latter taxa (Fig. 3 and S5). Unlike monotremes in which the lateral processes of the interclavicle extends the entire length of the clavicle to reach acromio-clavicular joint, the rigid sutural contact of the clavicle to the interclavicle is limited to proximal one-fourth of the clavicle in eleutherodonts.

The two manubria are fused at the midline in the adult specimen of *Maiopatagium* (BMNH2940) and in eleutherodont BMNH2942, but their suture is clearly present in the mid-line between the two abutting manubrial parts in the juvenile eleutherodont BMNH3258 (Figure S4). BMNH3258 was examined via CT scanning (Video S1), and the mechanical preparation of other specimens show that all eleutherodonts have three post-manubrial sternebrae and a short, gracile xiphoid process. Overall, the clavicle-interclavicle-sternal structure is gracile and small by comparison to the broad, thick manubrial structure of tritylodontids, *Sinoconodon,* and extant monotremes (35; 36; 67; 68; 69).

The scapula of *Maiopatagium* has an extensive infraspinous fossa that makes up the entire lateral aspect of the scapular plate. The scapula spine is on the anterior margin of the scapula and its crest bends laterally from the infraspinous part of the scapular plate to form a shallow trough with the infraspinous fossa (Fig. S4). The spine shows an anteriorly facing surface. A similar anteriorly faced surface in the scapula of *Morganucodon* was interpreted by Jenkins and Parrington (1976) (11) to be an attachment surface, albeit a small size, for the incipient supraspinous muscle (70). This is very different from the fully developed supraspinous muscle fossa of eutriconodonts and trechnotherian mammals, which is well documented by many studies (reviewed by Ref. 36). The postero-ventral corner of the scapular plate has a small triangular area for attachment of the teres major muscle.

The acromion is a prominent and oblong structure on the anterior end of the scapular spine, and it is located on the cranial margin of the scapula. The metacromion is present and forms a notch with the rest of the spine. The acromion has a rounded and thickened anterior end. In *Maiopatagium* type specimen and BMNH3258, acromions on both scapulae show a shallow fossa (Fig. S5), suggesting a mobile articulation of the lateral (distal) end of the clavicle. Our examination of this joint indicates that the acromio-clavicular joint is mobile in all eleutherodonts in which the scapulae and clavicles are well preserved.

The coracoid is gracile, elongate and slightly curved, morphologically identical to those of *Morganucodon* and *Kayentatherium* (35). This is a small bone that is nearly triangular in shape and has a coracoid foramen. The glenoid region of the entire scapula-coracoid structure is tripartite and formed by the procoracoid, coracoid, and scapula. The glenoid

fossa for the gleno-humeral joint is formed exclusively by the scapula and coracoid. The procoracoid almost borders on the glenoid fossa, but we interpret it to be excluded from the articulating surface of the fossa, as in *Morganucodon* (11). In extant monotremes with a similar scapula-coracoid structure, the acromio-clavicular joint is formed by a thickened acromion and the blunt distal end of the clavicle, and it is synovial and mobile (Fig. S6).

The scapula of *Maiopatagium* is nearly identical to that of *Haldanodon* for most scapular features, although *Maiopatagium* possesses a smaller teres major area than *Haldanodon* (8), and it is also similar to that of *Sinoconodon* (36). The combined structure of the coracoid, procoracoid and glenoid part of the scapula is identical to that of *Morganucodon* (11), and it also bears strong similarity to that of tritylodontids (35) (Fig. 3). However, eleutherodonts are more plesiomorphic than docodonts in that docodonts have lost the procoracoid, which is a plesiomorphic feature for mammaliaforms (8).

Our study corroborates many of the eleutherodont characteristics of the shoulder girdles that were originally recognized by Bi et al. (2014) (16) for the eleutherodont *Shenshou*. However, we point out that the *Maiopatagium* and other eleutherodont specimens of this study indicate that the shoulder girdle of eleutherodonts is different from the reconstruction of *Shenshou* by Bi et al. (2014) (16) in the following important features:

1. The proximal ends of clavicles abut and are joined to each other. The clavicles do not separately articulate with the ventral side of the interclavicle.
2. The proximal section of the clavicle and the interclavicle form a rugose junction with each other that is comprised of parallel ridges and grooves. The junction between the clavicle and the lateral process of the interclavicle is an immobile joint. The clavicles do not have mobile claviculo-interclavicular joints in the style of multituberculates, as previously reconstructed for *Shenshou* (16).
3. The fused claviculo-interclavicular structure is Y-shaped and similar in morphology (i.e., analogous) to the avian furcula. The clavicles and interclavicle do not form a T-shaped structure (16).
4. The proximal end of the acromion is a short and rounded platform, not a long and sharply pointed structure (16).
5. The procoracoid in *Maiopatagium* and eleutherodonts identified by us is also present in the specimens of *Shenshou*, which we confirmed by our own firsthand examination of *Shenshou* paratype specimens. Although the clavicle and interclavicle in *Shenshou* paratype 1 were displaced *post mortem*, the clear outline formed by the intact claviculo-interclavicle structure in its entirety can be seen on the *Shenshou lui* paratypes. This structure is consistent with the *in situ* claviculo-interclavicle structure of BMNH2940 and 2942.

Features of the forelimb and hand. The humerus, radius, and ulna are gracile and elongate. The humeral head is spindle-shaped and slightly reflected posteriorly, and it has a discernible greater tubercle and a tiny lesser tubercle. The radial and ulnar condyles on the distal humerus are separated and the radial condyle is continuous with the small, rounded ectepicondylar shelf. The radius and ulna are longer than the humerus, with a radius length to humerus length ratio (i.e., brachial index) of 108%. The semilunar notch and the olecranon process of the ulna are very short, with an olecranon index of 10% (*sensu* Ref. 71) or 6.7% (*sensu* Ref. 31).

In the proximal carpal row, the scaphoid and the triquetrum are much larger than the lunate. In the distal carpal row, the trapezium is the largest carpal. The well-preserved pisiform is the largest among all carpals, almost twice the length of the triquetrum, as seen on the right manus (Fig. S5). In general, the scaphoid and the trapezium are aligned with digit ray 1 and are enlarged, corresponding to the wider (thicker) metacarpal 1. The triquetrum and the pisiform near the ulnar side of the wrist are hypertrophied, corresponding to a thicker and short metacarpal 5, as already described for *Shenshou* (16). The enlargement of these bones indicates an enhanced capability for the wrist for manual grasping (16, 43). Further, the enlargement of the pisiform likely provides improved support for the plagiopatagium.

The metacarpals are relatively short compared to the elongate phalanges, as described for *Arboroharamiya* and *Shenshou* (15; 16). The proximal phalanges are slightly grooved on the palmar (ventral) aspect for accommodating the tendons for the flexor digitorium and the distal condyles of the proximal phalanges. These are features common for hands with strong and habitual grasping capability. The palmar bases of the intermediate phalanges are more enlarged relative to their shafts, likely for the insertion of the flexor digitorium superfacialis. The proximo-intermediate phalangeal joints appear to be habitually flexed in almost all specimens as preserved, as documented here and also for *Arboroharamiya* and *Shenshou* (16). Distal ends of the intermediate phalanges have well-developed distal condyles that allow a wide range of rotation of the terminal phalanges. The manual phalangeal index of digit 3 is 270% (*sensu* Ref. 33) (Fig. S8), and the phalangeal slenderness index for digit ray 3 is 340% (*sensu* Refs. 72 and 73). These values support the qualitative observation that the phalanges are especially long and slender. Both indices are consistent with arboreal specialization, and the extra elongation of phalanges may indicate gliding adaptation (Fig. S8). However, we did not detect residues of skin membranes between manual digit rays (Figs. 1 and S2), as seen in dermopterans (Fig. S2). Thus, we interpret *Maiopatagium* and likely other gliding eleutherodonts (e.g., BMNH2942) to be similar to volant rodent and marsupial species in lacking skin membranes between manual digit rays.

Pelvis, hindlimb and foot. The pelves of *Maiopatagium* (BMNH2940) are appressed to the vertebral column, as preserved. Nonetheless, the exposed features are similar to those of the unnamed eleutherodont BMNH1133, which has pelvic features that are better preserved than BMNH2940. In BMNH1133, the ilium shows a prominent lateral iliac crest, which is posteriorly continuous with the iliac rim of the acetabulum. The crest separates the lateral surface of the ilium into a gluteal area and an iliopsoas area (74; 75). The posterior process of the ilium is the posterior contact point of the iliac with the sacral vertebrae, as in tritylodontids and in monotremes (35). The ilium, ischium, and pubis of *Maiopatagium* are joined by open sutures in the acetabulum. However, the ischium and pubis (but not the ilium) are co-ossified in BMNH1133. The acetabulum is emarginated with a notch on the dorsal rim. The ischium bears a large acetabular notch. The dorsal margin of the ischium is slightly concave, but the ischial tuberosity at the end of this curvature is not enlarged (16). The pubis shows a small tuberosity on the anterior margin, which is interpreted to be the psoas minor tuberosity and is known from other Mesozoic mammals (76). The ischium and the pubis form an obdurator foramen. This

foramen is smaller than the estimated size of the acetabulum, a plesiomorphic feature for mammaliaforms.

Long bones of the hindlimb are elongate and gracile. The proximal part of the femur has a posteriorly reflected and spherical head, but the head lacks a neck that is distinctive from the shaft. The proximo-medially oriented lesser trochanter is well developed, although it is somewhat smaller than the dorsolaterally directed greater trochanter. Overall, features of the proximal part of the femur are nearly identical to those of *Morganucodon* and the docodont *Agilodocodon* (9, 11). Thus, there is no distinctive femoral neck and the lesser trochanter is not a posteriorly directed structure in eleutherodonts, and these observations contradict the previous character scoring on these features by Bi and his colleagues (16) for *Shenshou* and *Xianshou*.

The fibula is extremely slender. Its proximal part is mediolaterally compressed and has a rhomboid outline. It is wider in lateral profile than the cylindrical main shaft. The proximal end of fibula has an articulation for the distal femur, and there is no parafibular element in *Maiopatagium* and other eleutherodonts. The distal end is truncated and shows no distinctive features such as a fibular malleolus. The proximal end of the tibia is slightly wider than the main shaft of the bone. It has a proximolateral tuberosity to articulate with the fibula. The distal end of the tibia is truncated and lacks a tibial malleolus.

The astragalus is an oblong bone without a discernible astragalar neck or head. The calcaneum is wide and rectangular. There is an obtuse and short peroneal process. The calcaneal tuber is represented by a short protuberance on the posterolateral corner of the calcaneum. The calcaneal width to length ratio is about 80% for *Maiopatagium* (BMNH2940), and it is about 70% in BMNH2942 and the unnamed eleutherodont represented by BMNH1133. *Maiopatagium* (BMNH2940) and other eleutherodonts (e.g. BMNH2942) retain the plesiomorphic features of a broad calcaneal width relative to length, as seen in *Megaconus*, and a short calcaneal tuber, as in *Megaconus* and *Morganucodon*. The rectangular (nearly square) outline of the calcaneus and the short calcaneal tuber are similar to the calcanei of extant monotremes (14, 39). However, eleutherodonts are unique in that the calcaneal tuber is laterally turned to articulate with the calcar.

In *Maiopatagium* and BMNH1133, there is a cone-shaped bone directly articulated to the short calcaneal tuber. This bone is interpreted to be the calcar (Fig. S7). The base of the calcar has a V-shaped shallow trough that fits to the convex end of the calcaneal tuber. As the pes is positioned in a habitually everted position, the calcar's distal apex is pointed posteriorly, presumably projecting into the uropatagium.

The calcar is the skeletal base or attachment associated with the uropatagium in bats. This structure can have a wide range of morphologies and states of ossification (40; 41; 77; 78). It can range from a rod-like or digitiform cartilage as seen in most bats with this structure, to a short and cone-shaped structure as in some phyllostomids (41). It can be fully cartilaginous or can ossify partly at the base (40; 41). Overall, the calcar as identified here for *Maiopatagium* bears some resemblance to the short calcar bone of the phyllostomid bat *Desmodus rotundus* (41). However, the base of the calcar is more conical

and more massive, therefore also distinctive from the relatively slender calcar of *Desmodus* (41).

Alternative Hypothesis on Calcar. An alternative hypothesis about the identity of the ossified base of the calcar is that it could be the os calcaris, or the ossified base for the extratarsal spur. This element was identified by Bi et al. (2014) (16) as the os calcaris for the extratarsal spur in *Shenshou lui* and *Xianshou songae*. There are two major differences between the os calcaris and the calcar.

First, the os calcaris is topographically closer to the astragalus than to the calcaneus in monotremes, the only extant mammals that retained this structure (79). In the Mesozoic mammals where the os calcaris is preserved, it is closer to the astragalus, either in contact with the astragalus, or more often in association with the distal ends of tibia and fibula (79). In eleutherodontids where this element is preserved, it is in direct articulation with calcaneal tuber, and away from the astragalus, as obvious from the intact astragalus and calcaneus (Fig. S8).

Second, the os calcaris of extant monotremes has no direct articulation with any tarsal bones. Rather, it is embedded in the connective and ligamentous tissues near the astragalus. The preservation of the os calcares in most Mesozoic mammals is either near the distal parts of the tibia and fibula, or near the astragalus. This is consistent with this soft-tissue anatomy of this structure in monotremes. By contrast, the calcar articulates directly with the calcaneal tuber: the base of the calcar bears a V-shaped notch that fits onto a convex surface on the calcaneal tuber. This morphology of the calcar-tuber contact is consistently preserved all in all specimens, in which the ankle region is well preserved. Given the bone morphology and the intact articulating relationship as preserved in multiple eleutherodonts, we believe the element in this discussion is the calcar (Fig. S7), but not the os calcaris as hypothesized by Bi and colleagues (2014) (16).

Furthermore, the os calcaris co-exists with the calcar in several eleutherodonts that we examined. In BMNH1137 (not illustrated) and BMNH1133 (Fig. S7), an os calcaris is associated with the distal tibia and fibula (Fig. S7). In *Shenshou* paratype 3, an os calcaris appears to be preserved in the distal ends of the tibia and the fibula, in addition to the calcar element directly articulated with the calcaneal tuber of the same specimens. Therefore, both the calcar element and the os calcaris for an extratarsal spur are likely present in eleutherodonts.

The entocuneiform is a rectangular bone, and it has a slightly convex contact surface for the flat and widened proximal end of metatarsal 1. There is no reciprocal saddle-shaped joint between the distal end of the entocuneiform and the proximal end of the metatarsal 1, which is in contrast to the scoring for eleutherodonts in the phylogenetic character analysis of Bi et al. (2014) (16). These structures are characteristic of multituberculates (11; 24) but do not exist in eleutherodonts.

Metatarsals 1 and 5 are thicker and shorter than metatarsals 2-4, and all metatarsals have slightly wider distal ends than their shafts. The proximal phalanges have well defined palmar grooves for the flexor tendons and well-developed distal condyles. The palmar bases of intermediate phalanges are hypertrophied. Overall, the proximo-intermediate

phalangeal joints of all digits have an enhanced capability to flex. The proximal and intermediate phalangeal segments are elongate relative to the metatarsal of the same digit ray for all pedal digits, as in extant bats. They are far more elongate than all extent gliding and nongliding arboreal mammals. In bats, the overall lengths of digit rays 1-5 are equal, due to extraordinary elongation of digit ray 1. By comparison, overall lengths of digit rays 2 – 5 of eleutherodonts are almost equal (a derived feature) but digit ray 1 is still shorter (a plesiomorphic feature of all mammaliaforms) (Fig. S7). We interpret these features of eleutherodonts to indicate that their pedes have a strong capability for habitual gripping, similar to that seen in the finger-suspending roosting behavior of bats (see Part H below).

Part D. Skeletal Size and Body Mass Estimate of *Maiopatagium furculiferum*

Size Measurements. The pre-sacral vertebral column is measured to be 84 mm long. This length includes seven cervical vertebrae. If assessed by zygapophyses and transverse processes (as preferred here), there are 13 thoracic vertebrae and eight lumbar vertebrae. However, there are 15 dorsal vertebrae with ribs and six lumbar vertebrae without mobile ribs. The pelvis is 23.5 mm long. The preserved section of caudal vertebral column, which is incomplete, is measured to be 93 mm long. Assuming an estimate of the skull length of 33 mm long (more below), the total head-rump length is approximately 140 mm. Measurements of individual postcranial elements are provided in Table S2.

Body Mass Estimates. Our estimates of body mass for the *Maiopatagium* type specimen are based primarily on the scaling relationship of humeral and femoral lengths to body mass of all mammals, following the study of Campione and Evans (2012) (80) and summarized in Table S3. In addition, we discuss the issue of assessing the body mass by skull length (81). In previous body mass estimate studies, the mandibular length is also a key metric (16, 82). However, we cannot use this feature due to the fact that the mandible is not preserved in the *Maiopatagium* type specimen.

We first estimated the body mass for *Maiopatagium* by the scaling relationship to length of humerus, which is based on an all-mammal dataset (80):

$$\text{Log}_{10}\text{BodyMass} = 2.8626 \times \text{Log}_{10}(\text{Humerus length}) - 1.8476$$

Based on this equation (80), the body mass of *Maiopatagium* is estimated to be 160 grams when using 26 mm for humerus length (the measured length of the left humerus) or 178 grams when using 27 mm for humerus length (the measured length of the right humerus).

We also estimated the body mass for *Maiopatagium* using the scaling relationship of femoral length to body mass of all mammals, as developed by Campione and Evans (2012) (80):

$$\text{Log}_{10}\text{BodyMass} = 2.993 \times \text{Log}_{10}(\text{Femur length}) - 2.341$$

Using this regression and a measured femoral length of 30 mm, the body mass of *Maiopatagium* is estimated to be 120 grams.

We further estimated body mass using the regression equation produced from a dataset of the skull length of extant insectivores, primates and other small mammals (78), as previously applied to other Mesozoic mammals (7; 82):

$$Log_{10}BodyMass = 3.68 \times Log_{10}(Skull\ length) - 3.83$$

The skull of the *Maiopatagium* type specimen is incomplete, but from the preserved part (rostrum to full parietal and most of the squamosal cranial moiety) we estimate its skull length to be approximately 33 mm. Based on the above regression equation, the body mass of *Maiopatagium* would be about 57 grams. We consider this to be an under-estimate.

As discussed by Bi and colleagues (16), eleutherodontids have similar skull proportions to extant rodents and therefore it is most reasonable to use a skull versus body mass regression from an extant rodent dataset (83):

$$Log_{10}BodyMass = 3.488 \times Log_{10}(Skull\ length) - 3.332$$

Using this regression equation, we estimate the body mass of *Maiopatagium* to be 92 grams on a reconstructed skull length of 33 mm for BMNH2940. The estimate from rodent-based regression is much closer to the stylopod estimates for body mass than using the regression based on primates and insectivores (81; 82). This is clearly more compatible with additional estimates, as suggested by Bi and colleagues (16).

However, it has been well-documented that extant gliding mammals have significantly smaller skulls and shorter skull lengths relative to their body mass (26; 27; 81). Thus, it is expected that the body mass estimate by skull length alone for *Maiopatagium* is likely to be an underestimate. This is supported by the smaller estimates from skull length than from the humeral length or from the femoral length.

For mammals as a whole, the stylopodial femur and humerus are considered to be more conserved than additional distal limb elements (80). By comparison to other extant sciurid squirrels, glissant pteromyine squirrels show an elongation of forearm bones, relative to the humeral length. The humeral length tends to be more conserved than the more distal limb elements (27), and therefore better for body mass estimate for gliders. Thus, we consider the most reliable body mass estimates to be those estimated from stylopodial elements, and we estimate *Maiopatagium*'s body mass to be in the range of 120 grams (based on the femur length) to 178 grams (based on humerus length).

Part E. Pelage of *Maiopatagium* and Comparison of Skin Membranes

The pelage of *Maiopatagium* is represented by an extensive halo of carbonized fur and skin membrane. This consists of both the long guard hairs and the short under hairs. This halo also contains different carbonized residues of hairs and other integumentary structures, such that it shows a distinctive pattern from the rock matrix of the shale slab under UV fluorescent lighting (Fig. S1).

Based on the carbonized filaments of hairs, we estimate that the guard hairs have averaged 10 mm in length on the fringes of the plagiopatagia, 5-7 mm in length on the fringe of the uropatagia, and about 3-5 mm in length along the forearm region of the

propatagium (Fig. S1). The tail has the longest hairs of the entire animal, and these hairs are approximately 13 to 15 mm long. The long tail hairs are preserved in an arrangement of parallel and pinnate pattern relative to the caudal vertebrae, known as distichous pattern of tail hairs (i.e., "feathertail") (17; 84; 85).

Based on limb and body length measurements, we estimate the dimensions of the skin membranes (i.e., patagia) of *Maiopatagium*. The plagiopatagium can be as wide as 60 mm from the vertebral column to the lateral edge when both the forelimb and the hindlimb are maximally extended at the elbow and knee joints. The uropatagium is about 50 mm wide from the hip joint to the ankle and as deep as 20 mm, assuming that the trailing edge of the uropatagium, in life, extended from the calcar on the ankle to near the junction of the third and fourth post-pelvic caudals. The propatagium can be at least 50 mm wide from the wrist to the cheek of the skull and approximately 15 mm deep from the leading edge to the humerus, but narrow from the leading edge to the radius or more distally to the carpals.

Comparative Patagial Morphology of *Maiopatagium* and Extant Mammal Gliders. The skin membranes are a key structure of all extant volant (gliding and flap flying) mammals (17; 19). The full complement of patagia of volant mammals includes the propatagium (of the forelimb and neck region), the plagiopatagium (on the flank of the torso between forelimbs and hindlimbs), and the uropatagium (between the hind feet and the tail). However, the extent of plagiopatagium may vary widely among extant gliding rodents and marsupials, and the propatagium and uropatagium, as seen in placental gliders, are not as fully developed in marsupial gliders as in placental gliders, although some studies have characterized it to be present in marsupials (28).

Maiopatagium (BMNH2940) and the unnamed eleutherodont BMNH2942 are comparable to extant dermopterans and most of the gliding sciurid rodents in having the full complement of the propatagium, plagiopatagium and uropatagium (Figs. S1 and S2). The well-preserved plagiopatagium extends from torso flanks to the wrist and the ankle in *Maiopatagium*. In this attachment pattern, the eleutherodont glider is similar to the flying squirrels (Rodentia, Sciuridae, Petauristinae) and most marsupial gliders (26; 28; 84; 85). *Maiopatagium* differs slightly from the African scaly-tailed squirrels (i.e., anomalurid rodents) in which the plagiopatagium extends from the forelimb elbow (not from the wrist) to the ankle (28; 84). Although it has a large and elongate pisiform at the wrist, *Maiopatagium* clearly lacks the cartilaginous styliform from the wrist of most rodent gliders (29; 85; 86). There is no evidence of a styliform cartilage extending from the ulnar olecranon, as in the anomalurid rodent gliders and the marsupial greater glider (28; 84; 87), and the exceptional quality of the fossil preservation can help us rule out the possibility that this is due to lack of preservation.

Maiopatagium differs from the marsupial gliders in having more developed propatagium and uropatagium. Marsupial gliders have under-developed skin flaps, but not the fully developed propatagium and uropatagium (28; 84; 85). In the greater glider (*Petauroides volans*) and the feathertail glider (*Acrobates pygmaeus*), the plagiopatagium extends from the elbow of the forelimb to the crural region (tibia) of the hindlimb, and it is less expanded than in rodent gliders and in *Maiopatagium*.

Several eleutherodont specimens (BMNH2940, BMNH1133; Jizantang Museum of Chaoyang, Liaoning JZT0061) have a calcar bone on the calcaneal tuber. The association of the calcar and the calcaneal tuber is similar to those of microchiropteran bats and Eocene fossil bats, although it is not similar to the uropatagial spur of the megachiropterans that attaches to the tendon of the gastrocnemius muscle (40; 78). As in extant microchiropteran bats, the edge of the preserved uropatagium extends directly to the calcar in *Maiopatagium* (Figs. 1 and S1). The calcar shows no cartilaginous extension from the calcified calcar, which is present in microchiropterans. We interpret that the elongate cartilaginous rod from the ossified calcar is absent and that this absence is unlikely due to any lack of preservation of cartilage, especially since the cartilaginous costal ribs are preserved elsewhere in the same fossil. By contrast, bats usually have a cartilaginous extension of the calcar (38; 78). By the presence of a calcar, *Maiopatagium* differs from extant therian gliders, all of which lack calcars. Nonetheless, the calcar is a volant feature that is present in extant and extinct bats (78).

We tentatively interpret *Maiopatagium* to lack patagial webbing between its hand fingers. Under UV fluorescent light (Fig. S1), some soft tissue traces appear to be present in between the phalanges of the intact right hand of BMNH2940. However, these soft tissues appear to be uneven. The well-preserved hand bones of BMNH1113 show no soft tissue preservation. In lacking hand webbing, *Maiopatagium* is similar to the rodent and marsupial gliders, but it differs from dermopterans that are capable of using hand-membranes for steering (19). The propatagium of *Maiopatagium* is not as extensive as the propatagium associated with the elongate cervical vertebral column of dermopterans (30).

The feathertail hair pattern is preserved on the right side of the caudal vertebrae 5-12 of *Maiopatagium* (BMNH2940). This shows a typical distichous characteristic, which is also seen in the marsupial feathertail glider (*Acrobates pygmaeus*) and small flying squirrels (17; 85). From the flattened caudal vertebrae 5-9 and the preserved feathertail appearance of the long tail hairs, we interpret *Maiopatagium* to have a flattened tail, as in small flying squirrels and in the marsupial feathertail glider. The tail region of the additional gliding eleutherodont specimen BMNH2942 is not well preserved enough to be assessed for these features.

Part F. Comparative Morphology of Skeletal Features for Gliding Locomotion and Roosting Behavior

Maiopatagium (BMNH2940), BMNH2942 and BMNH1113 possess skeletal features that are characteristic of extant gliders. Long bones of the limbs are extremely gracile, consistent with the universal pattern of slender and elongate limb bones of extant mammalian gliders (Figs. S8, S9) (26; 27; 31; 32; 84; 85; 89; 90; 91). The humerus, radius, femur and tibia are relatively elongate, as compared to the vertebral column, or to the skull or jaw length as a proxy to overall skull size (20, 81). The antebrachium (i.e., radius and ulna) are elongate relative to the humerus. The ulnar shaft is elongate relative to the olecranon process (Fig. S8) (31; 32).

Both *Maiopatagium* (BMNH2940) and BMNH2942 have a relatively elongate lumbar region. We can confirm that in the *Maiopatagium* type specimen, thoraco-lumbar

transition of vertebral segmental identities occurs on dorsal vertebra 13 (thoracic) and dorsal vertebra 14 (lumbar), as in *Shenshou* (Bi et al. 2014) (16). However, lumbar vertebrae 14 and 15 still have short mobile lumbar ribs. The eight lumbar vertebral segments are almost the same length as the 13 thoracic vertebrae. Among sciurid squirrels specialized for different locomotor modes, the lumbar region as a whole is more elongate relative to the thoracic region, and the individual lumbar centra are also longer in the petauristine gliders than in nongliding arboreal squirrels (27).

Maiopatagium has relatively long feet via elongation of pedal phalanges despite the relatively short metatarsals (Fig. 4), as previously described for *Arboroharamiya*, *Shenshou* and *Xianshou* (15-16). We corroborate that all eleutherodonts discovered in recent years from the Late Jurassic sites of Tiaojishan Formation in Jianchang (Liaoning) and Qinlong (Hebei) are arboreal (15-16). However, the haramiyidan *Megaconus* from the geochronologically older Daohugou site of the Tiaojishan Formation is not arboreal (14).

The pedal proximal and intermediate phalanges are exceedingly elongate relatively to the metatarsals and to the limb bones (Fig. 4). Eleutherodonts (including *Maiopatagium*) exceed the range of pedal phalangeal index for extant gliding and arboreal mammals. They are comparable to bats by proportions of digital ray segments, and even surpass bats in values of their phalangeal index (Fig. 4C, Table S7).

Bats are specialized for hindlimb suspension in resting posture and roosting behavior. They hang by habitually flexed long digits of the hind feet, biomechanically facilitated by a tendon locking mechanism (92; 93). This chiropteran adaptation occurred in their earliest evolution in the Eocene (78). The similar metatarsal-phalangeal proportions of digits 2-5 of eleutherodonts and bat (Fig. 4C, Table S7) suggest that eleutherodonts (including *Maiopatagium*) were capable of similar behavior to grip on and to suspend from branches by the habitual flexion of long pedal digits. However, pedal digit 1 is much shorter than digits 2-5 in eleutherodonts, a plesiomorphic mammalian feature and different from bats in which digit 1 is almost as long as digits 2-5 (40). Based on the manual digit proportions (Fig. S8, Table S5), we further speculate that the forelimbs and hands of eleutherodonts are also capable of a similar grasping function. This suggests that eleutherodonts used all four limbs during roosting behavior (Fig. 4B)

On both the manus and the pes of eleutherodonts, the proximal phalanges have a well-defined shallow groove on the palmar side. Each intermediate phalanx has a hypertrophied palmar base. In extant dermopterans and many (although not all) extant bats, the palmar groove of the proximal phalanx accommodates the common flexor tendons, which forms the flexor tendon lock mechanism (TLM) with the flexor ligament retinaculum. The enlarged palmar base of intermediate phalanx is for the insertion of the flexor digitorium superfacialis. In extant bats and dermopterans, these anatomical structures made it feasible for the pedal digits to flex for extended time with reduced involvement of digital flexor muscles and minimal muscle activities in general (92; 93). These volant extant mammals suspend themselves in their roosting posture by flexing their pedal digits to grab suspending substrate structures. The TLM is variable and may not be present in all bats. It is also known from non-volant rodents with climbing locomotor adaptations.

The pronounced longitudinal groove on the flexor aspect of proximal phalanges and the well developed tendon of the flexor digitorum profundus muscle are common characteristics of mammals with enhanced gripping capability. For instance, this is present and well developed in arboreal didelphids and some Cretaceous mammals inferred to be scansorial or arboreal (42; 43). Because the TLM is a soft-tissue structure that is not fossilized here in eleutherodont fossils under the current studies, there is no data to determine its presence or absence. However, it is well justified to infer that the flexor digitorum profundus is well developed and is deeply pressed into the flexor tendon groove as in extant mammals with enhanced capacity for gripping.

The morpho-functional complexes of hand and foot phalanges of *Maiopatagium* are consistent with the hypothesis that this mammaliaform had a limb suspension for resting posture and a roosting behavior similar to those of modern dermopterans (45; 89). Its phalangeal functional adaption is similar to pedal phalanges of bats for roosting by pedal suspension.

A unique shoulder girdle feature of eleutherodonts is the rigidly articulated (or even fused) clavicles and interclavicle (Fig. S5), resulting in a structure that is morphologically similar to the furcula (wishbone) of birds. While a rigid articulation (or fusion) of clavicles and interclavicle is a plesiomorphic feature of mammaliaforms (36), the claviculo-interclavicular complex shows a distinctive angle of 70–90 degrees when preserved intact. This clavicular angle is derived and differs from the T-shaped claviculo-interclavicular structure of monotremes and *Sinoconodon* (36).

The furcula is a distinctive feature of extant birds that is unique among extant vertebrates. Although presence of the furcula is a plesiomorphic feature of pre-avian theropod dinosaurs (94), the avian furcula shows distinctive morphotypes that can be correlated to different flying requirements (95). The avian wishbone shows a continuum of variation from the U-shaped wishbone with strongly curved clavicles to the more V-shaped wishbone with relatively straight clavicles that join each other at the midline with a pronounced angle. The V-shaped wishbone with relatively straight clavicles tends to be identified with birds adapted to soaring with no flapping (95). This is a functional convergence to gliding, a locomotor mode that we hypothesize for *Maiopatagium* with a similarly V-shaped wishbone (i.e., furcula) (Figs. 1 and S5).

Part G. Morphometrics of Eleutherodonts and Extant Mammalian Ecomorphotypes

Intrinsic Proportions of Hands

For small extant mammals, hand metacarpal and phalangeal proportions are indicative of their different substrate preferences and locomotor modes. Analyses of intrinsic hand proportions have proven to be helpful in discriminating the substrate preferences in extant mammals, and to further infer the substrate preference of extinct mammals (33; 73). More recently, the proportions of pedal digit bones were also examined using a similar approach (15; 16). Analyses of intrinsic hand and pedal proportions of the Mesozoic mammals have been effective in inferring the locomotor modes of these extinct mammals (9; 15; 16). Here, we use a similar approach to assess the locomotor mode(s) and likely substrate preference of *Maiopatagium* and related eleutherodonts.

To produce and expansive dataset of manual and pedal digit proportions, we measured skeletal elements of extant mammals of known locomotor mode (i.e., terrestrial/semifossorial, arboreal/scansorial, and gliding), and we combined this data with those of previous analyses (9, 15, 33). By comparing measurements of the eleutherodonts to those of the expanded datasets, this allows a robust assessment of the locomotor function(s) in extinct eleutherodonts.

Manual measurements are of the third digit ray of modern mammals and include maximum lengths for the metacarpal, proximal phalange, and intermediate phalange. The total sample of extant mammal taxa is 193 data points belonging to 161 unique species that represent multiple orders of mammals (Tables S4 and S5). If multiple specimens were measured for a species by the same source, then the species average was used for analysis. However, specimens or species averages reported by unique sources from separate studies were not averaged. If unique sources measured the same species, data from separate studies for the same species were all used. (For example, if three specimens were measured for *Didelphis virginiana* by one source and two were measured by a second source or study, then the species averages for both sources were included as two unique data points in this study.) Any specimen labeled "sp." was treated as a unique species. Results are presented as a ternary diagram of metatarsal-phalangeal proportions, and as phalangeal indices (Fig. S8, Table S5).

The manus measurements of Mesozoic mammaliaforms are from specimens in the Beijing Museum of Natural History collection. Additional measurements of Mesozoic mammals are from data published by Zheng et al. (2013) (15) and other primary literature (see sources in Table S5). For eleutherodonts *Xianshou songae* and *Shenshou lui,* we estimated the lengths of manual elements from published images by Bi et al. (2014) (16), as the lengths of the digit elements were not tabulated but were included in the published manual proportions ternary plot (Bi et al. 2014) (16). Due to this limitation, only measurements of the holotype of *Shenshou lui* (LDNMF2001) were included in our analyses. In our manual phalangeal analyses, we could not include *Volaticotherium antiquum*, a Jurassic eutriconodont mammal previously interpreted to be a glider by Meng et al. (2006) (20), because the complete manual phalanges were not preserved in that fossil.

The phalangeal index is the sum of the intermediate phalanx and proximal phalanx lengths divided by the length of the metacarpal, and multiplied by 100 (e.g., Refs. 15 and 33). This index has been an effective means of discriminating some locomotor modes in modern taxa (33). Eleutherodont results for this index support the conclusions that at least some taxa are gliders, as eleutherodont values are closest to the mean value for modern gliders (Fig. S8). Eleutherodonts and extant gliders possess phalanges that are especially elongate relative to metacarpals (Fig. S8, Table S5). However, it is worth noting that these values are considerably greater than those of almost all modern mammals sampled in this study, and we hypothesize that this is associated with roosting behavior (see discussion in Part G and below). Given our dataset on intrinsic hand and foot proportions, our assessment of the locomotor modes or substrate preferences of the several Mesozoic mammals are very similar to the qualitative assessment of their respective locomotor modes in earlier studies (see sources in Table S5). This suggests

that our overall assessment of Mesozoic mammal locomotor modes, including our hypothesis of eleutherodonts as gliders, is consistent with previous studies on phalangeal proportions.

The ternary analyses of ratios of metacarpal, proximal phalanges and intermediate phalanges also show that eleutherodonts (including *Maiopatagium*) are most similar to extant gliders (which are also obligate arborealists) and extant nongliding arboreal mammals (Fig. S8). In this ternary plot, eleutherodonts are outside the morphospace region (i.e., blue polygon) of extant gliders, resulting from their phalangeal proportions that are even more elongate than those of rodent gliders and marsupial gliders that represent a majority of extant gliders. We interpret that the exceptional elongation of phalanges is an adaptive feature for resting posture and roosting behavior by flexed long phalanges, as seen in dermopteran gliders and volant bats but not in rodent and marsupial gliders.

Intrinsic Proportions of Feet

The pedal proportions analyses were first developed by Zheng et al. (2013) (15) and Bi et al. (2014) (16), and those studies used 26 modern mammal species for comparison to fossil taxa. We incorporated data published by Zheng et al. (2013) (15), and we expanded the dataset of extant mammals by measuring 62 species at the Field Museum of Natural History (FMNH) (Fig. 4, Tables S6 and S7). As with the manual proportions analyses, species averages are used unless the species are repetitively (and separately) measured by different studies. This results in a sample of 88 data points that represent 81 unique species. The total sample of new measurements and published data includes 25 chiropteran species, results for which are reported as the mean values from 42 total specimens measured (Table S7).

The longest digit was measured for this analysis, which is the third digit in most taxa besides several marsupials. For the metatarsal length and proximal phalanx length of *Volaticotherium antiquum*, we used published values for the "longest metatarsal" and the "longest proximal phalange" by Meng et al. (2006) (20). See the "Intrinsic Proportions of Hands" section of the Supplementary Information for additional discussion of the methods.

Results for the pedal proportions are summarized as phalangeal index box plots (Fig. 4D) and a ternary diagram (Fig. 4C). The pedal proportions of extant arborealists and extant gliders are not considerably different from one another. And, as with the manual proportions, eleutherodont results are unique from those of modern arborealists and gliders. However, eleutherodont pedal proportions are very similar to those of chiropterans (Fig. 4, Table S7), which use their feet for grasping and roosting behavior. This provides considerable evidence for the conclusion that eleutherodonts were roosting animals, convergent to extant dermopteran mammals.

Limb Bone Functional Indices

Body size to limb length ratio. Gliding mammal species have relatively longer limbs than the nongliding arboreal species of the same taxonomic groups. For example, the gliding petauristine sciurids have longer limb bones than the nongliding arboreal sciurids.

Longer limb bones provide attachment for more extensive skin membranes (26, 27). It was also observed that gliding mammals tends to have a relatively smaller skull to the rest of the body (81). In general, gliders are adapted to maximize their limb lengths for attachment of patagia, resulting in elongated long limbs relative to body size (Fig. S9, Table S13; Ref. 20).

Meng et al. (2006) (20) calculated the ratio of the dentary length (as a proxy for body size) to the summed lengths of limb bones of extant mammals, and they used results to infer the locomotor mode of *Volaticotherium*. This index (i.e., ratio) is defined as the length of the dentary divided by the sum of the lengths of the humerus, radius, femur, and tibia. Using the mandible length as a proxy for body size (a widely accepted method in fossil studies), this ratio approximates the relative lengths of the limbs to the size of the mammal (20). An advantage of this ratio is that it is more widely applicable to fossil mammals as the mandible tends to be more frequently preserved than skulls. For this analysis of the jaw to limb length ratio (Fig. S9), a majority of measurements were directly collected from specimens of the FMNH collection. Our new data were merged with the data published by Meng et al. (2006) (20), producing a total sample of 44 extant mammalian species (Fig. S9, Table S13).

Results for the jaw to limb length ratio provide additional support for the hypothesis that eleutherodonts are arborealists and that some are gliders (Fig. S9, Table S13). However, we clarify that *Maiopatagium* (BMNH2940) has not preserved a dentary, and therefore is not scored for this index. All eleutherodonts have ratios that are within the range of extant arborealists. *Maiopatagium* (BMNH2940), the unnamed eleutherodont BMNH1113, and *Shenshou lui* have the lowest values and are most similar to those of extant gliders.

It is surprising that *Volaticotherium*, which is inferred to be a glider by Meng et al. (2006) (20), is outside of the range of extant gliders in our reference dataset, and is not even within the 75% quantile of the non-gliding arboreal mammals (Fig. S9A). Other Mesozoic mammals inferred to be arboreal, such as *Eomaia* and *Sinodelphys*, are also outside of the arboreal range according to this index. Thus, the locomotor inferences made by Meng et al. (2006) (20) may have been the result of using a small sample of modern mammals, and the expanded dataset of this study provides contradictory evidence for the locomotor modes of taxa such as *Volaticotherium*.

Analyses of Limb Bone Proportions. Previous studies have demonstrated that limb skeletal dimensions can be strongly influenced by locomotor function due to the direct relevance of the limb bones to locomotion (27; 31; 32; 96; 97; 98). For instance, the olecranon process of the ulna acts as an in-lever during extension of the elbow. A longer olecranon process maximizes mechanical advantage of the lever, and a shorter process maximizes forearm speed and flexibility. Fossorial mammals, which require strong upper limbs for digging, possess a relatively large olecranon process, while volant mammals tend to have the shortest olecranon process. The olecranon length index (OLI) is calculated as the olecranon length divided by functional ulnar length, and it has been used to differentiate mammalian locomotor modes to a considerable degree (Fig. S8). Altogether, we chose six functional indices (i.e., ratios) from those used by Samuels and Van Valkenburgh (2008) (31) to analyze the limb skeletal elements of Mesozoic fossil

taxa. Our choice of indices is based largely on their functional significance for locomotion and the preservation of skeletal elements of the eleutherodonts. The general rationale for using these ratios in multivariate analyses is summarized by Samuels and Van Valkenburgh (2008) (31), and literature cited therein. A brief summary of these functional indices is given here, and the results of their analyses are presented in Figures 4, S8 and S9:

- Femoral epicondylar index (FEB) = epicondylar breadth of femur divided by the femoral length (Extended Data Fig. S9). This index measures the slenderness of the femur.

- Pes length index (PES) = metatarsal 3 length divided by femoral length (Fig. S8e). This measures the relative length of the metatarsal of the pes to the proximal portion of the hindlimb.

- Brachial index (BI) = length of radius divided by the length of humerus (Extended Data Fig. S8). This measures the antebrachium elongation, relative to the humerus.

- Olecranon length index (OLI) = olecranon process length divided by functional length of ulna (Extended Data Fig. S8).

- Crural index (CI) = length of tibia divided by length of femur (Extended Data Fig. S9). This measures the lower hindlimb elongation, relative to the femur.

- Intermembral index (IM) = summed length of the humerus and radius divided by the summed lengths of the tibia and the femur (Extended Data Fig. S9)

Gliding squirrels often possess longer forearms (i.e., antebrachium) relative to upper arms (humerus) than nongliding arboreal squirrels (26, 27), and this difference is apparent in our brachial index analysis of all mammals (Fig. S9, Table S8). Gliding squirrels tend to have greater hindlimb-to-forelimb length ratios than non-gliders (27) and this distinction of gliding squirrels, marsupials, and dermopterans from non-gliding arboreal mammals is also manifest in our mammalian dataset.

Of these functional indices, the hypothesis that some eleutherodonts are gliders is most strongly supported by the values of the pes length index (PES), the olecranon index (OLI) and the brachial index (BI) (Fig. S8). It is worth noting that these three indices appear to be especially effective in separating modern gliders from nongliding arboreal species. Also, eleutherodonts are clustered with extant gliders and separated from other extant mammalian ecomorphotypes. Further, the intermembral index (IM) separates modern gliders from additional locomotor groups to a lesser extent, and eleutherodonts are within the range of modern gliders.

The femoral epicondylar (FEB) index captures the relative epicondylar breadth of the femur, which is here used as a proxy for the relative widths of the long bones. Gliding mammals tend to have gracile long bones with thinner mid-shafts relative to the long bone lengths (21; 27). However, in fossils preserved in slabs, the long bones tend to be compressed and become largely two-dimensional. The eleutherodont limb elements

described in this study have been crushed. The flattening of the cylindrical diaphyses may artificially inflate their mid-shaft diameters, thus biasing the results on assessment of slenderness of the long bones. However, epiphyses of the long bones, such as the femoral epicondyles, are made of compact bone that is less likely to deform during fossilization. Crushing may not affect their breadth as strongly as the breadth of diaphyses. Results of the femoral epicondylar index suggest that some eleutherodonts are gliding arboreal mammals, while others are likely nongliding arboreal mammals (Fig. S9).

The crural index (CI) helps to differentiate the gliding locomotor mode from the non-gliding arboreal mode. However, the non-gliding arboreal mode is not well differentiated from the terrestrial and semifossorial locomotor modes among extant mammals, based on our reference dataset. This index is also helpful for differentiating most eleutherodonts as gliders (Fig. S9).

Given the strong indication for gliding locomotor mode from five of the six limb proportion indices considered in this study, the case is strong that *Maiopatagium* and BMNH2942 were gliders. In comparison to other Mesozoic mammals, it is apparent that results for eleutherodonts are consistently more closely oriented with extant gliders (Figs. 4, S8 and S9).

In general, results for all eleutherodont specimens are similar for functional indices, and these results tend to match up best with a single modern locomotor preference. For example, eleutherodonts have a narrow range of values for the PES index, and these results best match those of modern gliders. The following list includes additional indices (including phalangeal indices) in which all (or nearly all) eleutherodont specimens are closest to the mean value of a single locomotor mode of modern mammals:

- Pedal phalangeal index (Fig 4c and 4d): All eleutherodonts are closest to modern arborealists.
- Manual phalangeal index (Fig S8a and S8b): All eleutherodonts are closer to the glider mean but also closer to the arboreal range.
- PES: All eleutherodonts are closest to gliders (Fig. S8e).
- OLI (Fig S8c): All eleutherodonts are closest to gliders.
- BI (Fig S8d): All but *Xianshou* are closest to gliders.

For four out of five of these indices, results for all eleutherodonts (except *Xianshou* for BI) are closest to modern gliders. This provides considerable support for the conclusion that many (if not all) eleutherodonts are gliders.

However, to better examine which taxa may be gliders and which may be non-gliding arborealists, it is best to examine indices in which results for eleutherodonts are more variable. The following list summarizes these indices, with closeness to modern taxa based on mean averages for modern groups:

- Jaw length/limbs length (Fig S9a): three eleutherodonts are closer to gliders and two are closer to arboreal (*Xianshou* and BMNH2942).
- IM (Fig S9b): four eleutherodonts are closer to gliders and two (*Shenshou* and BMNH1137) are closer to arboreal.

- FEB (Fig S9c): four eleutherodonts are closer to gliders and two (*Maiopatagium* and BMNH1133) are closer to arboreal.
- CI (Fig S9d): four eleutherodonts are closer to gliders and three (BMNH1133, *Shenshou* and BMNH1137) are closer to arboreal.

These results emphasize that not all eleutherodonts can be regarded as gliders by all of the limb bone proportion analyses. The strength of support to infer an eleutherodont to be gliding, or simply non-gliding arborealist, can vary from species to species. In considering the summarized results, it is worth noting that *Shenshou* and BMNH1137 are both closer to the non-gliding arboreal category for two indices (IM and CI). This suggests that although these two taxa are certainly arboreal, they may not be gliders, and this conclusion is supported by results from the multivariate results (see below).

Multivariate analyses

In our multivariate analyses, we aim to differentiate locomotor modes of the extinct mammaliaforms by combining their skeletal measurements with those of extant mammals of known ecomorphotypes. This is to specifically address the skeletal differences between gliders and non-gliding arboreal mammals.

We note that the limb bone proportions, as characterized above by ratio indices, can be individually validated for its effectiveness (or lack thereof) as an indicator for locomotor modes and substrate preference categories. However, these can and have been further tested by multivariate analyses (31, 32, 99). Analyses exclusively by linear ratios and indices derived from simple linear measurements can have caveats in some cases. First, biomechanical requirements for different locomotor modes can have similar (convergent) influence on some indices. Thus the locomotor modes inferred from indices may be conflated. For example, the manual digits and their phalanges can become elongate in volant bats and in terrestrial cursorial ungulate mammals, such as derived equids. The semi-aquatic mammals of several clades tend to develop elongate autopods (especially feet), which occur also in other locomotor modes. Thus indices of singular linear measurements (and ratios thereof) can conflate locomotor modes that are obviously distinctive in other regards (see discussion by Ref. 32).

The proportions and ratios of the entire forelimb and hindlimb elements have been examined by multivariate analyses to distinguish the locomotor modes and substrate preference types of extant mammals (31, 32). Combining multiple functional indices into a multivariate analysis can be informative for differentiating the likely locomotor modes of extinct taxa (e.g., Refs. 31; 32; 97; 98) and for studying ecomorphological divergence of extinct Mesozoic mammals (32).

Here, two multivariate analyses were performed on the data for the six functional indices, incorporating both the extant and extinct taxa. For both analyses, some fossil specimens were not included because of missing data due to a lack of preservation of certain skeletal elements. All analyses were performed using PAST (34).

PCA Analysis. The first multivariate analysis is a principal components analysis (PCA), which ordinates data using a covariance matrix and summarizes variance along axes, with

principal component (PC) axis 1 (i.e., PC1) capturing the greatest amount of variance. Loadings, eigenvalues, and percentage of explained variance for the PCs are given in Table S12. Results for the first three PCs are shown in Figures S9e and S9f, and these PCs account for a majority (>90%) of the total variance. Based on the loadings, it appears that the crural index (CI) and intermembral index (IM) have the largest influence on PC1, and the brachial index (BI) has the largest influence on PC2 (Table S12). Index results for *Maiopatagium* are especially close to the mean extant glider ratios for CI and BI (Figs. S8 and S9), helping to explain why *Maiopatagium* plots within (or very near) the gliding morphospace region in the PCA results (Fig. S9).

The results of our PCA (Fig. S9) show that *Maiopatagium*, BMNH2942 and BMNH1133 are clustered within or very close to the morphospace region (i.e., blue polygon) of extant gliding mammals. However, *Shenshou* and BMNH1137 are further away in morphospace from extant gliders, especially for PC3 (Fig. S9f). Thus, the PCA results support the inference that *Maiopatagium*, BMNH2942, and BMNH1133 are gliders. There is less evidence from the PCA that *Shenshou* and BMNH1137 are gliders.

Discriminant Analysis. To better segregate groups of taxa by their locomotor modes, we also performed a multi-group linear discriminant analysis (LDA) using the data for the six functional indices. This analysis requires group assignments (e.g., locomotor modes), and the axes are based on variance between groups (rather than variance among all individual taxa as examined in a PCA). Therefore, this analysis may be preferred for differentiating taxa that belong to distinct categories (e.g., Ref. 32). In our LDA analysis, locomotor modes of fossil taxa were treated as unknowns and were not assigned, *a priori*, to locomotor groups. To facilitate illustration, fossil taxa were colored in analysis plots (Fig. 4) to match the locomotor mode previously estimated for individual Mesozoic mammals (e.g., *Volaticotherium antiquum* was previously inferred to be a glider and is therefore labeled blue with modern gliders).

Loadings, eigenvalues, and percentage of explained variance for the linear discriminant functions are given in Table S12. The first three discriminant functions explain 100% of the total variance, and results are shown in Figure 4. The loadings for the first discriminant function (i.e., LDA axis 1) are greatest for BI, IM, and OLI, suggesting that these indices are best at discerning locomotor modes of extant mammals. This is consistent with results for the individual indices (Figs. S8 and S9). As with the PCA, most eleutherodonts plot closest to the modern gliders, although *Shenshou* and BMNH1137 are further from the gliders along the second and third LDA axes (Fig. 4).

To validate whether the LDA is successful in discerning groups, posterior probabilities can be used to classify taxa into their most probable group. Taxa are assigned to a group (i.e., locomotor mode) based on which group results in the minimal Mahalanobis distance to the group mean. Table S10 summarizes these results, showing that 68.3% of modern taxa were correctly classified by the discriminant function. Although a higher success rate is preferable, it should be noted that all nine extant gliders in our reference dataset were correctly assigned. This indicates that the functional indices of this study are successfully in differentiating gliders from other locomotor modes, including non-gliding arboreal locomotion.

Using posterior probabilities, the LDA can be helpful for classifying taxa of unknown locomotor mode (i.e., fossil taxa) into their most probable locomotor mode. Table S11 reports the most probable locomotor mode for the fossil taxa. Three of the six eleutherodont taxa are classified as gliders. These are *Maiopatagium* (BMNH2940), BMNH2942 and *Xianshou*. The remaining three eleutherodonts analyzed here (BMNH1137, BMNH1133, and *Shenshou*) are classified as non-gliding arboreal.

We note that *Rugosodon* was interpreted as terrestrial in its original publication (24), but it was recently re-classified as scansorial based on results of multivariate analyses (32). The latter conclusion is supported here by the LDA, which classifies *Rugosodon* as arboreal (Table S11). However, some individual indices (e.g., OLI and PES) support the original interpretation of terrestrial locomotion. Thus, LDA classification of locomotor modes for fossil taxa can and should be further tested.

Volaticotherium antiquum is classified as arboreal by the LDA of the dataset of extant mammalian ecomorphotypes. *Volaticotherium* was considered to be a glider primarily based on presence of a fossilized patagium. Although the gliding inference is supported by some osteological traits of extant gliders (20) (Fig. S8: OLI index), this inference seems to be inconsistent with other osteological features, such as BI (Fig. S8), and FEB index (Fig. S9). As mentioned above, our re-analysis of the jaw length to limb lengths ratio using a more expanded reference dataset has also yielded surprising results, both for *Volaticotherium* and for other taxa that were inferred to be arboreal, such as *Eomaia* and *Sinodelphys*, by other features (Fig. S9). Application of this index in locomotor inference requires further examination.

The classification of three eleutherodonts (BMNH1137, BMNH1133, and *Shenshou*) as arboreal but non-gliding is a conservative inference, especially since some results from the morphometric analyses suggest that these taxa are also gliders. In addition, preservation biases of the flattened specimens certainly can compress and flatten long bones in such a way that the width and thickness of the limb bones could be exaggerated more than the length. Thus the direct measurement of width versus length can cause biases in estimates for indices such as FEB (which includes femoral breadth), away from the gliding modes. Thus, this bias works against the inference that some eleutherodonts are gliders.

Perhaps the most important caveat for morphometric analyses that classify the locomotor modes of extinct mammals according to datasets of extant mammals involves the extant mammals themselves. Modern mammals likely represent some imperfect functional analogs to the long extinct Mesozoic mammaliaforms, due to the long divergent evolutionary histories of those of extinct Mesozoic mammal clades.

Part H. Phylogenetic Placement of *Maiopatagium* and Eleutherodontids

The phylogenetic placement of haramiyidans has been debated. Historically, haramiyidans were considered to belong to the allotherian group that would include both haramiyidans and multituberculates (16, 51). However, this view was questioned (12; 100). The debate about this historical problem of basal mammal phylogeny has continued more recently, mostly prompted by the new discoveries of haramiyid fossils and the

contrasting phylogenies of haramiyidans (14, 16). Although Bi et al. (2014) (16) had supported the allotherian hypothesis to place haramiyidans with multituberculates, the more recent reanalysis of the characters and character scoring by Bi and colleagues has resulted in an evolutionary tree topology in which all haramiyidans are mammaliaforms (Luo et al. 2015a) (10). With the new, well preserved fossil specimens of eleutherodontids, such as *Maiopatagium* and BMNH2942, we have now identified additional characters that are phylogenetically informative. The new phylogenetic analyses (including maximum parsimony and Bayesian analyses) of the expanded character dataset have corroborated that haramiyidans are a stem mammaliaform clade. The details of these new analyses are presented in Ref. 25 (Luo et al. manuscript in review).

Part I. Extended Data Tables of Measurements and Multivariate Analyses

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Table S13. Dentary Length (Proxy for Body Size) ratio to the Sum Lengths of the Limbs.

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Table S1. Dental Measurements of *Maiopatagium furculiferum* (BMNH2940), in comparison to putatively related *Shenshou lui* (Bi et al., 2014).

	Maiopatagium furculiferum **Type specimen (BMNH2940)**	***Shenshou lui*** **(data from Bi et al. 2014)**
Lf P3 length	0.75 cm	--
Lf P3 width	0.6 cm	--
Lf P4 length	1.65 cm	--
Lf P4 width	1.25 cm	--
Lf M1 length	1.8 cm	--
Lf M1 width	1.2 cm	1.58 cm
Lf M2 length	1.8 cm	1.78 cm
Lf M2 width	1.3 cm	1.55 cm
Lf p4 length	--	2.01 cm
Lf p4 width	--	--
Lf m1 length	--	1.9 cm
Lf m1 width	--	--
Lf m2 length	--	1.78 cm
Lf m2 width	--	--
Rt P3 length	--	--
Rt P3 width	--	--
Rt P4 length	1.6 cm	--
Rt P4 width	1.3 cm	--
Rt M1 length	1.8 cm	--
Rt M1 width	1.2 cm	1.6 cm
Rt M2 length	1.85 cm	1.8 cm
Rt M2 width	1.15 cm	1.57 cm
Rt p4 length	--	1.99 cm
Rt p4 width	--	--
Rt m1 length	--	1.81 cm
Rt m1 width	--	--
Rt m2 length	--	--
Rt m2 width	--	--

Table S2. Skeletal measurements of *Maiopatagium furculiferum* (BMNH2940).

Cervical C1-C7 centra sum lengths	17 mm
Thoracic vertebrae T1-T13 sum lengths	34 mm
Lumbar Vertebrae L1-L8 sum lengths	34 mm
Preserved post-pelvic caudals C4-C14	93 mm
Manubrium+sternebrae (1-3) length	13 mm
Scapula, length	20 mm
Clavicle length	15 mm
Humerus, length left	26 mm
Humerus, length right	27 mm
Radius, length	28.5 mm
Radius, mid-shaft diameter left	1.5 mm
Radius, mid-shaft diameter right	1.2 mm
Ulna, total length left	32 mm
Ulna, total length right	33 mm
Ulna, mid-shaft diameter left	2 mm
Ulna, mid-shaft diameter right	1.2 mm
Olecranon length (posterior to pivot) (*sensu* Hildebrand 1985)	3 mm
Olecranon length (posterior to notch) (*sensu* Chen & Wilson 2014)	2 mm
Manual ray 3 metacarpal	4.4 mm
Manual ray 3 proximal phalanx	6.5 mm
Manual ray 3 intermediate phalanx	5.4 mm
Manual ray 3 terminal phalanx	4.5 mm
Pelvic length (ilium+ischium)	23.5 mm
Ilium length	13 mm
Ischium length	10.05 mm
Femur, length left	30 mm
Femur, length right	29.5 mm
Femur, mid-shaft diameter	3 mm
Tibia, length	31 mm
Tibia, mid-shaft diameter	2.5 mm
Fibula, length	32 mm
Fibula, mid-shaft diameter	1 mm
Pedal ray 3 metatarsal	4 mm
Pedal ray 3 proximal phalanx	6.8 mm
Pedal ray 3 intermediate phalanx	6.3 mm
Pedal ray 3 terminal phalanx	4.1 mm

Table S3. Body mass estimates for *Maiopatagium furculiferum* (BMNH2940).

***Maiopatagium* Estimate: mean (min-max)**	**Anatomical Measurement**	**Scaling Equations BM=Body Mass (g) L = length (mm)**	**Comparative Taxa**	**Sources of equations**
160-178 g	Humerus Length 26-27 mm	$Log_{10}BM=2.8626xLog_{10}L-1.8476$	All mammals	Campione & Evans 2012
120 g	Femur Length = 30 mm	$Log_{10}BM=2.993x Log_{10}L-2.341$	All mammals	Campione & Evans 2012
57 g	Skull length (estimate) = 33 mm	Log10BodyMass = 3.68 x Log10(SkullLength) – 3.83	Placental primates and insectivores	Gingerich and Smith 1984
92 g	Skull length (estimate) = 33 mm	$Log_{10}BodyMass = 3.488 x Log_{10}(Skull length) – 3.332$	Extant rodents	Millien & Bovy 2010

Table S4. Taxonomic summary of extant mammalian groups used in the manual digit ray 3 ternary diagram and analysis of manual phalangeal index (Figure S8). All data are at the species level. The "Group total" includes separate measurement values of the same species by different studies, which are treated as independent measurements from multiple sources in the analysis (see SI text). Measurement data by individual species are presented in Table S5.

Order	**Zheng et al. 2013**	**Kirk et al. 2008**	**New measurements (FMNH specimens)**	**Group total**	**Total unique species**
Carnivora	0	7	5	12	7
Dermoptera	1	2	2	5	2
Insectivorans	2	0	6	8	8
Marsupialia	8*	17	14	39	26
Primates	7	45	5	57	52
Rodentia	8	54	0	62	59
Scandentia	0	5	5	10	7
TOTAL	**26**	**130**	**37**	**193**	**161**

**Caluromys philander* is supplemented from Chen & Luo 2012.

Table S5. Manual digit 3 phalangeal proportions and phalangeal indices by individual species and the data sources of their measurements. Analyses are presented in Figure 4. In cases where multiple specimens of the same species were measured, the mean values of length measurements were used in analyses. In such cases, multiple specimen numbers are listed. Abbreviations: BMNH, Beijing Museum of Natural History; FMNH, Field Museum of Natural History; IPM, intermediate phalanx of manus; PI, manual phalangeal index ((PPM + IPM)/MC x 100); PPM, proximal phalanx of manus; MC, metacarpal. All measurements are in millimeters.

Group	Species	Substrate preference	MC	PPM	IPM	PI	Source
Carnivora	*Arctictis binturong*	Arboreal	34.1	22.5	14.4	108%	Kirk et al. 2008
	Nandinia binotata	Arboreal	19.8	14	9.94	121%	Kirk et al. 2008
	Nandinia binotata	Arboreal	19.56	15.06	10.38	130%	FMNH224514
	Nasua nasua	Terrestrial	22.2	10.8	8.74	88%	Kirk et al. 2008
	Nasua nasua candace	Arboreal	20.44	10.46	8.3	92%	FMNH70739
	Paradoxurus hermaphroditus	Arboreal	17.9	11	8.28	108%	Kirk et al. 2008
	Paradoxurus hermaphroditus philippinensis	Arboreal	17.67	10.81	7.34	103%	FMNH68713
	Potos flavus	Arboreal	22.2	16	10.1	118%	Kirk et al. 2008
	Potos flavus chiriquensis	Arboreal	21.04	15.72	10.5	125%	FMNH15131
	Procyon lotor	Terrestrial	30.6	14.4	9.85	79%	Kirk et al. 2008
	Viverra tangalunga	Terrestrial	29.6	12	8.28	69%	Kirk et al. 2008
	Viverra tangalunga tangalunga	Arboreal	27.88	12.13	7.74	71%	FMNH62277
Dermoptera	*Cynocephalus volans*	Gliding	23.9	15.3	20.4	149%	Kirk et al. 2008
	Cynocephalus volans	Gliding	24.42	15.09	16.12	128%	Mean of FMNH-56530, -61032, -61030, -198917, -87713
	Galeopterus variegatus	Gliding	27.85	15.6	24.05	142%	Zheng et al. 2013
	Galeopterus variegatus	Gliding	24.8	14.9	20.8	144%	Kirk et al. 2008
	Galeopterus variegatus natunae	Gliding	22.12	14.22	20.67	158%	FMNH124001
"Insectivora"	*Erinaceus concolor*	Terrestrial	14.21	5.51	4.33	69%	FMNH84448
	Erinaceus europaeus	Terrestrial	6.89	4.31	2.83	104%	Zheng et al. 2013
	Erinaceus sp.	Terrestrial	10.38	4.12	3.35	72%	Zheng et al. 2013
	Microgale brevicaudata	Terrestrial	3.34	2.3	1.55	115%	FMNH183959
	Myosorex kihaulei	Terrestrial	3.34	1.87	1.15	90%	FMNH204863
	Sorex cinereus cinereus	Terrestrial	2.18	1.53	0.96	114%	FMNH124111
	Suncus murinus	Terrestrial	5.04	2.91	1.87	95%	FMNH165500
	Tenrec ecaudatus	Terrestrial	14.3	6.08	4.05	71%	FMNH175921
Marsupialia	*Aepyprymnus rufescens*	Terrestrial	11.2	4.7	3.65	75%	Kirk et al. 2008
	Caluromys derbianus	Arboreal	8.16	7.31	4.25	142%	Kirk et al. 2008
	Caluromys philander	Arboreal	7.67	6.79	3.83	138%	Chen & Luo 2012

	Caluromys philander	Arboreal	6.92	6.58	3.56	147%	FMNH61877
	Caluromys philander	Arboreal	7.67	6.79	3.85	139%	Kirk et al. 2008
	Caluromysiops irrupta	Arboreal	9.09	8.55	4.37	142%	Kirk et al. 2008
	Chironectes minimus	Terrestrial	16.7	11.1	6.74	107%	Kirk et al. 2008
	Dasyurus viverrinus	Terrestrial	11.45	6.06	4.85	95%	Zheng et al. 2013
	Dasyurus viverrinus	Terrestrial	11.63	6.8	4.21	95%	FMNH42759
	Didelphis marsupialis	Terrestrial	15.86	11.27	6.41	111%	Zheng et al. 2013
	Didelphis marsupialis	Terrestrial	16.9	10.5	5.49	95%	Kirk et al. 2008
	Didelphis marsupialis caucae	Terrestrial	18.07	12.03	6.3	101%	FMNH128387
	Didelphis virginiana	Terrestrial	18.62	11.5	6.66	98%	Zheng et al. 2013
	Didelphis virginiana	Terrestrial	17.8	10.7	5.29	90%	Kirk et al. 2008
	Didelphis virginiana virginiana	Terrestrial	17.05	11.57	5.99	103%	FMNH153786
	Hemibelideus lemuroides	Arboreal	9.77	10.36	5.42	162%	FMNH60926
	Marmosa robinsoni	Arboreal	4.8	4.08	2.25	132%	Kirk et al. 2008
	Micoureus demerarae	Arboreal	4.63	4.72	2.63	159%	Kirk et al. 2008
	Monodelphis brevicaudata	Terrestrial	4.56	2.9	1.42	95%	Kirk et al. 2008
	Monodelphis brevicaudata brevicaudataf	Terrestrial	4.58	3.59	1.94	121%	FMNH60738
	Monodelphis domestica	Terrestrial	5.18	3.1	1.83	95%	Kirk et al. 2008
	Myrmecobius fasciatus	Terrestrial	11.85	3.92	3.51	63%	FMNH19982
	Petauroides volans	Gliding	10.6	14.6	6	194%	Kirk et al. 2008
	Petauroides volans minor	Gliding	9.88	12.73	6.915	199%	FMNH60908
	Petaurus australis	Gliding	10.2	9.7	5.6	150%	Kirk et al. 2008
	Petaurus breviceps	Gliding	5.56	6.01	4.65	192%	FMNH129430
	Petaurus breviceps	Gliding	6.25	6	3.3	149%	Kirk et al. 2008
	Petaurus norfolcensis	Gliding	7.42	6.66	4.96	157%	FMNH46005
	Petrogale sp	Terrestrial	12.35	4.32	3.27	61%	Zheng et al. 2013
	Philander opossum	Terrestrial	11.89	7.66	3.65	95%	FMNH60097
	Philander opossum	Terrestrial	11	7.04	3.55	96%	Kirk et al. 2008
	Potorous tridactylus	Terrestrial	12.3	4.9	4	72%	Kirk et al. 2008
	Pseudocheirus peregrinus	Arboreal	10.3	10.97	5.51	160%	Zheng et al. 2013
	Pseudocheirus peregrinus viverrinus	Arboreal	9.9	9.91	5.83	159%	FMNH47320
	Sarcophilus laniarius	Terrestrial	30.49	13.45	7.77	70%	FMNH129428
	Trichosurus vulpecula	Arboreal	13.81	13.7	8.91	164%	FMNH47320
	Trichosurus vulpecula	Arboreal	18.1	15.5	9.86	140%	Kirk et al. 2008
	Trichosurus vulpina	Arboreal	16.86	14.66	8.92	140%	Zheng et al. 2013
	Vombatus ursinus	Terrestrial	24.55	9.01	7.89	69%	Zheng et al. 2013
Primates	*Aotus trivirgatus*	Arboreal	17	15.5	10.8	155%	Kirk et al. 2008

Arctocebus calabarensis	Arboreal	8.06	6.89	3.73	132%	Kirk et al. 2008
Avahi laniger	Arboreal	22	18.2	11.4	135%	Kirk et al. 2008
Callicebus moloch	Arboreal	16	15.6	10.5	163%	Kirk et al. 2008
Callicebus sp.	Arboreal	17.84	16.57	11.66	158%	FMNH58973
Callithrix jacchus	Arboreal	11.7	9.53	6.29	135%	Kirk et al. 2008
Cebus capucinus	Arboreal	21.17	19.2	13.49	154%	Zheng et al. 2013
Cheirogaleus major	Arboreal	10.7	9.51	5.94	144%	Kirk et al. 2008
Cheirogaleus medius	Arboreal	7.52	6.73	4.44	149%	Kirk et al. 2008
Daubentonia madagascariensis	Arboreal	35.9	42.1	18.7	169%	Kirk et al. 2008
Eulemur coronatus	Arboreal	17.9	15.8	10.6	147%	Kirk et al. 2008
Eulemur fulvus	Arboreal	21	18.2	11.8	143%	Kirk et al. 2008
Eulemur macaco	Arboreal	21.8	19.2	12.6	146%	Kirk et al. 2008
Eulemur mongoz	Arboreal	19.4	16.9	11.4	146%	Kirk et al. 2008
Eulemur rubriventer	Arboreal	22.1	20	12.8	148%	Kirk et al. 2008
Euoticus elegantulus	Arboreal	11	12	7.27	175%	Kirk et al. 2008
Galago alleni	Arboreal	11.36	13.01	7.66	182%	Zheng et al. 2013
Galago moholi	Arboreal	8.26	8.18	5.71	168%	Kirk et al. 2008
Galago senegalensis	Arboreal	11.48	14.48	9.22	206%	Zheng et al. 2013
Galago senegalensis	Arboreal	9.24	9.48	6.3	171%	FMNH58976
Galago senegalensis	Arboreal	8.3	8.54	5.77	172%	Kirk et al. 2008
Galago zanzibaricus	Arboreal	8.94	8.67	6.23	167%	Kirk et al. 2008
Galagoides alleni	Arboreal	10.4	10.8	7.02	171%	Kirk et al. 2008
Galagoides demidoff	Arboreal	6.05	6.48	4.42	180%	Kirk et al. 2008
Hapalemur griseus	Arboreal	16	14.6	9.41	150%	Kirk et al. 2008
Hapalemur simus	Arboreal	19.5	17.7	11.7	151%	Kirk et al. 2008
Indri indri	Arboreal	5.19	4.35	2.69	136%	Zheng et al. 2013
Indri indri	Arboreal	51.6	43	26	134%	Kirk et al. 2008
Lemur catta	Arboreal	21.1	17.9	12.1	142%	Kirk et al. 2008
Lemur fulvus fulvus	Arboreal	17.61	16.99	10.3	155%	FMNH20785
Lemur varius	Arboreal	23.61	22.06	16.24	162%	Zheng et al. 2013
Leontopithecus rosalia	Arboreal	21.6	15.1	10	116%	Kirk et al. 2008
Lepilemur leucopus	Arboreal	13.2	12.9	8.24	160%	Kirk et al. 2008
Lepilemur mustelinus	Arboreal	17.4	16.4	9.98	152%	Kirk et al. 2008
Lepilemur ruficaudatus	Arboreal	12.3	13.1	7.71	169%	Kirk et al. 2008
Loris lydekkerianus nordicus	Arboreal	8.9	8.92	6.44	173%	FMNH95028
Loris tardigradus	Arboreal	7.84	8.43	5.06	172%	Kirk et al. 2008
Microcebus murinus	Arboreal	5.48	5.04	3.79	161%	Kirk et al. 2008
Mirza coquereli	Arboreal	10.5	9.71	5.75	147%	Kirk et al. 2008
Nycticebus coucang	Arboreal	11.9	12.7	7.07	166%	Kirk et al. 2008
Nycticebus pygmaeus	Arboreal	9.96	11.4	6.77	182%	Kirk et al. 2008
Nycticebus tardigratus	Arboreal	9.29	12.35	8.74	227%	Zheng et al. 2013

	Otolemur crassicaudatus	Arboreal	13.4	13.6	8.64	166%	Kirk et al. 2008
	Otolemur garnettii	Arboreal	13.6	14.5	8.75	171%	Kirk et al. 2008
	Perodicticus potto	Arboreal	14.6	15.5	8.09	162%	Kirk et al. 2008
	Phaner furcifer	Arboreal	11.1	10.5	6.61	154%	Kirk et al. 2008
	Propithecus diadema	Arboreal	40.7	34.7	21.9	139%	Kirk et al. 2008
	Propithecus verreauxi	Arboreal	30.7	26.4	16.4	139%	Kirk et al. 2008
	Saguinus midas	Arboreal	14.1	11.3	7.07	130%	Kirk et al. 2008
	Saguinus oedipus	Arboreal	14.2	11.8	6.95	132%	Kirk et al. 2008
	Saimiri sciureus	Arboreal	14.8	12.3	9.25	146%	Kirk et al. 2008
	Tarsius bancanus	Arboreal	11.8	14.3	10.4	209%	Kirk et al. 2008
	Tarsius sp.	Arboreal	10.1	13.6	8	214%	Zheng et al. 2013
	Tarsius spectrum	Arboreal	10.3	11.6	7.87	189%	Kirk et al. 2008
	Tarsius syrichta	Arboreal	11	12	8.47	186%	Kirk et al. 2008
	Tarsius syrichta fraterculus	Arboreal	10.72	11.52	8.7	189%	FMNH142007
	Varecia variegata	Arboreal	28	25.1	15.7	146%	Kirk et al. 2008
Rodentia	*Akodon boliviensis*	Terrestrial	3.2	1.9	1.3	100%	Kirk et al. 2008
	Akodon cursor	Terrestrial	4.3	2.6	1.7	100%	Kirk et al. 2008
	Akodon longipilis	Terrestrial	4	2.6	1.5	103%	Kirk et al. 2008
	Akodon urich	Terrestrial	3.7	2.2	1.4	97%	Kirk et al. 2008
	Ammospermophilus leucurus	Terrestrial	7.03	4.62	3.23	112%	Kirk et al. 2008
	Anomalurus sp.	Gliding	9.86	10.31	8.51	191%	Zheng et al. 2013
	Aplodontia rufa	Terrestrial	11.8	7.13	5.48	107%	Kirk et al. 2008
	Apodemus sylvaticus	Terrestrial	4.1	2.66	1.64	105%	Kirk et al. 2008
	Callosciurus erythraeus	Arboreal	10.8	9.1	6.65	146%	Kirk et al. 2008
	Chiropodomys calamianensis	Arboreal	4.29	3.26	2.08	124%	Kirk et al. 2008
	Coendou prehensilis	Arboreal	17.65	12.4	9.67	125%	Kirk et al. 2008
	Cynomys ludovicianus	Terrestrial	13.2	7.83	5.45	101%	Kirk et al. 2008
	Dactylomys dactylinus	Arboreal	9.7	7.6	5.8	138%	Kirk et al. 2008
	Dendromus mystacalis	Arboreal	2.19	2.24	1.66	178%	Kirk et al. 2008
	Dremomys pernyi	Arboreal	9.62	7.55	5.83	139%	Kirk et al. 2008
	Erethizon dorsatum	Arboreal	18.17	12.84	9.68	124%	Kirk et al. 2008
	Eutamias sibiricus	Terrestrial	7.22	5.3	4.12	130%	Zheng et al. 2013
	Funisciurus lemniscatus	Arboreal	8	6.3	4.2	131%	Kirk et al. 2008
	Funisciurus pyrropus	Arboreal	9.6	7.25	5	128%	Kirk et al. 2008
	Glaucomy volans	Gliding	6.18	5.55	4.71	166%	Zheng et al. 2013
	Glaucomys sabrinus	Gliding	6.19	5.37	5.57	177%	Zheng et al. 2013
	Glaucomys sabrinus	Gliding	6.07	5.65	4.45	166%	Kirk et al. 2008
	Heliosciurus rufobrachium	Arboreal	11.1	9.07	6.28	138%	Kirk et al. 2008
	Lariscus hosei	Terrestrial	10.2	7.2	5.3	123%	Kirk et al. 2008

	Liomys pictus	Terrestrial	3.85	2.38	1.27	95%	Kirk et al. 2008
	Marmota caligata	Terrestrial	23.2	14.8	9.05	103%	Kirk et al. 2008
	Marmota himalayana	Terrestrial	24.7	15.5	7.6	94%	Kirk et al. 2008
	Marmota monax	Terrestrial	21.3	13.7	8.6	105%	Kirk et al. 2008
	Menetes berdmorei	Terrestrial	8.6	6.3	4.6	127%	Kirk et al. 2008
	Micromys minutus	Arboreal	2.27	1.65	1.03	118%	Kirk et al. 2008
	Microsciurus alfari	Arboreal	7.6	7.3	5.7	171%	Kirk et al. 2008
	Microsciurus flaviventer	Arboreal	6.7	6.2	4.9	166%	Kirk et al. 2008
	Mus musculus	Terrestrial	2.7	1.7	1.12	104%	Kirk et al. 2008
	Myosciurus pumilio	Arboreal	3.6	3.6	2.7	175%	Kirk et al. 2008
	Nannosciurus melanotis	Arboreal	5.7	5.2	3.6	154%	Kirk et al. 2008
	Paraxerus cepapi	Arboreal	8.3	6.35	4.35	129%	Kirk et al. 2008
	Paraxerus ochraceus	Arboreal	7.3	5.6	4	132%	Kirk et al. 2008
	Pedetes capensis	Terrestrial	9.15	6.65	5.45	132%	Kirk et al. 2008
	Perognathus amplus	Terrestrial	2.95	1.62	1.18	95%	Kirk et al. 2008
	Petaurista philippensis	Gliding	13.07	14.63	11.16	197%	Zheng et al. 2013
	Phloeomys cumingi	Arboreal	16.5	12.5	8.5	127%	Kirk et al. 2008
	Rattus rattus	Terrestrial	6.77	4.22	2.5	99%	Kirk et al. 2008
	Ratufa bicolor	Arboreal	14.34	13.36	10.76	168%	Zheng et al. 2013
	Ratufa bicolor	Arboreal	14.8	14.1	9.6	160%	Kirk et al. 2008
	Ratufa macroura	Arboreal	13.3	11.4	8.3	148%	Kirk et al. 2008
	Ratufa sp.	Arboreal	18.14	17.95	10.65	158%	Zheng et al. 2013
	Ratufa sp.	Arboreal	16.3	13.8	10.1	147%	Kirk et al. 2008
	Sciurotamias davidianus	Terrestrial	11	7.03	5.15	111%	Kirk et al. 2008
	Sciurus aberti	Arboreal	13.8	11.3	9.15	148%	Kirk et al. 2008
	Sciurus carolinensis	Arboreal	12	9.5	7.48	142%	Kirk et al. 2008
	Sciurus niger	Arboreal	15.2	11.6	8.95	135%	Kirk et al. 2008
	Spermophilus richardsonii	Terrestrial	9.75	5.83	3.67	97%	Kirk et al. 2008
	Sundasciurus lowii	Arboreal	7.7	6.2	4.2	135%	Kirk et al. 2008
	Sundasciurus samarensis	Arboreal	9.65	8	5.5	140%	Kirk et al. 2008
	Tamias amoenus	Terrestrial	6.15	3.92	2.83	110%	Kirk et al. 2008
	Tamiasciurus douglasii	Arboreal	10.1	7.55	6.2	136%	Kirk et al. 2008
	Tamiasciurus hudsonicus	Arboreal	9.1	7.2	5.75	142%	Kirk et al. 2008
	Tamiops swinhoei	Arboreal	7.13	6.43	4.7	156%	Kirk et al. 2008
	Trogopterus xanthipes	Gliding	8.75	9.11	4.46	155%	Zheng et al. 2013
	Trogopterus xanthipes	Gliding	9.5	10.4	8.1	195%	Kirk et al. 2008
	Xerus erythropus	Terrestrial	12	7.7	5.1	107%	Kirk et al. 2008
	Xerus inauris	Terrestrial	12.3	7	4.4	93%	Kirk et al. 2008
Scandentia	*Dendrogale murina frenata*	Arboreal	6.41	3.7	2.66	99%	FMNH46630

	Ptilocercus lowii	Arboreal	6.1	4.8	3.5	136%	Kirk et al. 2008
	Tupaia glis	Terrestrial	9.5	5.13	3.43	90%	Kirk et al. 2008
	Tupaia glis	Terrestrial	9.67	5.05	3.65	90%	FMNH104808
	Tupaia longpipes	Terrestrial	9.93	5.33	3.91	93%	FMNH140928
	Tupaia gracilis gracilis	Arboreal	7.18	4.71	3.88	120%	FMH76819
	Tupaia longipes	Terrestrial	10.3	5.85	4.23	98%	Kirk et al. 2008
	Tupaia minor	Arboreal	6.85	4.89	3.83	127%	Kirk et al. 2008
	Tupaia minor caedis	Arboreal	5.94	4.25	3.79	135%	FMNH76865
	Tupaia tana	Terrestrial	10.6	6.26	4.23	99%	Kirk et al. 2008
Eleuther-	BMNH1133	? (to be estimated)	5.13	6.04	5.84	232%	BMNH1133
odontids	BMNH2942	? (to be estimated)	3.56	4.6	4.17	246%	BMNH2942
	Maiopatagium (BMNH2940)	? (to be estimated)	4.8	6.42	5.36	245%	BMNH2940
	Arboroharamiya jenkinsi	? (to be estimated)	8.36	10.71	10.12	249%	Zheng et al. 2013
	Shenshou lui (LDNMF2001)	? (to be estimated)	5.62	7.1	5.95	232%	Bi et al. 2014*
	Xianshou songae	? (to be estimated)	3	4.3	3.7	267%	Bi et al. 2014*
Mesozoic	*Agilodocodon scansorius*	Arboreal?	3.9	3.06	2.32	138%	Meng et al. 2015
mammals	*Eomaia scansoria*	Arboreal?	3.95	2.85	2.29	130%	Chen & Luo 2012
	Jeholodens jenkinsi	Terrestrial?	3.2	1.93	1.3	101%	Zheng et al. 2013
	Maotherium sinsensis	Terrestrial?	6.1	3.4	2.4	95%	Rougier et al. 2003
	Rugosodon eurasiaticus	Terrestrial?	8.36	5.93	4.67	127%	BMNH1143
	Sinobaatar lingyuanensis	Terrestrial?	4.8	2.8	2.1	102%	Zheng et al. 2013
	Sinodelphys szalayi	Arboreal?	3.67	2.9	2.2	139%	Zheng et al. 2013

*Measurements of Shenshou (Bi et al. 2014) were obtained from published images.

Table S6. Taxonomic summary of extant mammalian groups used in the pedal digit ray 3 ternary diagram and analysis of pedal phalangeal index (Figure 4). All data are at the species level. The "Group total" includes separate measurements of the same species by this study, and by other studies, which are treated as data from different sources in the analysis (see SI text). Data for the species are presented in Table S7.

Order	Zheng et al. 2013	New measurements (FMNH specimens)	Group total	Total unique species
Carnivora	0	5	5	5
Chiroptera	0	25	25	25
Dermoptera	1	2	3	2
Insectivorans	2	6	8	8
Marsupialia	8*	14	22	17
Primates	7	5	12	11
Rodentia	8	0	8	8
Scandentia	0	5	5	5
TOTAL	**26**	**62**	**88**	**81**

**Caluromys philander* is supplemented from Argot 2002.

Table S7. Pedal digit 3 phalangeal proportions and phalangeal indices by individual species and the data sources of their measurements (for Figure 4). Analyses are presented in Figure 4. In cases where multiple specimens of the same species were measured, the mean values of length measurements were used in analyses. In such cases, multiple specimen numbers are listed. Abbreviations: BMNH, Beijing Museum of Natural History; FMNH, Field Museum of Natural History; IPM, intermediate phalanx of manus; PI, pedal phalangeal index ((PPP + IPP)/MT x 100); PPM, proximal phalanx of pedes; MT, metatarsal. All measurements are in millimeters.

Group	Species	Substrate preference	MT	PPP	IPP	PI	Source
Carnivora	*Nandinia binotata*	Arboreal	29.18	15.58	10.57	90%	FMNH224514
	Nasua nasua candace	Terrestrial	25.68	10.87	8.53	76%	FMNH70739
	Paradoxurus hermaphroditus philippinensis	Arboreal	23.82	10.86	7.76	78%	FMNH68713
	Potos flavus chiriquensis	Arboreal	27.56	16.05	9.73	94%	FMNH15131
	Viverra tangalunga tangalunga	Terrestrial	38.62	12.6	8.45	55%	FMNH62277
Chiroptera	*Alionycteris paucidentata*	Flight/roost	2.525	2.49	1.985	177%	Mean of FMNH-146599, -146601
	Artibeus lituratus lituratus	Flight/roost	4.19	4.235	3.22	178%	Mean of FMNH-124949, -124937
	Artibeus planirostris	Flight/roost	4.175	3.925	2.94	164%	Mean of FMNH-169908, -169919
	Balionycteris maculata	Flight/roost	1.7	1.89	1.92	224%	FMNH109057
	Centurio senex senex	Flight/roost	2.73	2.56	2.13	172%	FMNH128412
	Cynopterus brachyotis luzoniensis	Flight/roost	3.18	3.75	3.07	214%	Mean of FMNH-142380, -142379, -142378
	Desmodus rotundus murinus	Flight/roost	3.95	4.17	2.95	180%	FMNH47697
	Eidolon dupreanum	Flight/roost	8.42	8.81	7.78	197%	FMNH169701
	Eidolon helvum	Flight/roost	6.845	7.875	6.77	214%	FMNH42379
	Epomophoru wahlbergi	Flight/roost	4.81	5.36	4.93	214%	FMNH150045
	Epomops franqueti	Flight/roost	5.03	6.315	5.33	232%	Mean of FMNH-160229, -165104
	Harpyionycteris whiteheadi whiteheadif	Flight/roost	5.065	5.56	5.285	214%	Mean of FMNH-146648, -146647, -146651
	Lissonycteris angolensis	Flight/roost	5.13	5.48	5.17	208%	Mean of FMNH-204049, -144257, -144275
	Noctilio albiventris affinis	Flight/roost	3.85	3.77	3.14	179%	FMNH124640
	Phyllostomus hastatus hastatus	Flight/roost	4.55	4.245	3.72	175%	Mean of FMNH-174737, -93513
	Platyrrhinus infuscus	Flight/roost	3.67	3.28	2.74	164%	FMNH170139
	Ptenochirus jagori	Flight/roost	4.58	5.02	4.23	202%	Mean of FMNH-150802, -150798, -146673

	Pteropus alecto gouldi	Flight/roost	11.48	12.72	12.8	222%	FMNH119872
	Pteropus giganteus	Flight/roost	11.855	13.055	12.71	217%	Mean of FMNH-57669, -119872
	Pteropus hypomelanus cagayanus	Flight/roost	9.29	9.305	9.285	200%	Mean of FMNH-150860, -135672
	Pteropus rufus	Flight/roost	11.605	12.29	11.685	207%	Mean of FMNH-189889, -189893
	Pteropus vampyrus natunae	Flight/roost	12.53	13.82	13.86	221%	FMNH76958
	Rousettus amplexicaudatus amplexicaudatus	Flight/roost	5.405	4.82	4.28	168%	Mean of FMNH-140657, -140664
	Taphozous nudiventris	Flight/roost	4.63	4.74	3.44	177%	FMNH96527
	Trachops cirrhosus	Flight/roost	4.86	4.13	3.46	156%	FMNH174893
Dermoptera	*Galeopterus variegatus*	Gliding	24.41	11.4	11.05	92%	Zheng et al. 2013
	Cynocephalus volans	Gliding	24.42	15.09	16.12	128%	Mean of FMNH-56530, -61032, -61030, -198917, -87713
	Galeopterus variegatus natunae	Gliding	19.74	10.83	10.27	107%	FMNH124001
"Insectivora"	*Erinaceus concolor*	Terrestrial	15.41	6.14	4.14	67%	FMNH84448
	Erinaceus europaeus	Terrestrial	12.03	5.12	4.14	77%	Zheng et al. 2013
	Erinaceus sp.	Terrestrial	10.79	5.1	3.31	78%	Zheng et al. 2013
	Microgale brevicaudata	Terrestrial	4.25	2.4	1.73	97%	FMNH183959
	Myosorex kihaulei	Terrestrial	4.51	2.11	1.25	75%	FMNH204863
	Sorex cinereus cinereus	Terrestrial	4.31	2.11	1.33	80%	FMNH124111
	Suncus murinus	Terrestrial	5.77	2.9	2.24	89%	FMNH165500
	Tenrec ecaudatus	Terrestrial	14.02	6.4	3.2	68%	FMNH175921
Marsupialia	*Caluromys philander*	Arboreal	10.25	9.65	6.35	156%	Argot 2002
	Caluromys philander	Arboreal	8.36	6.83	4.27	133%	FMNH61877
	Dasyurus viverrinus	Terrestrial	26.48	8.85	6.45	58%	Zheng et al. 2013
	Dasyurus viverrinus	Terrestrial	24.05	9.06	5.46	60%	FMNH42759
	Didelphis marsupialis	Terrestrial	18.69	13.18	11.05	130%	Zheng et al. 2013
	Didelphis marsupialis caucae	Terrestrial	19.31	12.14	7.76	103%	FMNH128387
	Didelphis virginiana	Terrestrial	20.09	11.05	6.61	88%	Zheng et al. 2013
	Didelphis virginiana virginiana	Terrestrial	20.07	10.85	6.69	87%	FMNH153786
	Hemibelideus lemuroides	Arboreal	12.14	12.3	5.42	146%	FMNH60926
	Monodelphis brevicaudata brevicaudataf	Terrestrial	6.19	3.99	2.6	106%	FMNH60738
	Myrmecobius fasciatus	Terrestrial	19.71	7.85	4.59	63%	FMNH19982
	Petauroides volans minor	Gliding	12.12	14.035	7.385	177%	FMNH60908
	Petaurus breviceps	Gliding	6.97	7.13	4.89	172%	FMNH129430
	Petaurus norfolcensis	Gliding	9.4	8.38	5.26	145%	FMNH46005

	Petrogale sp	Terrestrial	27.84	9.25	4.85	51%	Zheng et al. 2013
	Philander opossum	Terrestrial	15.76	8.8	4.6	85%	FMNH60097
	Pseudocheirus peregrinus	Arboreal	9.9	10.56	6.25	170%	Zheng et al. 2013
	Pseudocheirus peregrinus viverrinus	Arboreal	12.39	12.01	7.65	159%	FMNH47320
	Sarcophilus laniarius	Terrestrial	31.3	13.18	9.14	71%	FMNH129428
	Trichosurus vulpecula	Arboreal	16.04	16.11	9.25	158%	FMNH47320
	Trichosurus vulpina	Arboreal	15.46	13.76	6.99	134%	Zheng et al. 2013
	Vombatus ursinus	Terrestrial	20.19	9.08	8.36	86%	Zheng et al. 2013
Primates	*Callicebus sp.*	Arboreal	30.09	18.28	13.75	106%	FMNH58973
	Cebus capucinus	Arboreal	32.06	20.55	13.98	108%	Zheng et al. 2013
	Galago alleni	Arboreal	11.37	12.54	8.17	182%	Zheng et al. 2013
	Galago senegalensis	Arboreal	12.78	13.94	7.15	165%	Zheng et al. 2013
	Galago senegalensis	Arboreal	11.3	10.1	6.24	145%	FMNH58976
	Indri indri	Arboreal	5.12	3.62	2.17	113%	Zheng et al. 2013
	Lemur fulvus fulvus	Arboreal	18.54	16.49	10.79	147%	FMNH20785
	Lemur varius	Arboreal	28.71	23.34	14.41	131%	Zheng et al. 2013
	Loris lydekkerianus nordicus	Arboreal	11.45	11.23	6.49	155%	FMNH95028
	Nycticebus tardigratus	Arboreal	12.39	14.84	9.78	199%	Zheng et al. 2013
	Tarsius sp.	Arboreal	12	14	9	192%	Zheng et al. 2013
	Tarsius syrichta fraterculus	Arboreal	11.31	10.76	7.18	159%	FMNH142007
Rodentia	*Anomalurus sp.*	Gliding	15.82	10.56	6.4	107%	Zheng et al. 2013
	Eutamias sibiricus	Terrestrial	14.2	5.92	3.96	70%	Zheng et al. 2013
	Glaucomy volans	Gliding	12.58	5.73	4.27	79%	Zheng et al. 2013
	Glaucomys sabrinus	Gliding	14.52	5.98	4.48	72%	Zheng et al. 2013
	Petaurista philippensis	Gliding	24.78	12.27	8.3	83%	Zheng et al. 2013
	Ratufa bicolor	Arboreal	27.49	13.94	12.02	94%	Zheng et al. 2013
	Ratufa sp.	Arboreal	30.19	16.34	16.2	108%	Zheng et al. 2013
	Trogopterus xanthipes	Gliding	16.41	9.43	7.02	100%	Zheng et al. 2013
Scandentia	*Dendrogale murina frenata*	Arboreal	12.5	4.81	4.1	71%	FMNH46630
	Tupaia glis	Terrestrial	15.96	6.16	4.85	69%	FMNH104808
	Tupaia gracilis gracilis	Terrestrial	15.15	5.36	4.81	67%	FMNH140928
	Tupaia longpipes	Terrestrial	18.51	6.7	4.96	63%	FMH76819
	Tupaia minor caedis	Arboreal	11.15	5.24	4.06	83%	FMNH76865
Eleuther-	BMNH1133	? (to be estimated)	5.41	6.67	6.07	235%	BMNH1133
odontids	*Maiopatagium* (BMNH2940)	? (to be estimated)	4.98	6.31	5.53	238%	BMNH2940
	BMNH2942	? (to be estimated)	3.5	4.47	4.09	245%	BMNH2942
	BMNH1137	? (to be estimated)	5.62	7.18	6.71	247%	BMNH1137
	Arboroharamiya jenkinsi	? (to be estimated)	9.66	11.29	9.53	216%	Zheng et al. 2013

	Shenshou lui (LDNMF2001)	? (to be estimated)	6.69	7.77	7.08	222%	Bi et al. 2014*
	Xianshou songae	? (to be estimated)	3	4	4	267%	Bi et al. 2014*
Mesozoic mammals	*Agilodocodon scansorius*	Arboreal?	3.91	2.89	2.33	134%	BMNH1138
	Eomaia scansoria	Arboreal?	3.68	2.63	2.1	129%	Zheng et al. 2013
	Jeholodens jenkinsi	Terrestrial?	3.16	2.05	1.69	118%	Zheng et al. 2013
	Maotherium sinsensis	Terrestrial?	7.3	4.1	3.15	99%	Rougier et al. 2003
	Rugosodon eurasiaticus	Terrestrial?	9.59	6.48	4.47	114%	BMNH1143
	Sinobaatar lingyuanensis	Terrestrial?	6.3	3.2	2.8	95%	Zheng et al. 2013
	Sinodelphys szalayi	Arboreal?	3.4	3	2.3	156%	Zheng et al. 2013
	Volaticotherium antiquus	Gliding?	8.95**	7.1**	5.3	139%	Meng et al. 2006

*Measurements obtained from published images.
**Recorded in Meng et al. 2006 as the "longest metatarsal" and "longest proximal phalange."

Table S8. Summary of species count of extant mammal groups used to calculate functional indices and multivariate analyses (Figures 4, S8, S9). Data for the species are presented in Table S9.

Group	S. & V.V. 2008	New measurements (FMNH specimens)	Group total	Total unique genera
Carnivora	7	5	12	12
Dermoptera	1	1	2	2
Insectivorans	1	6	7	6
Marsupialia	0	14	14	12
Primates	0	5	5	5
Rodentia	36	0	36	35
Scandentia	0	5	5	2
Xenarthra	1	0	1	1
TOTAL	**46**	**36**	**82**	**75**

Table S9. Functional indices of modern and fossil taxa based on skeletal measurements. The six indices (BI, OLI, CI, PES, IM, and FEB) are defined above ("Functional indices" section) and in Samuels and Van Valkenburg (2008). Abbreviations: S. & V.V. 2008, Samuels & Van Valkenburg 2008; Semifoss., Semifossorial. The newly added species of this analysis are listed by their FMNH (Field Museum of Natural History) specimen numbers.

Group	Species	Substrate preference	BI	OLI	CI	PES	IM	FEB	Source
Carnivora	*Ailurus fulgens*	Arboreal	0.774	0.159	0.983	0.359	0.901	0.207	S. & V.V. 2008
	Gulo gulo	Terrestrial*	0.807	0.168	0.981	0.396	0.909	0.284	S. & V.V. 2008
	Mephitis mephitis	Semifoss.	0.823	0.193	1.017	0.313	0.788	0.226	S. & V.V. 2008
	Mustela frenata	Terrestrial	0.67	0.176	1.088	0.401	0.79	0.096	S. & V.V. 2008
	Nandinia binotata	Arboreal	0.763	0.172	1.028	0.313	0.798	0.182	FMNH224514
	Nasua nasua candace	Terrestrial	0.810	0.201	0.964	0.309	0.805	0.201	FMNH70739
	Neovison vison	Terrestrial	0.705	0.212	1.102	0.497	0.804	0.215	S. & V.V. 2008
	Paradoxurus hermaphroditus philippinensis	Arboreal	0.772	0.153	0.960	0.304	0.852	0.200	FMNH68713
	Potos flavus chiriquensis	Arboreal	0.821	0.135	0.982	0.326	0.821	0.228	FMNH15131
	Procyon lotor	Terrestrial*	1.006	0.116	1.045	0.339	0.87	0.2	S. & V.V. 2008
	Taxidea taxus	Semifoss.	0.803	0.288	0.818	0.324	1.001	0.248	S. & V.V. 2008
	Viverra tangalunga tangalunga	Terrestrial	0.923	0.139	0.997	0.398	0.809	0.163	FMNH62277
Dermoptera	*Cynocephalus volans*	Gliding	1.433	0.046	1.062	0.174	1.011	0.206	S. & V.V. 2008
	Galeopterus variegatus natunae	Gliding	1.365	0.017	1.062	0.182	1.004	0.090	FMNH124001
"Insectivora"	*Erinaceus concolor*	Semifoss.	0.881	0.221	0.998	0.311	0.809	0.198	FMNH84448
	Microgale brevicaudata	Semifoss.	0.791	0.218	1.106	0.397	0.782	0.191	FMNH183959
	Myosorex kihaulei	Semifoss.	0.952	0.211	1.493	0.455	0.701	0.212	FMNH204863
	Sorex cinereus cinereus	Terrestrial	1.065	0.137	1.751	0.595	0.636	0.228	FMNH124111
	Sorex vagrans	Terrestrial	0.942	0.232	1.294	0.409	0.753	0.222	S. & V.V. 2008
	Suncus murinus	Terrestrial	0.837	0.167	1.144	0.364	0.694	0.230	FMNH165500
	Tenrec ecaudatus	Semifoss.	0.736	0.303	1.041	0.299	0.825	0.220	FMNH175921
Marsupialia	*Caluromys philander*	Arboreal	1.102	0.109	1.094	0.229	0.834	0.199	FMNH61877
	Dasyurus viverrinus	Terrestrial	1.044	0.120	1.171	0.428	0.797	0.193	FMNH42759
	Didelphis marsupialis	Terrestrial	0.990	0.161	1.046	0.249	0.814	0.180	FMNH128387

	caucae								
	Didelphis virginiana virginiana	Terrestrial	1.020	0.148	1.056	0.233	0.828	0.187	FMNH153786
	Hemibelideus lemuroides	Arboreal	1.021	0.118	0.986	0.187	0.790	0.182	FMNH60926
	Monodelphis brevicaudata brevicaudata	Terrestrial	1.003	0.155	1.078	0.298	0.800	0.202	FMNH60738
	Myrmecobius fasciatus	Semifoss.	1.034	0.182	1.129	0.433	0.684	0.221	FMNH19982
	Petauroides volans minor	Gliding	0.875	0.149	0.995	0.132	0.711	0.133	FMNH60908
	Petaurus breviceps	Gliding	1.173	0.092	1.140	0.205	0.867	0.161	FMNH129430
	Petaurus norfolcensis	Gliding	1.216	0.067	1.129	0.199	0.850	0.141	FMNH46005
	Philander opossum	Terrestrial	0.993	0.144	1.067	0.256	0.786	0.179	FMNH60097
	Pseudocheirus peregrinus viverrinus	Arboreal	0.947	0.149	0.931	0.187	0.762	0.190	FMNH47320
	Sarcophilus laniarius	Terrestrial	0.952	0.164	1.026	0.298	0.943	0.214	FMNH129428
	Trichosurus vulpecula	Arboreal	1.171	0.138	1.022	0.192	0.834	0.183	FMNH47320
Primates	*Callicebus sp.*	Arboreal	0.837	0.092	0.965	0.307	0.781	0.136	FMNH58973
	Galago senegalensis	Arboreal	1.066	0.097	0.935	0.159	0.510	0.119	FMNH58976
	Lemur fulvus fulvus	Arboreal	1.058	0.089	0.925	0.161	0.716	0.122	FMNH20785
	Loris lydekkerianus nordicus	Arboreal	1.154	0.036	1.002	0.165	0.906	0.115	FMNH95028
	Tarsius syrichta fraterculus	Arboreal	1.311	0.094	0.985	0.207	0.572	0.110	FMNH142007
Rodentia	*Ammospermophilus leucurus*	Semifoss.	0.949	0.163	1.131	0.476	0.723	0.188	S. & V.V. 2008
	Anomalurus pelii	Gliding	0.922	0.1	1.042	0.228	0.813	0.258	S. & V.V. 2008
	Chelemys macronyx	Semifoss.	1.032	0.267	1.207	0.433	0.711	0.2	S. & V.V. 2008
	Clethrionomys (Myodes) californicus	Terrestrial	0.91	0.113	1.189	0.466	0.779	0.136	S. & V.V. 2008
	Coendou prehensalis	Arboreal	0.881	0.118	0.952	0.265	0.885	0.254	S. & V.V. 2008
	Cynomys gunnisoni	Semifoss.	0.914	0.217	1.022	0.349	0.81	0.186	S. & V.V. 2008
	Dinomys branickii	Terrestrial	0.928	0.204	0.999	0.316	0.88	0.195	S. & V.V. 2008
	Erethizon dorsatum	Arboreal	0.995	0.126	0.982	0.22	0.913	0.26	S. & V.V. 2008
	Glaucomys sabrinus	Gliding	1.129	0.091	1.173	0.379	0.843	0.25	S. & V.V. 2008

	Hylopetes nigripes	Gliding	1.052	0.103	1.127	0.329	0.79	0.179	S. & V.V. 2008
	Hyomys goliath	Terrestrial	0.949	0.174	1.113	0.393	0.803	0.196	S. & V.V. 2008
	Hystrix cristata	Semifoss.	0.768	0.308	1	0.296	0.87	0.192	S. & V.V. 2008
	Marmota flaviventris	Semifoss.	0.816	0.237	0.975	0.334	0.825	0.124	S. & V.V. 2008
	Microtus californicus	Terrestrial	0.98	0.166	1.236	0.495	0.786	0.16	S. & V.V. 2008
	Napaeozapus insignis	Terrestrial	1.028	0.142	1.363	0.812	0.626	0.251	S. & V.V. 2008
	Neotoma cinerea	Terrestrial	0.968	0.14	1.129	0.367	0.769	0.191	S. & V.V. 2008
	Nyctomys sumichrasti	Arboreal	0.974	0.163	1.066	0.383	0.747	0.238	S. & V.V. 2008
	Onychomys leucogaster	Terrestrial	1.012	0.175	1.175	0.484	0.759	0.195	S. & V.V. 2008
	Oxymycterus dasytrichus	Semifoss.	1.048	0.246	1.219	0.526	0.691	0.142	S. & V.V. 2008
	Paraxerus cepapi	Arboreal	0.93	0.159	1.163	0.438	0.725	0.197	S. & V.V. 2008
	Perognathus parvus	Terrestrial	1.044	0.155	1.255	0.662	0.704	0.206	S. & V.V. 2008
	Peromyscus maniculatus	Terrestrial	1.186	0.141	1.326	0.513	0.677	0.157	S. & V.V. 2008
	Petaurista petaurista	Gliding	0.992	0.081	1.07	0.24	0.787	0.155	S. & V.V. 2008
	Phloeomys pallidus	Terrestrial	0.899	0.168	1.022	0.309	0.83	0.203	S. & V.V. 2008
	Rattus norvegicus	Terrestrial	0.973	0.19	1.17	0.462	0.771	0.233	S. & V.V. 2008
	Rattus rattus	Terrestrial	0.948	0.175	1.178	0.467	0.736	0.193	S. & V.V. 2008
	Ratufa affinis	Arboreal	0.824	0.16	1.023	0.397	0.78	0.189	S. & V.V. 2008
	Sciurus niger	Arboreal	0.941	0.16	1.137	0.422	0.731	0.185	S. & V.V. 2008
	Sigmodon hispidus	Terrestrial	0.917	0.148	1.127	0.357	0.768	0.262	S. & V.V. 2008
	Spermophilus beecheyi	Semifoss.	0.901	0.181	1.035	0.393	0.77	0.145	S. & V.V. 2008
	Sphiggurus mexicanus	Arboreal	0.967	0.109	1.001	0.235	0.881	0.24	S. & V.V. 2008
	Tamias palmeri	Semifoss.	0.979	0.182	1.143	0.5	0.739	0.123	S. & V.V. 2008
	Tamiasciurus hudsonicus	Arboreal	0.945	0.167	1.15	0.474	0.737	0.183	S. & V.V. 2008
	Tylomys nudicaudus	Arboreal	0.962	0.189	1.067	0.537	0.663	0.169	S. & V.V. 2008
	Xerus inauris	Semifoss.	0.94	0.192	1.161	0.432	0.644	0.191	S. & V.V. 2008
	Zapus princeps	Terrestrial	1.097	0.146	1.351	0.758	0.59	0.228	S. & V.V. 2008
Scandentia	*Dendrogale murina frenata*	Arboreal	0.979	0.083	1.075	0.523	0.786	0.177	FMNH 46630
	Tupaia glis	Terrestrial	0.900	0.172	1.084	0.444	0.746	0.169	FMNH104808
	Tupaia gracilis gracilis	Terrestrial	0.966	0.081	1.149	0.475	0.679	0.152	FMNH140928
	Tupaia longpipes	Terrestrial	0.962	0.117	1.077	0.409	0.690	0.149	FMNH76819

	Tupaia minor caedis	Arboreal	0.908	0.087	1.081	0.418	0.760	0.161	FMNH76865
Xenarthra	*Choloepus didactylus*	Arboreal	1.197	0.049	1.008	0.274	1.123	0.172	S. & V.V. 2008
Eleuther-	BMNH2942	? (to be estimated)	1.087	0.060	1.040	0.166	0.935	0.163	BMNH2942
odontids	BMNH1133	? (to be estimated)	1.107	0.067	1.014	0.177	0.902	0.184	BMNH1133
	Maiopatagium (BMNH2940)	? (to be estimated)	1.120	0.092	1.045	0.167	0.924	0.189	BMNH2940
	BMNH1137	? (to be estimated)	1.274	0.074	0.936	0.137	0.759	0.159	BMNH1137
	Arboroharamiya jenkinsi	? (to be estimated)	---	1.107	1.107	0.216	---	---	Zheng et al. 2013**
	Shenshou lui (LDNMF2001)	? (to be estimated)	1.078	0.069	0.841	0.163	0.807	0.152	Bi et al. 2014**
	Xianshou songae	? (to be estimated)	0.983	0.092	1.086	0.152	0.844	0.152	Bi et al. 2014**
Mesozoic	*Agilodocodon scansorius*	Arboreal?	0.744	0.153	1.062	0.301	0.911	0.272	BMNH1138
mammals	*Eomaia scansoria*	Arboreal?	0.932	---	1.250	0.230	0.789	---	Meng et al. 2006
	Jeholodens jenkinsi	Terrestrial?	0.933	---	1.000	0.333	0.763	---	Meng et al. 2006
	Maotherium sinensis	Terrestrial?	0.839	---	0.957	0.316	0.732	---	Meng et al. 2006
	Rugosodon eurasiaticus	Terrestrial?	0.746	0.214	0.870	0.338	0.691	0.278	BMNH 1143
	Sinodelphys szalayi	Arboreal?	0.513	---	1.228	0.250	0.674	---	Meng et al. 2006
	Volaticotherium antiquus	Gliding?	0.811	0.117	0.928	0.292	0.811	0.219	Meng et al. 2006**
	Zhangeotherium quiquecuspidens	Terrestrial?	0.774	---	1.068	0.391	0.862	---	Meng et al. 2006

* Described as “Terrestrial/scansorial” or “Terrestrial (Scansorial)” by Samuels and Van Valkenburg 2008.
**Some measurements obtained from published images.

Table S10. Discriminant analysis classification matrix for extant species of Table S7. Each taxon of a known group (rows) was assigned to a predicted group (columns) that results in the minimal Mahalanobis distance to the group mean. Incorrectly assigned taxa are represented in off-diagonal boxes. Fossil taxa were treated as "unknowns" and therefore not included.

	Predicted group					
Given group	Semifossorial	Gliding	Terrestrial	Arboreal	**Total**	**% correct**
Semifossorial	11	0	5	0	16	68.75
Gliding	0	9	0	0	9	100
Terrestrial	4	1	20	7	32	62.5
Arboreal	1	2	6	16	25	64
Total	16	12	31	23	82	68.29

Table S11. Discriminant analysis classification of fossil taxa. Taxa are assigned to a group (i.e., locomotor mode) based on which group results in the minimal Mahalanobis distance to the group mean.

Taxon	**Locomotor mode classification**
BMNH2942	Gliding
BMNH1133	Arboreal
Maiopatagium (BMNH2940)	Gliding
BMNH1137	Arboreal
Volaticotherium antiquus	Arboreal
Agilodocodon scansorius	Arboreal
Rugosodon eurasiaticus	Arboreal
Shenshou lui (LDNMF2001)	Arboreal
Xianshou songae	Gliding

Table S12. Loadings, eigenvalues, and percentage of variance explained by each function (LDA) or component (PCA) for the discriminant analysis (first three rows) and principal components analysis (last five rows).

Axis	BI	OLI	CI	IM	FEB	PES	Eigenvalue	Variance
DF1	-0.0454	0.0344	0.0173	0.0431	-0.0164	0.0172	1.5966	65.94%
DF2	0.0356	0.0046	0.0204	-0.0218	0.0178	-0.0127	0.6161	25.44%
DF3	0.0112	-0.0089	0.1035	0.0880	-0.0150	-0.00004	0.2088	8.62%
PC1	-0.1257	0.1186	0.6146	0.6913	-0.3363	0.0394	0.0332	46.80%
PC2	0.8976	-02326	0.3267	-0.0879	-0.0199	-0.1595	0.0243	34.27%
PC3	-0.0552	0.0254	0.3376	0.1224	0.9172	0.1617	0.0067	9.47%
PC4	0.2659	-0.0788	-0.6258	0.7048	0.1686	-0.0799	0.0041	5.82%
PC5	0.3208	0.8332	-0.0905	-0.0489	-0.0409	0.4366	0.0020	2.76%
PC6	0.0441	-0.4803	-0.0430	0.0192	-0.1235	0.8660	0.0006	0.88%

Table S13. Dentary length (mm) and the dentary (as a proxy for body size) divided by total length of the limbs (radius + humerus + tibia + femur).

Group	Species	Substrate preferences	Dentary length	Dentary/ limbs	Source
Marsupialia	*Caluromys philander*	Arboreal	34.62	0.269	Meng et al. 2006
	Caluromys philander	Arboreal	35.31	0.252	FMNH61877
	Dasyurus viverrinus	Terrestrial	52.63	0.240	FMNH42759
	Didelphis marsupialis caucae	Terrestrial	86.47	0.301	FMNH128387
	Didelphis virginiana virginiana	Terrestrial	100.92	0.312	FMNH153786
	Hemibelideus lemuroides	Arboreal	37.57	0.163	FMNH60926
	Micouereus demerarae	Arboreal	33.31	0.286	Meng et al. 2006
	Monodelphis brevicaudata brevicaudataf	Terrestrial	26.06	0.335	FMNH60738
	Myrmecobius fasciatus	Semifossorial	43.58	0.267	FMNH19982
	Petauroides volans minor	Gliding	34.93	0.111	FMNH60908
	Petaurus breviceps	Gliding	21.46	0.158	FMNH129430
	Petaurus norfolcensis	Gliding	27.21	0.146	FMNH46005
	Petaurus norfolkensis	Gliding	28	0.182	Meng et al. 2006
	Philander opossum	Terrestrial	66.24	0.291	FMNH60097
	Pseudocheirus peregrinus viverrinus	Arboreal	40.85	0.181	FMNH47320
	Sarcophilus laniarius	Terrestrial	111.46	0.269	FMNH129428
	Trichosurus vulpecula	Arboreal	59.41	0.192	FMNH47320
Rodentia	*Eutamias operarius*	Arboreal	20.77	0.253	Meng et al. 2006
	Glaucomys volans	Gliding	22.18	0.182	Meng et al. 2006
	Sciurus carolinensis	Arboreal	36.3	0.213	Meng et al. 2006
	Tamias striatus	Arboreal	27	0.274	Meng et al. 2006
Dermoptera	*Cynocephalus volans*	Gliding	53.56	0.114	Mean of FMNH-56530, -61032, -61030, -198917, -87713
	Galeopterus variegatus natunae	Gliding	49.82	0.111	FMNH174893
Scandentia	*Dendrogale murina frenata*	Arboreal	23.54	0.266	FMNH46630
	Tupaia glis	Terrestrial	33.91	0.259	FMNH104808
	Tupaia gracilis gracilis	Terrestrial	24.6	0.214	FMNH140928
	Tupaia longpipes	Terrestrial	35.68	0.224	FMH76819
	Tupaia minor caedis	Arboreal	24.37	0.250	FMNH76865
"Insectivora"	*Erinaceus concolor*	Semifossorial	43.55	0.243	FMNH84448
	Microgale brevicaudata	Semifossorial	13.18	0.328	FMNH183959
	Myosorex kihaulei	Semifossorial	10.83	0.257	FMNH204863
	Sorex cinereus cinereus	Terrestrial	6.94	0.213	FMNH124111
	Suncus murinus	Terrestrial	13.44	0.233	FMNH165500
	Tenrec ecaudatus	Semifossorial	69.71	0.399	FMNH175921

Primates	*Callicebus sp.*	Arboreal	38.71	0.113	FMNH58973
	Galago senegalensis	Arboreal	28.05	0.135	FMNH58976
	Lemur fulvus fulvus	Arboreal	59.47	0.156	FMNH20785
	Loris lydekkerianus nordicus	Arboreal	28.57	0.108	FMNH95028
	Tarsius syrichta fraterculus	Arboreal	24.56	0.144	FMNH142007
Carnivora	*Nandinia binotata*	Arboreal	70.61	0.208	FMNH224514
	Nasua nasua candace	Terrestrial	70.62	0.239	FMNH70739
	Paradoxurus hermaphroditus philippinensis	Arboreal	73.98	0.260	FMNH68713
	Potos flavus chiriquensis	Arboreal	62.12	0.203	FMNH15131
	Viverra tangalunga tangalunga	Terrestrial	77.3	0.220	FMNH62277
Eleutherodontids	BMNH2942	? (to be estimated)	16.68	0.200	BMNH2942
	BMNH1133	? (to be estimated)	18.8	0.161	BMNH1133
	Maiopatagium (BMNH2940)	? (to be estimated)	17	0.145	BMNH2940
	Shenshou lui (LDNMF2001)	? (to be estimated)	24.52	0.180	Bi et al. 2014*
	Xianshou songae	? (to be estimated)	18	0.237	Bi et al. 2014*
Mesozoic mammals	*Agilodocodon scansorius*	Arboreal?	23	0.449	BMNH1138
	Eomaia scansoria	Arboreal?	24.5	0.380	Meng et al. 2006
	Jeholodens jenkinsi	Terrestrial?	12.7	0.379	Meng et al. 2006
	Maotherium sinensis	Terrestrial?	27.1	0.346	Meng et al. 2006
	Rugosodon eurasiaticus	Terrestrial?	24.5	0.275	BMNH1143
	Sinodelphys szalayi	Arboreal?	20.5	0.404	Meng et al. 2006
	Volaticotherium antiquus	Gliding?	28.3	0.264	Meng et al. 2006
	Zhangeotherium quiquecuspidens	Terrestrial?	30.2	0.357	Meng et al. 2006

*Measurement obtained from published images.

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