Electronic supporting material for:

The asymmetry of the carpal joint and the evolution of wing folding in maniraptoran theropod dinosaurs

Corwin Sullivan, David W. E. Hone, Xing Xu and Fucheng Zhang

Key Laboratory of Evolutionary Systematics of Vertebrates, Institute of Vertebrate Paleontology & Paleoanthropology, Chinese Academy of Sciences, 142 Xiwai Street, Beijing 100044, People’s Republic of China

CONTENTS:

A. Additional Institutional Abbreviations

MOR, Museum of the Rockies, Bozeman, USA; NIGP, Nanjing Institute of Geology and Palaeontology, Nanjing, China; MPC, Mongolian Paleontological Center, Ulaanbaatar, Mongolia.

B. Arm and Feather Length Data

Table 1. Arm and feather length in proportion to femur length in various theropods. Italics denote estimated value. Abbreviations: A, total length of arm, excluding ungual of digit III; BF, body feather maximum length; F, femur length; H, humerus length; HF, hand feather maximum length; M, length of metacarpus; P, combined length of non-ungual phalanges of digit III (avian numbering); SI, supplementary information. All measurements in mm.

Taxon	H	U	M	P	F	A/F	BF	HF	HF/F	Source
Allosauroidea										
Allosaurus	318	254	118	188	742	1.18	X	X	X	MOR 693
Compsognathidae										
Sinosauropteryx	36	28	17	17	86	1.14	9	-	-	NIGP 127587
Sinocalliopteryx	114	100	54	76	221	1.56	66	-	-	Ji *et al.* 2007
Tyrannosauroidea										
Dilong	96	-	-	-	185	-	20	-	-	IVPP V 14243
Guanlong	212	178	90	*120*	408	1.47	X	X	X	IVPP V 14531
Ornithomimidae										
Harpymimus	150	137	50	115	267	1.69	X	X	X	Field #960910 KD
Sinornithomimus	212	147	55	80	323	1.53	X	X	X	Kobayashi & Lü 2003
Therizinosauroidea										
Beipiaosaurus	-	-	76	127	260	-	50	68	0.26	IVPP V 11559
Oviraptorosauria										
Caudipteryx	70	61	30	43	135	1.51	16	114	0.84	IVPP V 12430
Rinchenia	205	188	104	127	305	2.04	X	X	X	MPC-D100/42
Alvarezsauroidea										
Haplocheirus	121	88	58	85	214	1.64	X	X	X	IVPP V 15988
Mononykus	37	34	9	-	134	-	X	X	X	Perle *et al.* 1994
Troodontidae										
Anchiornis	69	55	34	48	66	3.12	18	78	1.18	Hu *et al.* 2009: SI
Dromaeosauridae										
Microraptor	74	70	44	43	86	2.69	33	202	2.35	IVPP V 13352
Sinornithosaurus	65	51	31	25	61	2.82	17	47	0.77	Ji *et al.* 2002
Aves										
Archaeopteryx	64	55	28	25	53	3.24	-	140	2.64	Berlin specimen Wellnhofer 1974
Eoconfuciusornis	38	35	18	29	36	3.33	13	128	3.50	Zhang *et al.* 2008

In conjunction with the increased asymmetry of the wrist in maniraptoran theropods, the proportional lengths of the arms and the brachial feathers increased markedly. In table 1, above, we provide a brief data set demonstrating these length increases. Some data were kindly provided by Philip J. Currie, based on his direct measurements of specimens, while the remainder were collected ourselves from specimens and the literature. An ‘X’ indicates that a given feature is not present in the specimen (e.g. no feathers are preserved for the tyrannosaur *Guanlong*) and a ‘-‘ indicates that it could not be easily measured (e.g. body feathers for the Berlin *Archaeopteryx* are present but cryptic). Since *Sinornithosaurus* is a juvenile specimen and the hand feathers are poorly preserved, the measured proportions may be misleading. The hand feathers may be much longer in the adult, or even longer in juveniles than the preserved example would indicate.

Femur length is known to correspond well with body mass in theropods and other dinosaurs (Carrano 2006 and references therein). Accordingly, we scale arm and feather lengths with respect to femur length to remove the effect of overall body size. Arm length is taken as the total length of the humerus, the ulna, metacarpal III and the non-ungual phalanges of digit III (numbering according to the avian convention used in Xu *et al.* 2009). Note that the ungual is excluded because feathers would not have been attached to this element.

The table shows that tetanurans and non-maniraptoran coelurosaurs generally have relatively short arms, with a total length less than 1.5 times that of the femur. Maniraptorans, however, tend to have higher values of this ratio (see Gauthier 1986), and within Maniraptora the ratio increases dramatically on the line to birds. All paravians in our data set have arms more than 2.5 times as long as the femur. This implies that even with the arm folded, the hands would tend to hang much closer to the ground in derived maniraptorans than in more basal theropods. The trend towards arm elongation was examined more rigorously using squared-change parsimony to examine ancestral states (see main manuscript) in Mesquite (figure S2, below). This analysis indicates a monotonic, relatively steady increase in relative arm length on the line to birds, with the origins of the trend extending back at least to the base of Avetheropoda.

With respect to feathers, supplementary table 1 shows that while the general plumage of the body varies in size without any clear trend, the large feathers of the manus are generally longer in derived than in basal maniraptorans. Body feather measurements refer to the typical plumage, as opposed to unusually elongate feathers like those on the tail of *Caudipteryx*, or the dorsal region of *Beipiaosaurus*. For hand feathers, the longest well-preserved feather on the manus or carpus was measured in each case, since this feather would presumably have been most vulnerable to contact with obstacles or the substrate. The longest feather was typically also the most distally placed. In general, the feathers of the manus were much larger than those of the more proximal arm segments, even in possibly non-volant taxa such as *Anchiornis*. Differences in hand feather length between maniraptorans and non-maniraptorans are difficult to assess because very little information is available for the latter group of taxa, but available descriptions of non-maniraptorans with preserved plumage (e.g. *Sinocalliopteryx*: Ji *et al.* 2007) strongly suggest that the manual feathers were short. It seems likely that hand feather length increased in early maniraptorans, and that the trend simply continued within this group to the point where the most elongate hand feathers became significantly longer than the femur.

C. Ancestral Character State Reconstructions

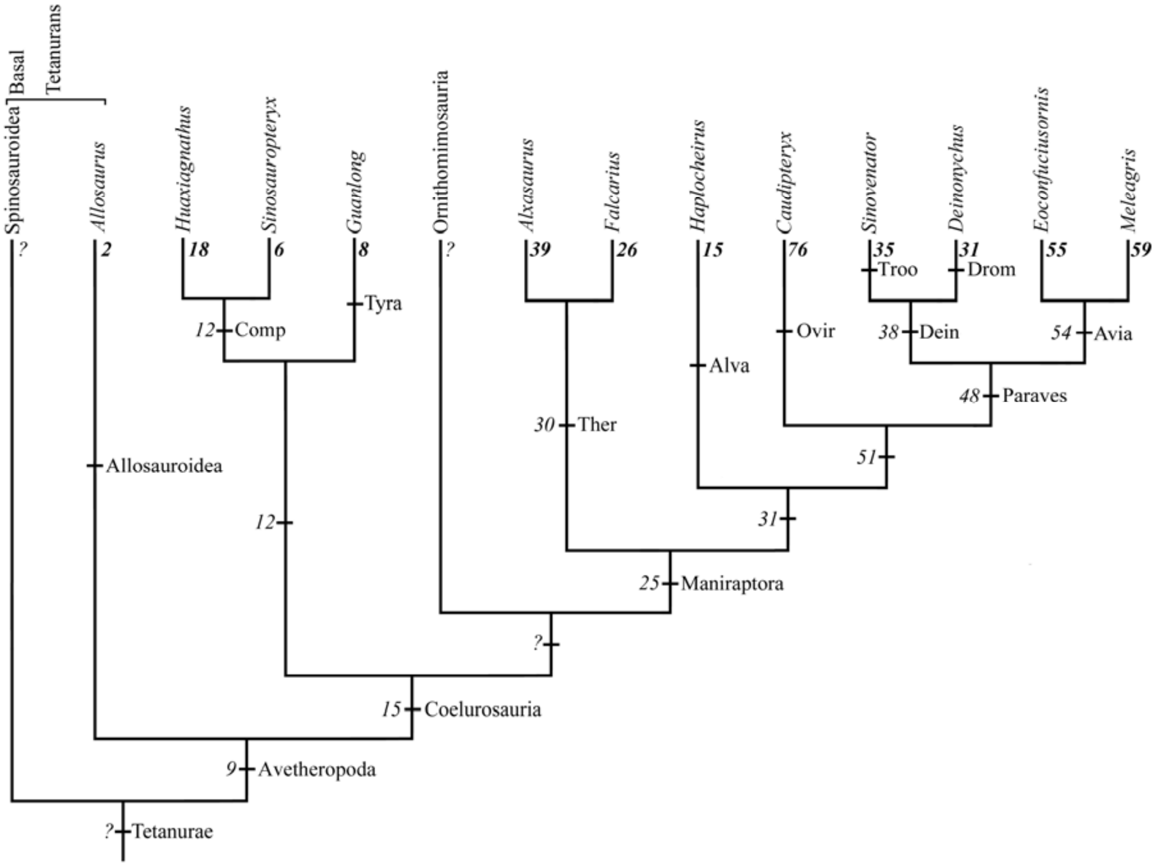

Figure S1. Cladogram showing all measurements used in reconstructing ancestral states for the radiale angle. Values in bold are direct measurements of the radiale angle, in degrees, in individual taxa; values in normal italic type are reconstructed ancestral states based on the squared-change parsimony algorithm of Mesquite (Maddison & Maddison 2009). Abbreviations: Alva, Alvarezsauroidea; Avia, Avialae; Comp, Compsognathidae; Dein, Deinonychosauria; Drom, Dromaeosauridae; Ovir, Oviraptorosauria; Ther, Therizinosauroidea; Troo, Troodontidae; Tyra, Tyrannosauroidea. Phylogeny after Smith *et al.* (2007) and Zanno *et al.* 2009.

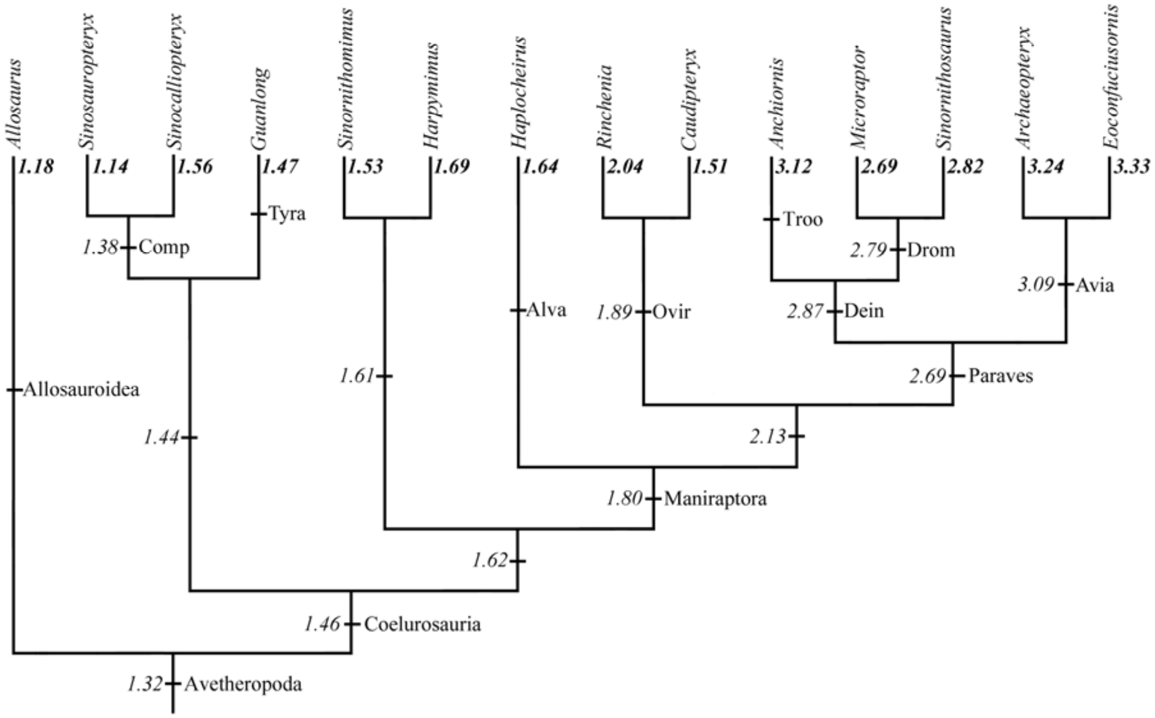

Figure S2. Phylogeny showing calculated and reconstructed values of the ratio of arm length (humerus + ulna + metacarpal III + non-ungual phalanges of digit III) to femur length for selected theropods. Values in bold are calculated from measurements taken from specimens or the literature, values in normal italic type are reconstructed ancestral states based on the squared-change parsimony algorithm of Mesquite (Maddison & Maddison 2009). Abbreviations as in figure S1. See Table 1, above, for data. Phylogeny after Zanno *et al.* 2009.

D. Forelimb Positioning in *Microraptor* and *Caudipteryx*

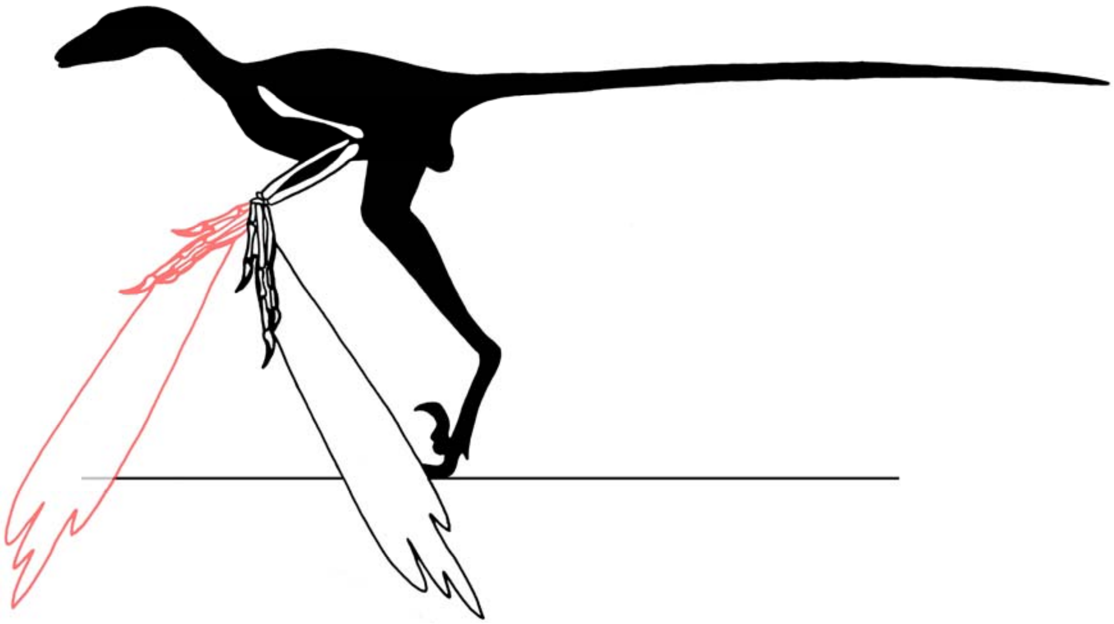

Figure S3. *Microraptor gui* with the elbow flexed approximately as in the “predatory strike” reconstructions of Padian (e.g. 2001: figure 3*a*), showing the left hand aligned with the antebrachium (red) and abducted by 60º (black). Image modified from Hu *et al*. 2009.

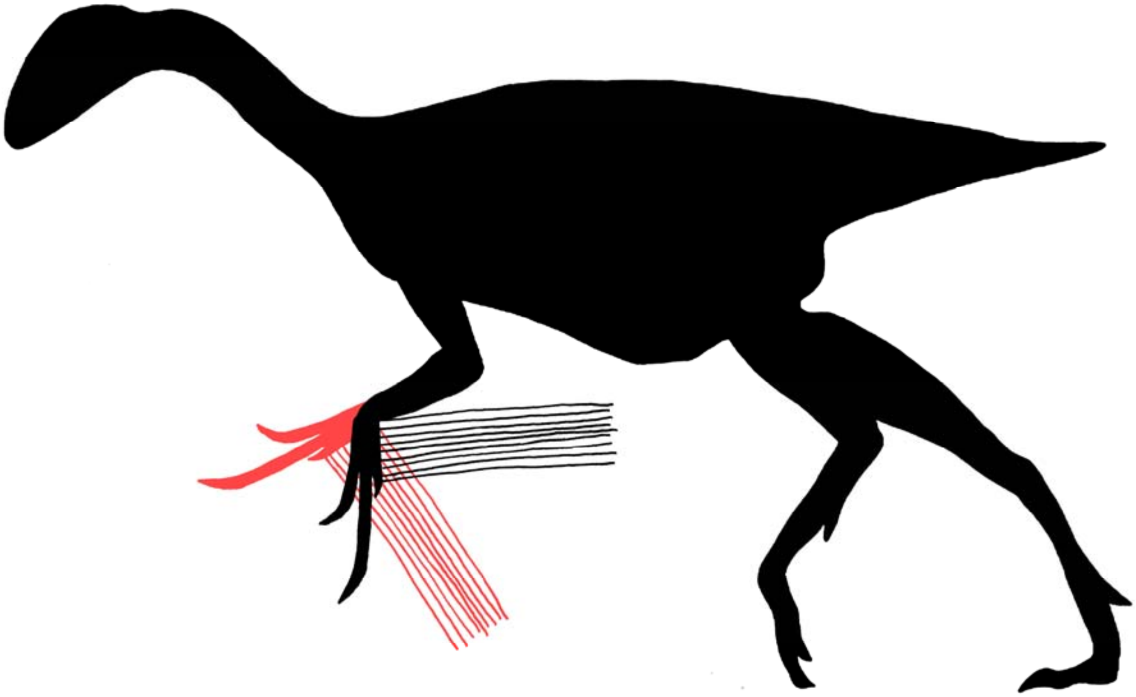

Figure S4. *Caudipteryx* with the left hand aligned with the antebrachium (red) and abducted by 60º (black). Image modified from an illustration by Luis Rey in Holtz 2007.

The extent to which a pennibrachium (forelimb with long feathers forming a planar surface, as in the wing of a bird) would have interfered with terrestrial locomotion depends critically on the position of the shoulder and elbow, as well as of the wrist. Figure S3 shows that with the humerus retracted and the elbow flexed, as in reconstructions of dromaeosaurids at the beginning of a predatory strike (e.g. Padian 2001: figure 3*a*), the feathers of the dromaeosaurid *Microraptor gui* would have contacted the substrate and probably suffered damage regardless of the position of the wrist. This would not have been true of taxa with shorter manual feathers, but it seems clear that arm positions in which the elbow was flexed were not feasible for *M. gui* during terrestrial locomotion unless retraction of the humerus was extreme (not figured) or the arm was pronated (causing the feathers to extend laterally). The proportions of *M. gui* (based on IVPP V 13352) also indicate that the feathers would have contacted the substrate if the arm was held straight in front of the body with the elbow and shoulder extended, again regardless of the position of the wrist. The implication is that, during terrestrial locomotion, *M. gui* must have either pronated the arms (potentially by abduction at the shoulder, with the elbow flexed) or assumed a position similar to that depicted in figure 3 of the main text. It is difficult to see how the arms could have been used in predation or manipulation.

Figure S4 shows the effect of abduction of the wrist joint in the basal oviraptorosaur *Caudipteryx*. Although the feathers of the pennibrachium would have been less prone to contact with the substrate than in *M. gui*, it is clear that rotation of the wrist joint through an angle of 60º would have moved the pennibrachium into a position in which it was less likely to encounter obstacles or collide with the substrate during terrestrial locomotion. In resting postures, which would have brought the body closer to the ground, the ability to fold the pennibrachium and protect the manual feathers from extensive contact with the substrate would also have been advantageous. The actual amount of abduction that was possible in oviraptorosaurs has never been explicitly determined, but the very high radiale angles seen in *Caudipteryx* and probably other members of this group (figure S1, and main text of paper) imply that the range of abduction was even greater than in dromaeosaurids.

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