Bird wing digits & their homologies: reassessment of developmental evidence for a 2,3,4 identity

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ABSTRACT – The theory of descent of birds from theropod dinosaurs demands that their fore-limb digit identities (1,2,3) are the same as those of birds and thus the conventional embryological identification of these as 2,3,4 remains a major problem for acceptance of this theory. Are the 2,3,4 identities of bird wing digits correct? The paper analyses the developing bird wing as a specialisation of the general developmental 'bauplan' for the pentadactyl skeleton. Evidence from the chick embryonic skeletogenic pattern supports interpretation of the main digits as 2,3,4 on the basis of timing, position & connections, using comparative methods eg comparison with other amniote patterns of limb skeletogenesis. Fresh support for 2,3,4 identity comes from evidence of i) a temporary embryonic digit 1 in the ostrich and of ii) a condensation-specific Sox9 molecular domain in a digit 1 position in the chick wingbud. In contrast, the recent 'frame shift' hypothesis of Wagner proposes molecular identity transformation by which theropod identities for 1,2,3 have become shifted to avian digit condensations 2,3,4. Support for 'frame shift' is claimed from evidence (Vargas & Fallon 2004) that the expression domain for Hox d 13 alone characterises digit 1, but a domain for Hox d 12 and 13 characterises digits 2-5. Here it is argued that this evidence for 'frame shift' is speculative and insufficiently convincing to support reinterpretation of the wing digits as 1,2,3. Evidence that wing digits have been correctly identified as 2,3,4 continues to provoke doubts about the 'dinosaur-bird' theory. The presence of well-defined feathers in the bird-like hands of certain dromaeosaurs (from Liaoning, China) may be due to their possibly being secondarily flightless birds, thus suggesting that birds may derive from a lineage separate from that of theropods.

Key words: digits, homology, theropods, Archaeopteryx, skeletogenesis, birds, wing, Hox

Les homologies des trois doigts de l'aile des Oiseaux: preuves embryonnaires que leur identité soit 2,3,4 - La théorie de l'origine des oiseaux parmi les dinosaures théropodes exige que l'identité des doigts (de l'aile) soit 1,2,3 et soit la même que celle des oiseaux actuels. Or, en embryologie, l'identité de ces doigts admise actuellement est 2,3,4 et cela pose une question fondamentale pour admettre cette théorie. Est-ce que cette identité des doigts (de l'aile) des oiseaux est correcte? Cet article analyse les étapes du développement de l'aile des oiseaux en tant que spécialisation de développement général du membre pentadactyle. L'interprétation du développement embryonnaire du squelette de l'aile de poulet suggère que ce sont les doigts 2,3,4 qui existent, interprétation fondée sur leur séquence d'apparition au cours de l'embryogenèse de l'aile, leur position relative et leurs relations de proximité par comparaisons avec les autres amniotes. Cette identité 2,3,4 est confirmée par des données récentes i) sur l'aile d'autruche où le doigt 1 a une existence embryonnaire temporaire ; ii) sur le domaine d'expression du gène Sox9 en position du doigt 1 dans le bourgeon d'aile du poulet. Au contraire, l'hypothèse récente proposée par Wagner du "décalage de lecture" (ou 'frame shift') de l'identité des doigts implique la transformation des doigts 2,3,4 des embryons des oiseaux qui deviennent des doigts d'identité 1,2,3 chez les théropodes d'après des données moléculaires. Ceci, parce que selon Vargas & Fallon (2004) le domaine d'expression du gène Hoxd13 est caractéristique du doigt 1 alors que les domaines d'expression des gènes Hoxd12 et Hoxd13 caractérisent la position des doigts 2-5. Dans ce travail, nous considérons que les preuves en faveur de l'hypothèse du décalage de lecture (= 'frame shift') de l'identité des doigts ne sont pas suffisamment convaincantes pour accepter de changer l'interprétation classique 2,3,4. Les preuves que l'identité des doigts des oiseaux a été correctement établie comme étant 2,3,4 jette aussi un doute sur l'hypothèse de la filiation dinosaures-oiseaux. La présence de vraies plumes sur le membre antérieur à allure d'aile et au niveau de la main de dromaeosaures (en provenance du Liaoning, Chine) pourrait être liée à la possibilité qu'il s'agisse d'oiseaux ayant secondairement perdu la capacité à voler, suggérant que les oiseaux puissent dériver d'une lignée séparée de celle des théropodes.

Mots clés: doigts, théropodes, aile, Archaeopteryx, oiseaux, Hox, homologie

INTRODUCTION

Palaeontologists sometimes ask why studies on skeletogenic patterning in chick wing buds have any bearing on the current discussion on the origins of birds and their possible derivation from theropod dinosaurs. This paper attempts to show how such a developmental perspective provides critically important evidence to this discussion. Essentially this is because it is only through the embryo and its developmental processes that definitive form – whether in fossils or extant forms – is or has been generated. Development thus must therefore provide perspectives on evolution as is now being widely recognised. Historically in classification, descriptive embryology has long been used (hence the term 'amniote', for those vertebrates with embryos with an amniotic membrane) but recently relevant developmental evidence has become available also from knowledge of the molecular patterning mechanisms of the embryo. In addition to classical structural morphology, it is now clear that molecular homology exists also, with similarities in the expression of pattern regulating genes (often Hox) for example in the control of limb development in a variety of tetrapods, eg amphibians (*Xenopus*), birds (chick) & mammals (mouse). One significant example of this new approach is Sordino and Duboule's recent attempt (1996) to demonstrate similarities in Hox a & d expression patterns in the embryonic buds of teleost fish & tetrapod paired appendages together with differences in such patterns specific to tetrapod limb buds which might explain both the similarities and differences between paired fins and limbs. It should be noted however that molecular-developmental and morphological homologies do not always point to the same evolutionary conclusions. Developmental homology is not some magic solution to problems of defining evolutionary relationships (since 'development itself evolves' – see Hall 1999) but developmental processes are frequently conserved which makes them an additional source of useable information on homology and therefore on phylogenetic relationships.

## THE DEVELOPING BIRD WING AS A SPECIALI-SATION OF THE GENERAL DEVELOPMENTAL 'BAUPLAN' OF THE PENTADACTYL SKELETON

Turning to the question of bird origins, can we illuminate these using studies on chick limb bud development to determine questions of digit homology in modern birds? In fact we can and evidence from embryo limb buds is important in view of the extreme specialisation of the definitive bird wing skeleton, which is scarcely recognisable as a form of the pentadactyl limb since it has only 3 digits with few phalanges and no individual carpus elements. This makes decisions about skeletal element identity difficult where these must be based on comparison of definitive elements or complexes alone. But the bird wing bud tells much about how the definitive wing skeleton is formed from embryonic elements which are homologous with those in other tetrapod

forms both in embryo & adult. For example, differentiation of carpal elements in the digital arch (or 'primary axis') is especially specialised in birds where the ulnare forms and then disappears to be replaced more ventrally by element X (Fig 2, Hinchliffe 1984). Thus on the basis of information derived from the embryo clear decisions can be reached about identity, in this case that an ulnare is absent from the definitive bird carpus.

I start with the assumption of a general developmental skeletogenic 'bauplan' for the tetrapod limb (Hinchliffe 2002). This is a large assumption and many qualifications should be noted, for example the heterochronic variants as in the urodeles' unique sequence of digit formation. Amniotes, however, have a stereotyped pattern ('the skeletogenic Bauplan'), which probably represents the conserved common developmental processes (including molecular ones) acting in amniote limb buds and assumed to underlie the structural homology of the definitive limb. There are three main phases in the skeletogenesis of limb elements: i) pre-chondrogenic **condensation** followed by ii) **chondrification** (cartilage matrix synthesis) producing the cartilage 'model' of the definitive element, usually completed by iii) **bone replacement** of the cartilage. Bone is of course the only part surviving in most fossils and is in practice all that is known for the adult limbs of many extant species. Usually the sequence is i to ii to iii in forming each definitive element, but there are many exceptions, for example disappearance of elements at either phase i or ii, fusion of elements (usually at phase ii) or failure of cartilage models to complete ossification. Phases i and ii are important because definitive bone skeletal elements cannot be formed without them. Where doubt exists about the identity of definitive elements, knowing the pattern of the first two phases may be the only way to determine this.

Features of the limb developmental bauplan are identified by examining the pattern of the phase i and ii processes, ie condensation and early chondrogenesis. Skeletogenesis follows a proximo-distal sequence: stylopod (humerus/femur), zeugopod (radius/ulna; tibia/fibula), carpus (or tarsus) with its 'digital arch' running from ulnare/fibulare through distal carpal/tarsal elements at the base of the five digit rays (generating meta-carpals/tarsals and phalanges). Timing is important; the digits form in an posterior-anterior sequence with first digit 4 followed by 3,2,1. Ulna, ulnare and digit ray 4 form early and according to Shubin & Alberch (1986) represent the 'primary axis'.

Stable features of the bauplan are the proximal elements (H, R, U), the digital arch and the 'primary axis' through the ulnare with d4 as first of the five digital rays to develop. Five is the maximum number and though digits are often lost in evolution, when 'extra digits' appear in evolution (eg panda, mole – review Hinchliffe 2002) they are not true digits but an ossification of tendinous or fibrous tissue. Despite these conserved stable features the 'bauplan'
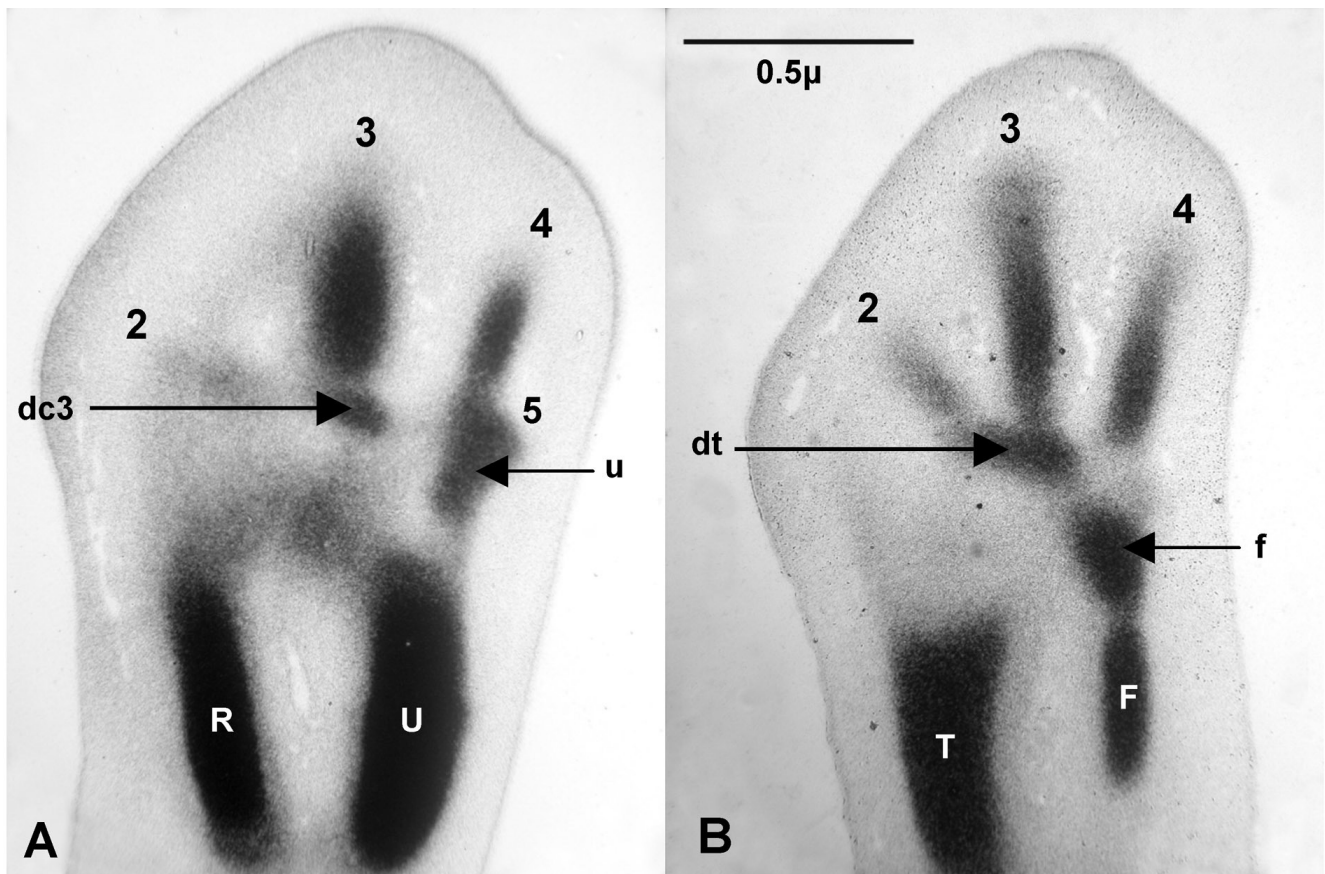
Figure 1 - Autoradiographs of chondroitin sulphate synthesis in chick stage 27/28 wingbud (A) and stage 26/27 legbud (B) (technique detail in Hinchliffe 1977). Digit rays numbered (for identity criteria see text); note similar post axial position of D4 in both limb buds. Abbreviations: dc3 distal carpal, dt distal tarsal, F fibula, f fibulare, R radius, T tibia, t tibiale, U ulna, u ulnare.

is clearly dynamic and capable of evolutionary modification. For example, there is no common single set of limb skeletal elements. Other unstable features include the number of carpus elements, eg the composition of the digital arch can be altered. Thus many tetrapod taxa have a distal carpal at the base of each digit ray while by contrast, birds have only a single distal carpal/tarsal element in wing- and leg-bud [see Figs 1,2]: nonetheless both have an identifiable digital arch. Finally, there is no fixed tetrapod-wide formula for the phalangeal number of each digit.

DEVELOPMENTAL EVIDENCE ON WING DIGIT IDENTITY

Embryologists and palaeontologists have differing views as to bird wing digit identity (Hinchliffe & Hecht 1985). Paleontologists have usually identified bird wing digits as 1,2,3, homologous with the three theropod dinosaur forelimb digits (eg *Deinonychus*, Ostrom 1977, Gauthier 1986). Evidence is that in the ancestral 5-digit reptile hand, for digits D1,2,3 the *phalangeal* formula is Ph2,3,4 respectively (Romer 1966), the same formula as in the surviving 3 digits of the fore limbs of a number of theropod species.

These digits are identifiable as D1,2,3 on the basis of a fossil record showing progressive reduction and loss of digits 4 and 5 (eg *Herrerasaurus*, Sereno 1993) during theropod evolution. Since the 3 wing digits of *Archaeopteryx* have the same phalangeal formula as in the theropod digits D1,2,3 it is argued they too should be identified as digits D1,2,3. A more simplistic argument (in which the 'dinosaur-bird' theory is used perhaps to over-rule relevant evidence) appears to be that since birds *are* theropod dinosaurs, they must have the same digits, D1,2,3.

But to embryologists the bird wing digits appear to be D2,3,4 on the basis of *timing* (eg D4 the first forming ray), *position* (D4 post-axial as in the legbud) & *connections* (ulnare at base of D4) (Shubin & Alberch 1986). These were the conclusions of comparison (first by Muller & Alberch, 1990 and then in more detail by Burke and Feduccia, 1997) of digit development in the wing with that in the chick legbud & with that in the legbuds of alligator (from the birds' closest living reptile taxa) and turtle which both have all 5 digits in the adult, making their digit identity certain.

The wing skeleton pre-cartilage condensations and
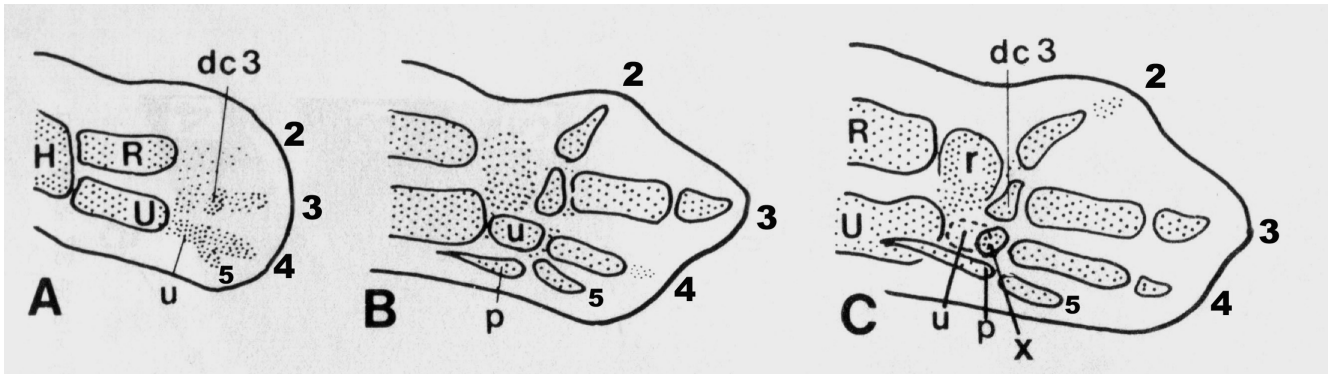
Figure 2 - Pattern of skeletogenesis in chick wingbud, A stage 27, B stage 28, C stage 30. Note the ulnare regression and replacement by the more ventral element x. Abbreviations as in Fig 1: p pisiform, r radiale.

early cartilages are clearly revealed in autoradiographs of 35SO4 uptake into chondroitin-6-sulphate (a major cartilage matrix component) in chick wing buds (Fig. 1, see also Figs 1-4 in Hinchliffe 1977, Fig 2 in Hinchliffe & Hecht 1984). This method shows the early skeletogenic pattern more clearly than older classical histological methods. Timing, position and connections supported the D2,3,4,(plus small 5) interpretation of the digit rays (Figs 1 & 2).

Regarding the similar phalangeal formula (Ph 2,3,4) of D1,2,3 in (some) theropods (eg *Deinonychus*) and in the first 3 digits in *Archaeopteryx*, it is argued on the basis of parsimony that *Archaeopteryx* retains the primitive reptile phalangeal formula for D1,2,3 and it must therefore (like theropods) have retained D1,2,3 but lost digits 4 and 5. This is seen as only one change. But embryology shows in other species that when mitosis is experimentally reduced, all digits may each lose a terminal phalange (Raynaud, 1990 on *Lacerta viridis* limb development) – this can equally be regarded as a single change. Thus loss of a terminal phalange from each D2,3,4 of the basal reptile digits would produce the same phalangeal formula as in the 3 digits of *Archaeopteryx* and be consistent with a D2,3,4 identity for them. Phalangeal formulae are in any case relatively labile as shown in experiment, mutants and comparative anatomy.

But it is clear that clinching embryological evidence would be the presence of an anterior D1 and until recently such evidence appeared absent. However, as Alan Feduccia (Nowicki & Feduccia 2002) and Michael Richardson (Welten et al 2005) respectively reported in their conference talks, there is now good evidence firstly that D1 appears briefly and achieves chondrogenesis in the ostrich wing bud and secondly for a D1 molecular domain (*Sox9*, specific for condensation and expressed briefly in anterior sub-ridge mesenchyme) in the chick wing bud although this is not followed by matrix synthesis. Thus the wing is (briefly) pentadactyl providing confirming evidence for the embryologists' identification of the main digits as D 2,3,4.

FRAME SHIFT HYPOTHESIS

The embryologists' view that the wing digits are D2,3,4 raises considerable problems for the hypothesis of bird origin from theropods. Similarities in the digits of *Archaeopteryx* wings and those of the forelimbs in some theropods represent critical evidence for this hypothesis. A new theory while accepting the D2,3,4 interpretation of the bird wing digit at the condensation stage may remove this problem.

According to Wagner & Gauthier's 'frame shift' (FS) hypothesis (1999) of molecular identity transformation, the theropod-type identities for D1,2,3 have become shifted to digit blastemas C2,3,4 in the evolution of birds. Put in another way, avian digit condensations have been correctly identified by embryologists as C2,3,4 but the developmental mechanism which specifies the morphological identities becomes shifted so that condensation C2 generates the theropod digit 1 morphology, C3 generates D2 morphology, & C4 forms D3. If accepted this would be an argument for nesting birds in the same clade as theropods.

There are some recent claims of support for the FS hypothesis from molecular work on limb development. Vargas & Fallon (2004) argue that in both mouse and chick hind limb buds and in the chick hind limb bud, digit 1 has one type of Hox d expression while digit 2 has another type and that the anterior wing bud digit has the Hox d expression characteristic of digit 1.

Possible general objections to the FS hypothesis are:

the position of the shift 'somewhere between *Allosaurus* & birds' appears arbitrary (Wagner & Gauthier 1999) but without any adaptive functional reason given (Galis et al 2003)

the shift would have to be confined to the fore limb digits without effect on the homologous hindlimb digits

FS assumes theropods would have had an embry-

onic C4 (it should be remembered that their D4 is much reduced or lacking) on which to impose the identity of D3 This transformed C4 would have to be substantial enough when transformed by FS to generate a digit with four phalangeal elements in an *Archaeopteryx*-type posterior digit.

FS would have to affect the distal carpus, reforming the semilunate at the base of the bird C2&3, as in *Archaeopteryx*.

the mechanism for such a shift simultaneously affecting four digit condensations, is unknown.

MOLECULAR EVIDENCE ON WING DIGIT IDENTITY AND THE FRAME SHIFT THEORY

Molecular evidence is now central to the understanding of limb evolution and development (Sordino et al 1996) and specifically of determination of digit identity. Thus the FS hypothesis must be compatible with such evidence and this is claimed in recent work on limb development by Vargas & Fallon (2004) who argue that in both mouse fore and hind buds and chick hind limb buds, prospective digit 1 is characterised by Hox d 13 expression alone while digits 2-5 have Hox d 13 *and* Hox d 12 expression. Since the anterior wing bud digit has only Hox d 13 expression they ague it is digit 1 on the grounds of molecular homology. However, in a review of this hypothesis Gallis (2005) argues convincingly that the molecular evidence cited is unconvincing as the mutants cited (eg talpid and Hox d deletion mutants) show only a weak correlation of Hox d 12/13 expression with digit identity (Kmita et al 2002, Galis 2005).

The gene networks of the limb bud are complex (Zakany et al 2004) and molecular developmental biologists are far from agreed that digit identity can be controlled by for example simple combinations of Hox expression. An earlier pioneering theory assigned a digit identity control role to 5 Hox d 9-13 expression domains each specifying one of pentadactyl digits 1-5 (Tabin 1992). But this idea was abandoned when later study showed the domains became overlapping in the distal limb bud well before digit differentiation. Hox d genes were instead allocated a role in regulating rate and timing of cartilage proliferation and differentiation with only indirect effects on digit identity (Tabin 1997). Other studies implicate different genes. In a study of digit reduction patterns in skinks by Shapiro et al (2003), variation in Shh (sonic hedgehog) expression was considered to control digit identity, rather than Hox d expression. Sanz-Ezquerro and Tickle (2001) discuss a critical role for BMPs (bone morphogenetic proteins) possibly in concert with Shh (sonic hedgehog) in digit identity control. Hox d expression is thus not the only suspect.

At present there seem too many unknowns to accept the 'Frame Shift' as a well established and convincing theory. Several new assumptions and factors have been introduced without real evidence. Molecular evidence is still too equivocal to overrule identity conclusions based on the criteria of classical homology. Parsimony thus appears to support the 2,3,4 identity for both the condensations and definitive digits of the bird wing.

IMPLICATIONS FOR THEORIES OF THE ORIGINS OF BIRDS

Developmental evidence of a 2,3,4 digit identity for the wings of birds as argued here continues to pose problems (Hinchliffe 1997, Feduccia 1999) for acceptance of the theory of origin of birds from theropod dinosaurs. Regarding bird origins, discussion now mainly centres on the significance of filamentous integumentary structures interpreted as possible proto-feathers in theropods such as *Sinosauropteryx* (Chen et al 1998). Rather than protofeathers, the alternative interpretation that they represent skin collagen fibres (Lingham-Soliar 2003, Feduccia et al. 2005) needs consideration. The discovery of well defined feathers in China (Liaoning Province) in 'dromaeosaurs' with bird-like hands, such as *Caudipteryx* (Ji et al 1998) may be explained by the possibility that these are secondarily flightless birds. Serious doubts still remain about the existence of both bird-like feathers and of bird-type digits in theropods making it possible that birds may derive from a lineage separate from that of theropods (Feduccia et al. 2005).

Note added in proof – Since the the Quillan Conference, reassessment of the theory of a theropod origin of birds has continued (Feduccia et al 2007). In addition to the evidence just described of a theropod-bird character mismatch of digit identity, evidence for protofeathers in theropods remains poor. Further work by Lingham-Soliar (2007) and his associates strengthens the interpretation that the so-called 'protofeathers' of *Sinosauropteryx* may represent artefactual filamentous integumentary structures similar to those produced by decomposing skin in several types of extant animals, as well as in the ceratopsian dinosaur, *Psittacosaurus*.

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