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# Evolution of the patellar sesamoid bone in mammals

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The patella is a sesamoid bone located in the major extensor tendon of the knee joint, in the hindlimb of many tetrapods. Although numerous aspects of knee morphology are ancient and conserved among most tetrapods, the evolutionary occurrence of an ossified patella is highly variable. Among extant (crown clade) groups it is found in most birds, most lizards, the monotreme mammals and almost all placental mammals, but it is absent in most marsupial mammals as well as many reptiles. Here we integrate data from the literature and first-hand studies of fossil and recent skeletal remains to reconstruct the evolution of the mammalian patella. We infer that bony patellae most likely evolved between four to six times in crown group Mammalia: in monotremes, in the extinct multituberculates, in one or more stem-mammal genera outside of therian or eutherian mammals, and up to three times in therian mammals. Furthermore, an ossified patella was lost several times in mammals, not including those with absent hindlimbs: once or more in marsupials (with some re-acquisition), and at least once in bats. Our inferences about patellar evolution in mammals are reciprocally informed by the existence of several human genetic conditions in which the patella is either absent or severely reduced. Clearly, development of the patella is under close genomic control, although its responsiveness to its mechanical environment is also important (and perhaps variable among taxa). Where a bony patella is present it plays an important role in hindlimb function; especially in resisting gravity by providing an enhanced lever system for the knee joint. Yet the evolutionary origins, persistence and modifications of a patella in diverse groups with widely varying habits and habitats -- from digging to running to aquatic, small or large body sizes, bipeds or quadrupeds -- remain complex and perplexing, impeding a conclusive synthesis of form, function, development and genetics across mammalian evolution. This meta-analysis takes an initial step toward such a synthesis by collating available data and elucidating areas of promising future inquiry.

1 **Evolution of the patellar sesamoid bone in mammals**

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8 Running head: Patellar evolution in mammals

## 9 INTRODUCTION

10 This meta-analysis addresses the evolution of the ossified patella (tibial sesamoid or “kneecap”  
11 bone) in mammals. Our focus was on the evolutionary pattern of how bony patellae evolved in  
12 the mammalian lineage, as evidence of osseous patellae is simplest to interpret. However, as  
13 explained further below we also consider non-bony sesamoids to also be potential character states  
14 of the patellar organ; vexing as the form, fossil record and ontogeny (and thus homology) of  
15 those soft-tissue structures are. We compiled voluminous literature and firsthand observational  
16 data on the presence or absence of the osseous patella in extinct and extant mammals, then  
17 conducted phylogenetic analysis of patellar evolution by mapping these data onto a composite  
18 phylogeny of mammals (Kielan-Jaworowska et al. 2004; Luo 2007a; Luo 2007b) using multiple  
19 phylogenetic optimization methods. We used the results to address patterns of acquisition and  
20 loss (i.e. gain and loss of ossification) of this structure within Mammaliaformes. In particular, we  
21 investigated whether an ossified patella was ancestrally present in all crown group Mammalia,  
22 and lost in particular groups especially marsupials (Metatheria), or whether it evolved multiple  
23 times in separate crown clades. Furthermore, if the bony patella had multiple origins, how many  
24 times was it gained or lost, and what did it become if it was lost (such as a vestigial fibrocartilage  
25 versus complete loss, without any evidence of a sesamoid-like tissue within the patellar tendon)?  
26 These were our study’s key questions. We provide some broader context here first.

27 Some aspects of the morphology of the knee in tetrapods (four-legged vertebrates bearing limbs  
28 with digits) are evolutionarily ancient. Tetrapods had their ancestry amongst lobe-finned  
29 sarcopterygian fish, in which jointed, muscular fins transitioned into limbs. Early stages of  
30 distinct bony articulations between the femur and tibia-fibula are evident in the hind fins/limbs of  
31 Devonian (~370 million years ago; Mya) animals such as *Eusthenopteron*, *Panderichthys*, and  
32 *Ichthyostega* (Ahlberg et al. 2005; Andrews & Westoll 1970; Boisvert 2005; Dye 1987; Dye  
33 2003; Haines 1942). These fossil sarcopterygians also have subtle differences between the  
34 homologous joints in the pectoral fin/forelimb and the pelvic fin/hindlimb, indicating that  
35 specification of forelimb/hindlimb identity was already in place (Boisvert 2005; Daeschler et al.  
36 2006; Shubin et al. 2006). Furthermore, the morphology of the forelimb and hindlimb joints  
37 indicates divergent functions of these limbs, with the forelimb evolving into a more  
38 “terrestrialized” capacity earlier than the hindlimb (Pierce et al. 2012). Developmental and  
39 morphological modifications to the hindlimb and particularly the mid-limb joint between the  
40 stylopod and zeugopod continued, until a recognizable knee articulation of almost modern,  
41 derived aspect arose in tetrapods of the Carboniferous period, ~350 Mya (Dye 2003).

42 Sesamoids are best defined as “skeletal elements that develop within a continuous band of regular  
43 dense connective tissue (tendon or ligament) adjacent to an articulation or joint” (Vickaryous &  
44 Olson 2007). The tibial patella is a sesamoid bone that arises during development within the main  
45 extensor tendon of the knee, subsequently ‘dividing’ it (though there remains some continuity)  
46 into the quadriceps and patellar tendons (the latter is sometimes inappropriately called the patellar  
47 ligament) (Bland & Ashhurst 1997; Fox et al. 2012; Pearson & Davin 1921a; Tecklenburg et al.  
48 2006; Tria & Alicea 1995; Vickaryous & Olson 2007). These tendons span from the quadriceps  
49 muscle group to the tibia (Fig. 1). The patella itself tends to be incorporated mainly into the  
50 vastus muscles of the quadriceps in mammals, with the tendon of *M. rectus femoris* lying more  
51 superficial to them (Tria & Alicea 1995), with variable degrees of attachment to it (Jungers et al.  
52 1980). Hereafter, the term “patella” implies ossification and hindlimb localization unless  
53 otherwise specified (some literature inconsistently and confusingly refers to non-ossified  
54 cartilaginous structures in this location as patellae—this homology in many cases needs better

55 testing), and implicitly refers to either a single patella or the left and right patellae normally  
56 present in an individual. There is an “ulnar patella” in the forelimbs of some taxa (notably lizards,  
57 but also some frogs, birds and mammals (Barnett & Lewis 1958; Haines 1940; Maisano 2002a;  
58 Maisano 2002b; Pearson & Davin 1921a; Pearson & Davin 1921b; Romer 1976; Vanden Berge &  
59 Storer 1995; Vickaryous & Olson 2007)) but a full discussion of this enigmatic structure is  
60 beyond the scope of this study. Figure 2 depicts the anatomical orientations used throughout this  
61 study to refer to tetrapod limbs.

62 The patella appears broadly similar amongst mammals possessing it, as far as has been studied,  
63 although it varies greatly in size, generally in accordance with body size. It ossifies  
64 endochondrally; from a cartilaginous precursor (i.e. anlage (Vickaryous & Olson 2007));  
65 relatively late in gestation (e.g. sheep, goats (Harris 1937; Parmar et al. 2009)) or sometime after  
66 birth (e.g. rabbits, rats, mice, humans (Bland & Ashhurst 1997; Clark & Stechschulte 1998;  
67 Patton & Kaufman 1995; Spark & Dawson 1928; Tria & Alicea 1995; Walmsley 1940)). Very  
68 recently, the development of the patella in mouse embryos was re-examined and the claim made  
69 that the patella develops as a process that branches off the femur, strongly influenced by  
70 mechanical loading in that region (Eyal et al. 2015). Whether this truly happens as described in  
71 mice, let alone other mammals, and whether it can be accepted as unexpected support for the  
72 “traction epiphysis” origin of patellar sesamoids (e.g. [Pearson & Davin, 1921a,b](#)), remains to be  
73 determined, but the surprising results deserve attention. The general form of the osseous patella  
74 in mammals is a hemispherical structure, with a superficial surface (covered by fibrocartilage  
75 (Clark & Stechschulte 1998) and quadriceps tendon fibres (Bland & Ashhurst 1997)) and a deep  
76 surface which articulates with the femur, gliding along the patellar sulcus or groove in that bone.  
77 In maturity, the patella is composed of an outer lamellar cortex enclosing an inner cancellous  
78 bone structure with marrow spaces, and has an articular hyaline cartilage lining on the deep  
79 surface for articulation with the patellar sulcus (groove) of the femur (Benjamin et al. 2006; Clark  
80 & Stechschulte 1998; Vickaryous & Olson 2007).

81 The vastus muscles’ tendons (especially M. vastus intermedialis) may have a fibrocartilaginous  
82 region at the approximate position of the patella, called the “suprapatella” or “patelloid” (Fig. 1).  
83 The latter two terms are sometimes used synonymously, though “suprapatella” is more usual  
84 when an osseous patella is also present, and “patelloid” when it is not. The suprapatella is  
85 described as proximal to the patella, occasionally with a fat pad interposed between it and the  
86 ossified patella (Fig. 1), whilst the patelloid is described as occupying the same approximate  
87 region that a bony patella would (though absence of a patella makes this difficult to objectively  
88 assess) (Bland & Ashhurst 1997; Jungers et al. 1980; Ralphs et al. 1991; Ralphs et al. 1998;  
89 Ralphs et al. 1992; Reese et al. 2001; Walji & Fasana 1983). It is not clear whether the fibrous  
90 patelloid in some marsupials (and perhaps some bats (Smith et al. 1995)) is homologous to the  
91 suprapatella, equivalent to an evolutionarily reduced patella, or an independently occurring  
92 structure. We revisit this problem later in this study.

93 The human patellar anlage is first visible at O’Rahilly stage 19, and chondrifies at stage 22.  
94 Ossification begins 14 weeks after birth (Merida-Velasco et al. 1997a; Merida-Velasco et al.  
95 1997b; Tria & Alicea 1995), but is not grossly visible until 4-6 years of age (when multiple,  
96 eventually-coalescing centres of ossification can be seen radiographically (Ogden 1984)) and  
97 sometimes not in its fully ossified form until adolescence. The patella is the only sesamoid bone  
98 counted regularly among the major bones of the human body (Vickaryous & Olson 2007),  
99 although there are other, much smaller sesamoids in the hands and feet (and in some cases even  
100 the spine (Scapinelli 1963)). The pisiform is often considered a sesamoid and deserves further

101 attention in a broad context similar to this study's. Other small sesamoids, such as the lunula,  
102 fabella, cyamella and parafibula, also occur in the knee joint in many tetrapod species including  
103 some mammals (Fig. 1); these occur sporadically in humans (Pearson & Davin 1921a; Sarin et al.  
104 1999).

105 The patella is covered by the thickest layer of articular cartilage in the human body (Palastanga et  
106 al. 2006). The patella may thus also play a protective role for the underlying joint architecture  
107 (Haines 1974), in addition to protecting the patellar tendon from excessive compressive stresses  
108 (Giori et al. 1993; Sarin & Carter 2000a; Wren et al. 2000). The patellar tendon itself, to the  
109 extent that its properties are known for some species (e.g. humans), is stiff and strong, able to  
110 withstand about twice as much stress as typical knee joint ligaments and enduring strains (i.e.  
111 lengthening) of up to 11-14% (Butler et al. 1986). Regional variations in the microscopic  
112 anatomy of the human patella have also been recognised, for example in tissue thickness and  
113 nerve arrangement, which may reflect load distribution (Barton et al. 2007; Eckstein et al. 1992;  
114 Toumi et al. 2006; Toumi et al. 2012). There is convincing evidence from numerous species that  
115 excessive loads on the patella can lead to degeneration of the articular cartilages and damage to  
116 the underlying bone, producing osteoarthritis (Aglietti & Menchetti 1995; Hargrave-Thomas et  
117 al. 2013; Tria & Alicea 1995), so those regional variations of patellar structure are likely  
118 important. Similarly, the tissues involved in anchoring the patellar tendon to the proximal and  
119 distal surfaces of the patella as well as to the proximal tibia (tuberosity/tubercle) vary in their  
120 composition and presumably are adapted, and exhibit phenotypic plasticity, to reduce the risk of  
121 tendon avulsion from the bone (Evans et al. 1991). Reduction of a bony patella to soft tissue  
122 presumably reduces its ability to act as a gear or lever (Alexander & Dimery 1985).

123 Functions of the patella notwithstanding, there was once some enthusiasm for its outright  
124 removal for treatment of certain joint problems. Patellectomy was first performed in 1860 and for  
125 some time was an established treatment option for several conditions (Pailthorpe et al. 1991;  
126 Sweetnam 1964). However, partial and complete patellectomies are now considered as last resort  
127 salvage procedures; this is also the mainstream view of the veterinary profession (Langley-Hobbs  
128 2009). The historical lack of clarity on the pros and cons of patellectomy was summarised  
129 eloquently by *The Lancet*, stating, "Sadly, most of our interventions on the patella are empirical,  
130 and are supported more by the enthusiasm of proponents than by a very deep knowledge of the  
131 biology or biomechanics of this unusual joint. The knee cap could do with more scientific  
132 attention" (Editors 1992).

133 The latter complaint regarding the dearth of scientific attention to form, development, function  
134 and clinical treatment of the patella applies even more so to non-human tetrapods. One exception  
135 is a study that measured the inter- and intra-specific variability of the patellae and other bones  
136 (Raymond & Prothero 2012). The latter study found generally greater variation in patellae (and  
137 other sesamoids) vs. "normal" long bones. The inference was that this greater variability might  
138 pertain to the "intermembranous" [*sic*- intramembranous] development of sesamoids, vs. an  
139 endochondral location in long bones. However, the patella and most other major limb sesamoids  
140 of mammals are pre-formed in cartilage and thus clearly are endochondral bones (Farnum 2007).  
141 Yet the latter study reinforces that sesamoids are more variable than most other bones, in part due  
142 to their mechanical environment, in part due to their embedding in soft tissues (themselves quite  
143 variable) such as tendons and ligaments (Bland & Ashhurst 1997; Clark & Stechschulte 1998)  
144 and perhaps due to other factors not yet understood. This uncertainty about the causes of  
145 variability in the patella may also relate to incomplete understanding of its mechanical loading  
146 and function *in vivo*, as follows.

147 Where a patella is present in its typical form, its primary function is to modify the mechanical  
148 advantage (ratio of output force to muscle force) at the knee joint, by increasing the moment arm  
149 of the tendon in which it is embedded and thereby altering the amount of force needed from the  
150 quadriceps muscles in order to generate a particular moment (torque; rotational force) about the  
151 knee joint (Alexander & Dimery 1985; Fox et al. 2012; Haines 1974; Heegaard et al. 1995;  
152 Herzmark 1938; Howale & Patel 2013; Tecklenburg et al. 2006). In humans, the patella causes  
153 the quadriceps muscle group's moment arm about the knee to increase as the knee becomes more  
154 extended, causing the amount of quadriceps muscle force required per unit of patellar tendon  
155 force (i.e. at the insertion onto the tibial tubercle) to vary significantly across knee joint flexion-  
156 extension (Aglietti & Menchetti 1995; Fellows et al. 2005). By articulating with the femur, the  
157 patella also transmits some forces of the quadriceps muscle group directly onto the femur (the  
158 patellofemoral joint reaction force); forces which can reach a maximum of 20-25 times body  
159 weight (Aglietti & Menchetti 1995).

160 The mobility of the patella is an important aspect of its function. While, in humans, the patella  
161 mostly flexes and extends relative to the femur as the knee is flexed and extended, it also  
162 translates and pitches (tilts) and rolls (Aglietti & Menchetti 1995; Fellows et al. 2005), leading to  
163 variable contact between the patella and femur that is reflected in the angled facets of the human  
164 patella (Lovejoy 2007). In contrast to the situation in humans (as well as in early hominins such  
165 as *Australopithecus*), in chimpanzees and presumably many other primates (as well as other taxa  
166 such as sheep (Bertollo et al. 2012; Bertollo et al. 2013)), the patella remains in tight articulation  
167 with the femur throughout the knee's range of motion, reducing patellofemoral stresses especially  
168 when the knee is strongly flexed, as it habitually is in those non-human primates (Lovejoy 2007).  
169 Other primates show varying degrees of specialization of patellar morphology that alter the  
170 moment arm of the patellar tendon, with great apes apparently having a patella most specialized  
171 for widely varying knee joint postures (Pina et al. 2014). It has been claimed that in hominids and  
172 ursids (bears) alike, there is an association between plantigrady (flat-footedness), increased knee  
173 range of motion, and patellar mechanics (Lovejoy 2007); that is an interesting hypothesis that  
174 could be rigorously tested.

175 In the elbow of humans and other mammals, there is an extension of the ulna called the olecranon  
176 (process), which serves a lever-like function analogous to that of the patella (Herzmark 1938).  
177 However, a mobile sesamoid bone like the patella has a more flexible ("dynamic gearing")  
178 function in improving mechanical advantage compared with an immobile retroarticular process  
179 like the olecranon (Alexander & Dimery 1985). There tends to be an inverse relationship between  
180 mechanical advantage and speed of joint motion (Hildebrand 1998), thus a high mechanical  
181 advantage is not necessarily useful in all cases, which may in part explain the variable  
182 occurrence, size and shape of the patella in animals with different lifestyles and modes of  
183 locomotion. Biomechanical studies of primates (Lovejoy 2007; Pina et al. 2014) and  
184 domesticated mammalian species (e.g. dogs (Griffith et al. 2007; Kaiser et al. 2001), sheep  
185 (Bertollo et al. 2012; Bertollo et al. 2013), horses (Schuurman et al. 2003; Wentink 1978)) have  
186 contributed some knowledge of how the patella functions in these groups, or in individual  
187 species, but a general "functional synthesis" for the patella is still lacking.

188 De Vriese performed pioneering comparative analyses and attempted syntheses of patellar size  
189 and morphology in comparison to other leg bones, between species and among multiple  
190 individuals in some species (De Vriese 1909). No clear correlations were observed between the  
191 size of the patella and other major hindlimb bones (femur, tibia, and fibula). A correlation was

192 claimed between the sizes of the patella and the talus (or intermedium) in the ankle, although no  
193 clear, plausible mechanistic/functional justification was suggested and no statistical analyses  
194 were performed. Somewhat oddly, no relationship was evident between the size and shape of the  
195 patella and the femoral patellar groove (De Vriese 1909). The more restricted but quantitative  
196 analysis of Valois (Valois 1917) focused mainly on primates and challenged many of De Vriese's  
197 claims that mechanical or physiological explanations of patellar morphology have "no scientific  
198 merit". Haxton (1944) also criticised De Vriese for focusing on relative length of bones; his own  
199 "patellar index" based on relative width found no correlation with animal speed or size, but he  
200 inferred that the patella confers functional advantages in knee extension. There has been little  
201 examination of these questions in a modern comparative, rigorously statistical or biomechanical  
202 context since these studies. A notable exception is a study of the distal femur and patellar groove  
203 in bovid mammals, indicating increased mechanical advantage of the knee in larger species  
204 (Kappelman 1988).

205 The occurrence of an ossified patella in the knee joint is not universal among tetrapods (Fig. 3). A  
206 bony patella is absent in extinct early Tetrapoda and crown clade Lissamphibia (Dye 1987;  
207 Haines 1942; Herzmark 1938; Vickaryous & Olson 2007), all non-avian dinosaurs, Crocodylia,  
208 and Testudines (turtles), and all other extinct tetrapods. Hebling et al. (2014; their fig. 3A)  
209 illustrate what seems to be a patella formed of soft tissue in the bullfrog *Lithobates catesbeianus*.  
210 That fascinating observation needs a more comprehensive examination across Anura and Urodela  
211 to test if a soft tissue "patelloid" is ancestral for Lissamphibia or smaller clades. In contrast, an  
212 ossified patella is present in many or most Squamata (lizards and kin) with limbs (Camp 1923;  
213 Carrano 2000; De Vriese 1909; Dye 1987; Dye 2003; Gauthier et al. 2012; Haines 1940; Haines  
214 1942; Hutchinson 2002; Hutchinson 2004; Jerez & Tarazona 2009; Maisano 2002a; Regnault et  
215 al. 2016; Vickaryous & Olson 2007). Patellar status (used throughout our study to refer to  
216 presence/absence of ossification in adults) is unknown for the (mostly extinct) Rhynchocephalia  
217 (sister group to Squamata), although a patella is at least sometimes present in the tuatara  
218 *Sphenodon* – the only extant rhynchocephalian (Regnault et al. 2016). An apparent sesamoid  
219 bone was noted in the knee joint region of a specimen of *Macrocnemus*, a mid-Triassic (~235  
220 Mya) reptile, which may be the earliest identified occurrence of a patella in any animal group  
221 (Rieppel 1989), although this structure may have been a different sesamoid bone or ossicle. There  
222 have been anecdotal accounts of fibrocartilaginous or "fibrovesicular" patelloids in some reptiles  
223 such as turtles and crocodiles (Haines 1940; Haines 1942; Pearson & Davin 1921a; Pearson &  
224 Davin 1921b), but these are not well-explored. Thus, although such fibrous tissues seem to be  
225 excellent candidates for intermediate evolutionary character states between "absence of ossified  
226 patella (normal extensor tendon)" and "presence of ossified patella", empirical grounding for this  
227 transformational sequence within Sauropsida is weak.

228 No patella has been observed in early, stem-group birds throughout the Jurassic and Cretaceous  
229 periods, except in the well-documented Cretaceous Hesperornithes, diving birds with vestigial  
230 wings and an extremely large and unusually shaped patella, resembling that in some extant diving  
231 birds (Lucas 1903; Marsh 1875; Martin 1984; Martin & Tate 1976; Shufeldt 1884; Thompson  
232 1890). A patella is found in some Cenozoic fossil bird specimens, most notably archaic penguins,  
233 and commonly among many crown clade birds (Dye 1987; Dye 2003; Hutchinson 2001;  
234 Hutchinson 2002; Ksepka et al. 2012; Shufeldt 1884; Vickaryous & Olson 2007; Walsh & Suarez  
235 2006). Our recent study (Regnault et al., 2014) inferred that a patella was probably ancestrally  
236 present in the common ancestor of Hesperornithes and living birds over 70 Mya. However, the  
237 bony patella was lost (and in some cases replaced by fatty cartilaginous tissue) in some large



238 flightless birds such as emus, cassowaries and the extinct moa, yet unexpectedly is present as a  
239 double ossification in the knee joints of ostriches (Chadwick et al. 2014).

240 An osseous patella is generally found in two of the three crown groups of Mammalia: Eutheria  
241 (Fig. 3) and Monotremata (see Fig. 4A-D), but not in most Metatheria (see Fig. 4E, F) (Dye  
242 1987,2003; Vickaryous & Olson 2007). This raises the question whether this patella represents  
243 independent, convergent evolutionary origins in the Eutheria and Monotremata, or an ancestral  
244 origin for all three groups, with loss of the ossified patella amongst most Metatheria. To address  
245 this question, we conducted phylogenetic character mapping with Mesquite software (Maddison  
246 & Maddison 2017) that reconstructed patellar evolution in Mammalia. Using likelihood methods,  
247 we also traced the most likely pattern of evolution over existing phylogenies, and considered  
248 alternate proposed topologies to test how they affected our reconstructions. Based on the  
249 predicted evolutionary patterns and individual morphologies, we propose suggestions as to the  
250 lifestyle of particular taxa, and consider where general correlations between lifestyle and patellar  
251 presence/absence might exist (or not).

252 Mottershead called the patella “that prince among sesamoids” but questioned whether it is “not  
253 typical of its kind” (Mottershead 1988). But is there even a “typical” patella (bony or otherwise)?  
254 Our synthesis of key data from morphology and function to phylogeny, development and genetics  
255 allows us to evaluate just how “typical” any patella is, even for a mammalian patella.

## 256 MATERIALS AND METHODS

257 Our methods followed standard phylogenetic character mapping (i.e. evolutionary  
258 reconstructions) methods in comparative biology (e.g. Baum & Smith 2013; Cunningham et al.  
259 1998; Huelsenbeck et al. 2003); with details as follow. We surveyed the literature and additional  
260 specimens (Fig. 4; Table S1 and Figs. S1-S3) and coded the patella as absent (score = 0),  
261 fibrocartilaginous (i.e. “patelloid”; score = 1), or ossified (score = 2) for each taxon in our  
262 analysis, with “?” denoting an ambiguous character coding. We did not code the “suprapatella”  
263 here as there is substantial confusion over its homology. We used two phylogenetic optimization  
264 methods in Mesquite software (Maddison & Maddison 2017) to reconstruct possible evolutionary  
265 polarity of the patella in the clade Mammaliaomorpha (with a focus on Mammaliaformes), as  
266 follows. First, for broad reconstruction across Tetrapoda, we used a phylogeny based on Gauthier  
267 et al. (1988) and Shedlock and Edwards (2009), with average branch lengths they derived from  
268 several studies. Some aspects of the phylogeny remain controversial, such as the position of  
269 Testudines (turtles; Hedges 2012). Reconstruction was performed using Mesquite’s parsimony  
270 algorithm and unordered character states and results are illustrated in Figure 3. As this analysis  
271 only involved major clades and not any stem lineages, it was intended as purely illustrative of  
272 general patterns and the current state of knowledge, given that patellar evolution across Tetrapoda  
273 had not been analyzed phylogenetically before.

274 We adopted composite phylogenetic trees for our study taxa (Archibald 1998; Beck 2012; Bi et  
275 al. 2014; Cardillo et al. 2004; Forasiepi et al. 2006; Gatesy et al. 2013; Goloboff et al. 2009;  
276 Kielan-Jaworowska et al. 2004; Luo et al. 2003; Luo 2007a; Luo et al. 2002; Luo 2007b; May-  
277 Collado et al. 2015; Meredith et al. 2009; Meredith et al. 2011; Mitchell et al. 2014; O’Leary et al.  
278 2013; O’Leary & Gatesy 2008; dos Reis et al. 2012; Rose 2006; Sánchez-Villagra et al. 2007;  
279 Song et al. 2012; Spaulding et al. 2009; Springer et al. 2003; Springer et al. 2007; Springer et al.  
280 2009; Thewissen 1990; Thewissen et al. 2007; Wible et al. 2007; Zack et al. 2005). As defined by

281 several authors, the clade Mammaliaformes includes crown group Mammalia plus closely related  
282 extinct stem-mammals such as the iconic *Morganucodon* and the more recently discovered  
283 *Sinoconodon*, and is characterised by diagnostic features involving the teeth, jaw and inner ear  
284 (Kielan-Jaworowska et al. 2004; Rose 2006). Extant mammals (crown group Mammalia) include  
285 three main clades: Placentalia, Marsupialia and Monotremata. Placentalia lie within the Eutheria;  
286 Marsupialia lie within the Metatheria, and Monotremata lie within the Australosphenida, all of  
287 which diverged during the Mesozoic, pre-dating the K-Pg extinction event ~66 Mya.

288 The overall phylogeny used for Mesozoic mammals (Fig. 5) was based on the topology of Bi et  
289 al. (2014); their main figure 4 and extended data figure 9. However, we chose to show  
290 *Henkelotherium* branching prior to *Vincelestes* following (Luo 2007) because their relationship  
291 with Theria was less well-resolved in Bi et al. (2014). Approximate divergence times for key  
292 clades were taken from Bi et al. (2014)'s figure 4. Divergence of *Vincelestes*, *Henkelotherium* and  
293 *Akidolestes* came from Luo (2007). The remaining undated divergences and branch lengths were  
294 estimated using data from the Paleobiology database (fossilworks.org), accounting for the date  
295 ranges of fossil taxa.

296 The topology of the metatherian tree was based on several sources that are all fairly congruent  
297 with one another. *Sinodelphys* was least nested, as in Luo et al. (2003), followed by *Asiatherium*,  
298 *Pucadelphys* + *Mayulestes*, *Herpetotherium*, and crown Marsupialia as shown by Sánchez-  
299 Villagra et al. (2007) (also by Beck 2012; Luo et al. 2003). Sparassodonta were sister to crown  
300 Marsupialia (Babot et al. 2002; Forasiepi et al. 2006; Suarez et al. 2016). The topology and  
301 divergence dates of crown Marsupialia were from Mitchell (2014). Divergence dates of  
302 *Sinodelphys*, *Asiatherium*, and of *Pucadelphys* from *Mayulestes* were from Luo et al. (2003).  
303 Dates within Sparassodonta were taken from Forasiepi (2009). The remaining undated nodes  
304 were estimated, so that the interbranch lengths between dated nodes was approximately equal.

305 The topology of basal eutherians used Hu et al.'s (2010), with *Juramaia* polytomous with *Eomaia*  
306 and crown Placentalia as in Luo et al. (2011), which also brought the basal eutherian node back to  
307 ~160mya. Alternative placement of *Eomaia* as a stem therian (as in O'Leary et al. 2013) was also  
308 explored as a supplementary analysis. The branch order of the main crown Placentalia clades  
309 (Xenarthra, Afrotheria, Euarchontoglires, and Laurasiatheria), as well as the placement of many  
310 of the extant and fossil groups, came from O'Leary et al. (2013). Divergence dates of extant taxa  
311 were estimated from the Timetree database Timetree.org (Hedges et al. 2006). Divergence dates  
312 of fossil taxa were from O'Leary et al. (2013) or estimated from fossil dates from the  
313 Paleobiology database as above.

314 Exceptions and expansions to the topology of O'Leary et al. (2013) were as follows: (1) The  
315 placement of Pantodonta and Taeniodonta is ambiguous, but both groups were suggested to be  
316 derived from the cimolestids (McKenna & Bell 1997). Here we placed these groups as stem  
317 eutherians (Rook & Hunter 2014). (2) Within primates, we placed *Omomys*, *Teilhardina*,  
318 *Archicebus*, *Notharctus* and *Plesiadapis* (Ni et al. 2013). (3) Within Glires, *Nonanomalurus* was  
319 classified with Anomaluroidea, diverging from the group containing Sciuridae (Marivaux et al.  
320 2016), and adopting a divergence date of 60MYA. Apatemyids like *Apatemys chardini* may be  
321 basal members of Euarchontoglires, with weak support for a sister-group relationship with Glires  
322 (Silcox et al. 2010). (4) The topology within Carnivora was based on Flynn et al. (2005). (5) The  
323 detailed topology within Cetartiodactyla followed Spaulding et al. (2009). *Maiacetus* was placed  
324 alongside *Rodhocetus* and *Artiocetus* (within Protocetiidae). *Gervachoerus* was placed tentatively  
325 alongside *Diacodexis* (as it is classified within Dichobunoidea); its actual placement is unclear.

326 *Paratylopus*, *Merychyus* and *Protoreodon* were placed near to *Camelus*, within Camelidamorpha,  
327 but again their exact relationships are unclear. (6) The detailed topology of Perissodactyla  
328 followed Holbrook & Lapergola (2011). Notoungulata and *Eoauchenia* (Litopterna) were placed  
329 sister to Perissodactyla (Welker et al. 2015). Following recent analyses (e.g. Cooper et al. 2014),  
330 we placed Phenacodontidae and Desmostylia as stem perissodactyls. (7) The position of  
331 Dinocerata is controversial. Here we placed Dinocerata within Laurasiatheria, close to  
332 Perissodactyla and Cetartiodactyla (Burger 2015), until more data on the placement of this group  
333 becomes available. (8) The detailed topology within Chiroptera followed Simmons et al. (2008).

334 Our analysis involved numerous challenges and caveats. Many anatomical studies of extant or  
335 extinct species omit any mention of the patella, leaving its provenance in these taxa as uncertain.  
336 Interpretation of patellar status is especially challenging in fossils due to the rarity of finds with  
337 extensive, articulated postcranial material, the potential occurrence of other small non-patellar  
338 bones in the knee joint, and the uncertain age of the animal at time of death versus the  
339 developmental timing of sesamoid ossification (usually unknown; often relatively late in  
340 ontogeny). For the present analysis, statements in the primary literature regarding patellar status  
341 were generally accepted at face value except when superseded by more recent observations. From  
342 some publications with high quality photographs, patellar status was tentatively interpreted even  
343 if not discussed in the original text. In some cases, patellar status was confirmed by direct  
344 observation (e.g. Fig. 4; Figs. S1-S3; Table S1). Drawings found in secondary citations were  
345 mostly not been taken as definitive evidence, as we noticed examples of discrepancies between  
346 primary references and such drawings found in review articles or even textbooks, which may  
347 simply assume patellar status in mammals. Also, many mammalian groups are found over long  
348 temporal and geological spans, thus we were cautious about using the presence of a patella in one  
349 or a few individual extant or fossil specimens to infer presence throughout the group, although in  
350 some cases there was clearly enough conservatism within a clade to score it for all members.

351 An important knee structure related to the patella is the femoral patellar or intercondylar sulcus  
352 (groove) (Norell & Clarke 2001; Polly 2007). This sulcus is anatomically associated with a true  
353 patella (Figs. 1,4) in terms of its direct role in guiding the patellar sesamoid and tendon's path of  
354 movement during leg flexion/extension, and in mediolaterally confining the patellar tendon,  
355 which may enhance osteogenic stresses favouring the formation of a patella (Sarin & Carter  
356 2000b; Wren et al. 2000). In the absence of an observed patella in fossil specimens, this sulcus at  
357 the distal end of the femur is sometimes treated as evidence of a patella even in the absence of the  
358 observed bone itself. We deemed this conclusion to be unwarranted. For example, the evolution  
359 of a patellar sulcus in early pygostylian birds substantially predated the evolution of an ossified  
360 patella in later ornithurine birds; moreover the sulcus was retained in some avian taxa that lost the  
361 patella (Clarke & Norell 2002; Hutchinson 2002; Livezey & Zusi 2006; Regnault et al. 2014). In  
362 contrast, a prominent sulcus is absent in many Squamata despite the presence of a patella (S.R.  
363 and J.R.H., pers. obs.). Together these observations indicate that these two anatomical features  
364 are not obligatorily coupled, so reliance on the observed presence of an ossified patella in fossil  
365 specimens was warranted. Nonetheless, at least among mammals the complete absence of a  
366 femoral patellar sulcus might be indicative of the absence of an ossified patella (Chester et al.  
367 2012).

## 368 RESULTS AND DISCUSSION

369 Our overall evolutionary reconstruction of the patella for Mesozoic mammals is shown in Fig. 5,  
370 for Metatheria/Marsupialia in Fig. 6, and for Cenozoic Eutheria/Placentalia in Fig. 7, with details  
371 for specific taxa in Table S1 and alternative phylogenetic analyses in Figs. S4 and S5. Here we  
372 sequentially summarize and discuss our findings for five subgroups of Mammaliaomorpha  
373 (especially Mammaliaformes): (1) Mesozoic pre-therians and stem-therians; (2) Mesozoic  
374 Metatheria and Eutheria; (3) Cenozoic Monotremata; (4) Cenozoic Metatheria, and (5) Cenozoic  
375 Eutheria. We then conclude with a general synthesis of our study's insights (as well as  
376 uncertainties) and a consideration of how available and emerging data on developmental genetics  
377 of the patella might help shed light on the “evo-devo” of the patella, augmenting the phylogenetic  
378 and anatomical insights that this study focuses on.

### 379 *1. Mesozoic pre-therian and stem-therian mammals*

380 The earliest mammals as widely construed include *Sinoconodon*, the Morganucodonta and  
381 Docodonta. These were mostly small, probably insectivorous animals, that appear to have lacked  
382 a patella, although it is unclear whether the known specimens contain sufficient postcranial  
383 material or are from verified adults, to allow for definitive conclusions. The absence of a clear  
384 patella in two stunningly preserved docodonts (the scansorial [climbing-adapted] *Agilodocodon*  
385 and fossorial [digging-adapted] *Docofossor*) lends credence to the conclusion that it was  
386 generally absent in early mammaliaforms (Luo et al. 2015b; Meng et al. 2015). There is  
387 convincingly strong evidence of absence of a bony patella in earlier pre-mammals in lineages  
388 dating from the divergence of Synapsida and Sauropsida/Reptilia (~320 Mya), including the early  
389 “pelycosaur”, therapsids and cynodonts (Kemp 2005).

390 Australosphenida, the clade containing and thus ancestral to extant Monotremata, diverged from  
391 other mammals extremely early, possibly in the mid-Jurassic (Kielan-Jaworowska et al. 2004).  
392 There is little postcranial material for any extinct members of this lineage however, and no  
393 hindlimbs (Kemp 2005). The patella in crown clade monotremes is discussed below.

394 *Fruitafossor*, from the late Jurassic (150 Mya), diverged after the Australosphenida (Luo & Wible  
395 2005). Its relationship to other early mammals is complicated by its mixture of characters in the  
396 molar teeth, middle ear and elsewhere. *Fruitafossor* is described as lacking a patella, and it is  
397 proposed to have had a fossorial lifestyle.

398 The Eutriconodonta were found abundantly across the world from the middle Jurassic to early  
399 Cretaceous periods (Kielan-Jaworowska et al. 2004). Among eutriconodonts, a poorly developed  
400 patellar groove on the distal femur is found but an ossified patella is absent.

401 The Allotheria were an extremely successful and widely dispersed group of mammals, among  
402 which the best understood are the multituberculates (Kielan-Jaworowska et al. 2004; Wilson et al.  
403 2012). Generally Allotheria are found from the late Triassic to the Eocene; thus this group  
404 spanned the heyday of the non-avian dinosaurs and survived the K-Pg extinction (Kielan-  
405 Jaworowska et al. 2004). Multituberculates were predominantly small animals, either herbivorous  
406 or omnivorous (Kielan-Jaworowska et al. 2004). A patella is noted for the nearly complete  
407 multituberculate *Ptilodus*, a proposed scansorial animal from the early Cenozoic. A patella is also  
408 present in the Cretaceous multituberculate *Chulsanbaatar*. It is unclear whether a patella is  
409 typical of all members of the multituberculate group and is under-reported due to lack of  
410 hindlimb material for most group members, or whether it occurs only among selected species,  
411 although the former seems more plausible. A patella is not reported, however, for the early  
412 Jurassic basal *Rugosodon*, a proposed multituberculate specimen with one relatively intact knee

413 joint (Yuan et al. 2013), so it is conceivable that an ossified patella evolved later within the  
414 Allotheria (Fig. 5).

415 Specimens of the diverse group “Haramiyida” are mostly restricted to cranial material, and the  
416 relationship of this ancient group to other Allotheria and Mammaliaformes has been controversial  
417 (Butler 2000; Kielan-Jaworowska et al. 2004; Rose 2006). However, several recently described  
418 more complete haramiyid specimens from the Jurassic with at least one preserved knee joint lack  
419 a patella (Bi et al. 2014; Zheng et al. 2013; Zhou et al. 2013). These new specimens have been  
420 interpreted to support an Allotheria clade including a paraphyletic “Haramiyida” (but a valid  
421 clade Euharamiyida including many “haramiyid” taxa) and Multituberculata (Fig. 5), although  
422 new analyses of a key specimen of *Haramiyavia* concluded that the haramiyids and  
423 multituberculates were not closely related (Luo et al. 2015a). The inclusion of the  
424 “Euharamiyida” in Allotheria pushes the divergence date of the group significantly earlier into  
425 the late Triassic, whereas multituberculates themselves appear only in the middle to late Jurassic.  
426 Final resolution of this controversy will undoubtedly require additional fossil material.

427 Symmetrodonta were a group of diverse, small mammals widely distributed in time from the late  
428 Triassic to the late Cretaceous (Kielan-Jaworowska et al. 2004). In the subgroup of  
429 spalacotheroids, a patella is reported for one fairly complete specimen (*Zhangheotherium*) but not  
430 for another (*Akidolestes*) (Chen & Luo 2012; Luo & Ji 2005) (these two specimens are coded  
431 oppositely in character matrices in some subsequent publications (Bi et al. 2014; Zhou et al.  
432 2013), probably in error); a patella seems absent in *Maotherium*.

433 Eupantotheria was a diverse group found commonly from the mid-Jurassic to the early  
434 Cretaceous (Kielan-Jaworowska et al. 2004). The patella is reported as absent in both an early  
435 European specimen (*Henkelotherium*, late Jurassic) and a later South American specimen  
436 (*Vincelestes*, early Cretaceous) (Fig. 5). The large group of dryolestid Eupantotheria possibly  
437 survived past the K-Pg boundary, have an unknown patellar status.

438 The tribotherians were the earliest-diverging group to share key molar features with the therians.  
439 However, no postcranial specimens have been reported; thus nothing is known of their patellar  
440 morphology (Kielan-Jaworowska et al. 2004).

441 The single specimen of *Juramaia* from the Jurassic (~160 Mya) unfortunately lacks hindlimb  
442 material; therefore its patellar status is unknown. Based on its forelimb, *Juramaia* is proposed to  
443 have been scansorial or possibly arboreal (Luo et al. 2011). The later specimen of *Eomaia* from  
444 the early Cretaceous includes all limb elements, and is described with a patella (Ji et al. 2002).  
445 Based on limb and foot features, *Eomaia* was probably scansorial or arboreal. In the original  
446 publication, *Eomaia* was described as the earliest eutherian mammal (Fig. 5), however a more  
447 recent and much more extensive analysis confidently placed *Eomaia* prior to the  
448 eutherian/metatherian divergence (O’Leary et al. 2013) and thus at least as a stem member of the  
449 clade Theria (see Fig. S4). *Eomaia* (and presumably *Juramaia*) postdate the divergence of the  
450 Symmetrodonta, but their positions relative to the Eupantotheria remain to be determined, as does  
451 any close relationship between these two key taxa. Lacking a better alternative, here we refer to  
452 these taxa as “Theria”, and in Fig. 5 vs. Fig. S4, consider the consequences of *Eomaia*’s  
453 phylogenetic position on our conclusions.

454 In surveying the available data mapped onto our composite phylogeny (Figs. 5, S4), it becomes  
455 evident that an ossified patella evolved multiple times (at least four) along the mammalian stem

456 lineages during the Mesozoic era, whether using parsimony or maximum likelihood optimisation  
457 methods: at some highly uncertain time in the long mammalian lineage that led to Monotremata,  
458 in multituberculates/Allotheria, in *Zhangheotherium* or a direct ancestor, and likely twice (or  
459 between one to three times, depending on the placement of *Eomaia*; see Figs. 5 and S4) in the  
460 clade containing *Eomaia* and Theria (Metatheria and Eutheria). This result remained the same if  
461 the Euharamiyida were not included with multituberculates but pre-dated crown Mammalia, as  
462 suggested by some recent studies (e.g. Luo et al. 2015a).

#### 463 2. Mesozoic Metatheria and Eutheria

464 The two major extant mammalian groups, the Metatheria and Eutheria (together forming the  
465 clade Theria), diverged as early as the Jurassic (Fig. 5). The earliest fossil identified as stem  
466 metatherian, *Sinodelphys*, dates from the early Cretaceous of China (125 Mya, approximately  
467 contemporary to *Eomaia*), and lacks a patella (Luo et al. 2003). A patella also seems absent in the  
468 less complete Cretaceous stem metatherian *Asiatherium* (Szalay & Trofimov 1996).

469 The earliest known occurrences of the patella in definitive stem eutherians (Figs. 5,7) were in the  
470 late Cretaceous *Ukhaatherium* (Horovitz 2003), a relatively unspecialized form, and in  
471 *Zalambdalestes* (Wible et al. 2005), a more specialized taxon sometimes described as resembling  
472 later lagomorphs (Rose 2006). Patellar status at the crown group node for Theria (plus *Eomaia*)  
473 remains ambiguous (Figs. 5,6,S4), as we consider below.

#### 474 3. Cenozoic Monotremata

475 The origins of the Monotremata (egg-laying mammals) are poorly understood. They are  
476 considered extant members of the clade Australosphenida (the alternative term Prototheria has  
477 been superseded), and hence with early roots in the Mesozoic. Molecular studies based on the  
478 sequenced genome of the platypus corroborate the long held interpretation that the monotremes  
479 diverged prior to the metatherian/eutherian split, consistent with proposed fossil-based  
480 phylogenies (Warren et al. 2008). Unfortunately, there are almost no reported hindlimb specimens  
481 of any extinct monotreme (including probable early monotreme fossils found in South America;  
482 (Musser 2003)), with the exception of the Pleistocene *Zaglossus* (echidna) from Australia and  
483 New Guinea (which may be the same as the extant species of that name). Unfortunately, although  
484 fossil *Zaglossus* hindlimb elements exist, including an articulated knee, neither presence nor  
485 absence of the patella has been reported (Murray 1984). The extant monotremes, the platypus  
486 (*Ornithorhynchus anatinus*) and the echidnas (Tachyglossidae, two genera *Zaglossus* and  
487 *Tachyglossus*; four known species) all have substantial patellae (see Fig. 4A, B, C, D) (Herzmark  
488 1938; Rowe 1988). It is unclear when the two extant monotreme genera diverged, although a date  
489 early in the Cretaceous has been proposed (Rowe et al. 2008), and it is impossible for now to date  
490 the appearance of the patella in the monotreme lineage. Regardless, an ossified patella is  
491 homologous for this crown clade (Fig. 5), and alternative phylogenetic topologies did not change  
492 the general pattern of patellar evolution (Fig. S4).

#### 493 4. Cenozoic Metatheria

494 All extant Metatheria are within the subgroup of Marsupialia, however non-marsupials did exist  
495 earlier during the Cenozoic. As documented in the pioneering study of sesamoids in Marsupialia  
496 by Reese et al. (2001), an ossified patella seems to be absent in the great majority of extant  
497 marsupial species, both from Australia and the Americas (Flores 2009; Herzmark 1938; Holladay  
498 et al. 1990; Reese et al. 2001; Rose 2006; Rowe 1988), including the sole surviving North  
499 American marsupial, the opossum *Didelphis virginiana* (Fig. 4E, F). Many marsupials have other  
500 sesamoid bones in the knee region (e.g. the parafibula, lateral sesamoid, or “sesamoid bone of

501 Vesalli”; Fig. 1), as well as a fibrocartilaginous “patelloid”, which may to some degree serve the  
502 mechanical function of a bony patella (Reese et al. 2001). However, the mechanics of a fibrous or  
503 bony patella remain essentially unstudied (to our knowledge) in non-placental mammals, so this  
504 is simply speculation. Studies have claimed some association between reduction of the patella in  
505 many marsupials and locomotor style or ecology (Holladay et al. 1990; Reese et al. 2001), but  
506 these deserve testing with more detailed sampling across phylogeny and ontogeny.

507 Nonetheless, an ossified patella is found in a small number of extant marsupial species among  
508 otherwise divergent clades, both from Australia: at least several Peramelidae or bandicoots, and  
509 the two marsupial mole species of *Notoryctes*); and from South America: *Tarsipes*, a honey  
510 possum; and several, and possibly all, Caenolestidae or shrew opossums (see Fig. 6: note collapse  
511 of several large clades in terms of total number of species, in which no species have been shown  
512 to possess a bony patella; Table S1).

513 Possibly uniquely among crown clade marsupials, bandicoots also possess a chorioallantois fused  
514 to the uterine epithelium (i.e. a true placenta) (Freyer et al. 2003; Padykula & Taylor 1976),  
515 which combined with an osseous patella led to the initial suggestion that they might actually be  
516 eutherians (Reese et al. 2001). However, more recent molecular and fossil-based phylogenetic  
517 studies provide no support for that hypothesis of eutherian bandicoots (Asher et al. 2004;  
518 Meredith et al. 2008b; Sanchez-Villagra et al. 2007; Westerman et al. 2012). Bandicoots clearly  
519 are metatherians, and their chorioallantois is thus a convergently evolved trait rather than  
520 plesiomorphic. It remains to be determined whether an ossified patella is present in all or only  
521 some bandicoots, as so far it is only reported in the Peramelinae of dry or temperate forests of  
522 Australia, not yet in the Peroryctinae of tropical rainforests of New Guinea, or the more distantly  
523 related bilbies (Groves & Flannery 1990; Meredith et al. 2008a; Westerman et al. 2012).  
524 Similarly, a comprehensive study of the Caenolestidae remains to be performed, much as a more  
525 thorough study of the major marsupial clade Diprotodontia (wombats, kangaroos and kin) is  
526 needed.

527 Not surprisingly given the absence of a bony patella in most extant marsupials, any evidence of a  
528 patella is absent in the early Cenozoic Metatheria *Pucadelphys*, *Mayulestes*, and the later  
529 *Herpetotherium*. Unexpectedly, a bony patella is reliably reported in the Borhyaenoidea, an  
530 unusual group of dog-like carnivorous South American marsupials found from the Palaeocene  
531 through the Miocene (Argot 2002; Argot 2003a; Argot 2003b; Argot 2003c; Argot 2004; Argot &  
532 Babot 2011; de Muizon et al. 1997). Patellar status in some members of Borhyaenoidea (e.g.  
533 *Borhyaena* itself and *Lycopsis* (Argot 2004)), and in the more inclusive group Sparassodonta, is  
534 uncertain due to the incomplete state of specimens. Szalay and Sargis (2001) noted other  
535 enigmatic fossil patellae from the Palaeocene of Brazil that they assigned to Metatheria, but the  
536 phylogenetic relationships of those fragmentary remains are unclear and no patellae were shown.  
537 However, no ossified patella is reported in extant or recent carnivorous marsupials such as  
538 *Thylacinus*.

539 Two related, pernicious problems remain for interpreting the evolution of the patella in  
540 Metatheria that may have ramifications for all of Mammalia/Mammaliaformes. First, Szalay and  
541 Sargis (2001:pp.164-5) reported the presence of an ossified patella in older individuals of  
542 *Didelphis virginiana* in their study of an ontogenetic series from this species. They stated (p.165)  
543 “In older individuals there is occasionally an elongated and small sesamoid ossification within  
544 the tendon of the quadriceps femoris where it crosses the knee joint when the knee is flexed.”  
545 However, this observation was not documented with illustrations or photographs (especially

546 tissue histology or x-rays) and hence remains a tantalizing anecdote. Similarly, Owen (1866)  
547 commented that some marsupials had no ossifications in their patellar tendon but others had  
548 “only a few irregular specks of ossification” and a “distinct but small bony patella in the  
549 *Macropus Bennettii*.” In contrast, Reese et al. (2001) and Holladay et al. (1990) respectively  
550 sampled 61 specimens (~39 adults) from 30 species of marsupials and 3 macropodid specimens  
551 (of unknown maturity), documenting no ossified patellae except as noted in bandicoots, and their  
552 studies used clear methods for identifying ossified tissues. It remains possible that patellar  
553 ossification occurs variably in older individuals among Metatheria, which would help explain its  
554 patchy description in known taxa.

555 If the latter situation is the case (i.e. the literature is unclear about patellar ossification in  
556 marsupials because they have more inherent variability), then it relates to a second problem, a  
557 cladistic one of character coding and transformational homology (*sensu* Brower & Schawaroch  
558 (1996); Pinna (1991)). Should character states of the patella in metatherians, or even all mammals  
559 and their kin, be coded as an ordered transformational series such as absent (0), fibrocartilaginous  
560 (1) or ossified (2), or as an unordered series (i.e. should evolutionary steps be required to go from  
561 0-1-2 as 2 steps, or unordered allowing 0-2 transformations as 1 step)? We chose the unordered  
562 character option by default for all crown group mammals, but where relevant explain how an  
563 ordered option changed (or did not change) our results. An endochondral ossification of the bony  
564 patella is certain, but a fibrocartilaginous or otherwise soft tissue composition of the patella  
565 (coded as state 1) in adults is not unambiguously the necessary (i.e. ordered) evolutionary  
566 precursor character state to state 2 (ossified patella in adults). The solution to both of these  
567 problems lies in more developmental data for the patella (bony and otherwise) in diverse  
568 mammalian species, in addition to more scrutiny of the adult morphology in extant and fossil  
569 Mammalia (especially Metatheria).

570 As noted briefly in the Introduction, many marsupials have a primarily fibrocartilaginous  
571 patelloid in place of an ossified patella and some other mammals may have a “suprapatella”. The  
572 developmental and evolutionary relationships of these structures remain somewhat unclear,  
573 particularly as some marsupials with an ossified patella (e.g. bandicoots) also possess a patelloid  
574 (Reese et al., 2001), suggesting that the patelloid is not developmentally equivalent to the patella  
575 in marsupials (Vickaryous & Olson 2007). If so, this would indicate independent evolutionary  
576 histories of these two structures. Further work is required to clarify the relationships of the  
577 patelloid and suprapatella at least in extant taxa, before definitive evolutionary trajectories can be  
578 inferred. We reiterate that, just because a patella-like structure is not ossified, that does not mean  
579 it is a distinct organ deserving a new name and different homology as a phylogenetic character—  
580 although it may be a distinct state of the character “patella”. However, either of these two  
581 possibilities needs careful testing particularly for Metatheria.

582 A non-osseous patelloid/suprapatella is also found in several closely related modern placental  
583 clades that lie far from the base of Eutheria (Fig. 7), suggesting that these represent independent  
584 acquisitions. We have not attempted to explicitly reconstruct the evolution of the patelloid in  
585 Eutheria. Lewis (1958) and Broome and Houghton (1989) speculated that the mammalian  
586 patelloid might be a precursor to the tibial epiphysis (Broome & Houghton 1989; Lewis 1958) --  
587 a so-called “traction epiphysis” (Vickaryous & Olson 2007). Yet considering that the patelloid  
588 evolved after the tibial tuberosity (and proximal tibial epiphysis as well as distal femoral  
589 epiphysis; Carter et al. 1998) of mammals, not before it, and lies proximal rather than distal to the  
590 patella, we reject this hypothesis. More study of the evolution of mammaliaform long bone  
591 epiphyses, however, is warranted to strongly and more generally test for associations between



592 any epiphyses and sesamoids. Furthermore, this same phylogenetic evidence indicates that the  
593 patelloid in Euarchontoglires, some Carnivora and bandicoots is not ancestrally associated with  
594 leaping or other behaviours (e.g. Jungers et al., 1980). As Walji & Fasana (1983) caution, the  
595 ancestral mechanical environment of the patelloid/suprapatella and its roles in different  
596 behaviours remain unclear, although it does seem to be associated with knee hyperflexion like a  
597 typical fibrocartilaginous “wrap-around” tendon (e.g. Ralphs et al. 1991; Alexander & Dimery,  
598 1985).

599 Our unordered parsimony reconstruction (Fig. 6) indicated that an ossified patella was absent in  
600 the ancestor of Metatheria, then evolved in the ancestor of Sparassodonta and Marsupialia. The  
601 bony patella may have been lost in the basal lineages of Marsupialia (reconstructed state here was  
602 equally parsimonious between an ossified and fibrocartilaginous patella), with subsequent re-  
603 acquisition in certain groups (Tarsipedidae, and possibly Notoryctidae and Thyblacomyidae +  
604 Peramelidae, and Tarsipedidae) (Fig. 6). Ordered parsimony reconstruction resulted in subtle  
605 differences; making some nodes less ambiguous (i.e. state 1 [patelloid present] within basal  
606 Marsupialia) and others more ambiguous (such as the ancestor of Sparassodonta and Marsupialia,  
607 which became equally parsimonious between states 1 and 2). In contrast, maximum likelihood  
608 reconstruction indicated a single origin of the osseous patella in Metatheria (Fig. 6), with  
609 reduction to a fibrocartilage patelloid (in Didelphidae and the clade containing  
610 Pseudocheiridae+Vombatidae) and re-acquisition of a bony patella (in Tarsipedidae) marginally  
611 more likely than multiple instances of ossified patella evolution. Because presence of a patelloid  
612 has not been clearly excluded in some extant marsupials (e.g. Petauridae, Acrobatidae) and is  
613 unlikely to be fossilised, its reconstruction must be treated carefully. Finally, alternative  
614 placement of Microbiotheriidae did not drastically alter our evolutionary reconstructions (Fig.  
615 S5), aside from making a single origin of the ossified patella slightly more likely. Overall, we  
616 caution that inferences about the evolutionary history of the patella in Metatheria must remain  
617 tentative until further data become available.

#### 618 5. *Cenozoic Eutheria*

619 The Placentalia include all extant Eutheria as well as some fossil stem taxa (Fig. 7). Although  
620 there is some fossil evidence for placentals pre-dating the K-Pg event (Archibald et al. 2011), as  
621 well as substantial molecular dating consistent with an older placental radiation, the timing of the  
622 placental radiation remains highly controversial. However, our major conclusions about patellar  
623 evolution in placentals are not dependent on how this controversy is ultimately resolved, as a  
624 recent large-scale phylogenetic analysis convincingly established the presence of an osseous  
625 patella as a derived character state in the ancestral placental irrespective of its true date of  
626 divergence (O’Leary et al. 2013).

627 Fossil evidence supports the presence of the bony patella in essentially all Cenozoic placental  
628 groups (Fig. 7; also see Table S1 and Figs. S1-S4, with citations therein). Specimens with  
629 sufficient hindlimb material to make a determination of patellar status are rare in the early  
630 Cenozoic Palaeogene period (~66-23 Mya), but Palaeocene groups in which an ossified patella  
631 has been reported include the Taeniodonta (small to medium sized fossorial animals), Pantodonta  
632 (early herbivores), Palaeonodonta (small, possible insectivores; perhaps related to pangolins),  
633 “Condylarthra” (a diverse assemblage of putatively related taxa, probably polyphyletic, including  
634 both herbivores and carnivores, many of which may be stem members of subclades within the  
635 placental crown group), and the Plesiadapiformes, a sister group to crown clade primates (and  
636 possibly members of the clade Primates as well) (Bloch & Boyer 2007; Silcox 2007). In general,

637 the evolutionary relationships between Palaeocene taxa and more recent placentals remain  
638 enigmatic.

639 Eocene placentals include examples whose close relationships to modern groups are well  
640 accepted. Among Eocene groups (Fig. 7, Table S1), an osseous patella has been reported in older,  
641 extinct groups such as “Condylarthra”, Creodonta (carnivores), Mesonychia  
642 (carnivorous/omnivorous artiodactyls or cetartiodactyls), Dinocerata (large hippo/equid-like  
643 herbivores), Brontotheriidae (large rhino-like herbivores), and Notoungulata (diverse South  
644 American hoofed herbivores; probably related to Afrotheria) (O’Leary et al. 2013), as well as in  
645 extinct species (in parentheses, see Table S1 for citations) recognized as stem members of several  
646 extant groups: Glires (*Rhombomylus*), Perissodactyla (*Propalaotherium*), early Sirenia retaining  
647 hindlimbs (*Pesoziren*, *Protosiren*), Proboscidea (*Numidotherium*, *Moeritherium*, *Barytherium*),  
648 Rodentia (the horse-sized *Pseudotomus*, *Paramys*), Pholidota (*Eomanis*), Artiodactyla  
649 (*Gervachoerus*), early Cetacea retaining hindlimbs (*Maiacetus*) and Chiroptera (*Icaronycteris*,  
650 *Tachypteron*). A bony patella is also reported for several Eocene primates, including the lemur-  
651 like Notharctidae (*Notharctus*) and the tarsier-like *Omomys* and *Archicebus*, in addition to the  
652 enigmatic primate *Darwinius*.

653 Despite an extensive literature search, we found no reports attesting to the presence of an osseous  
654 patella in certain widely cited Paleocene and Eocene species, including: *Protungulatum*,  
655 frequently cited as the earliest true placental; *Miacis*, *Vulpavus*, *Viverravus* and *Didymictis*, which  
656 were stem Carnivora (Gregory 1920; Heinrich & Houde 2006; Heinrich & Rose 1995; Heinrich  
657 & Rose 1997; Samuels et al. 2013); *Pakicetus*, a fully quadrupedal early cetacean (though  
658 sometimes reconstructed with a bony patella as in Fig. 7 and Fig. S1 M, N) (Thewissen et al.  
659 2001); *Leptictis*, possibly related to crown clade lagomorphs (Rose 1999); *Sinopa*, a creodont  
660 (Matthew 1906); and the early primates *Adapis*, *Leptadapis*, *Teilhardina*, and *Cantius* (Dagosto  
661 1983; Gebo et al. 2012a; Gebo et al. 2012b; Rose & Walker 1985; Schlosser 1887; Szalay et al.  
662 1975). There is no reason to expect that a bony patella is missing in these species. These absences  
663 are more likely due to incompleteness of the fossil record and/or literature descriptions and  
664 images. Moreover, the massive collections of Eocene specimens from the Messel and Green  
665 River lagerstätten in Germany and Wyoming have not yet been fully described (Grande 1984;  
666 Schaal & Ziegler 1992). There are many examples of an ossified patella in specimens from extant  
667 placental groups across the more recent Miocene, Oligocene, Pliocene and Pleistocene, but a  
668 comprehensive search of the literature for those geologic epochs was deemed redundant for our  
669 major conclusions.

670 Based on fossil/morphological evidence plus extensive genomic DNA sequencing, there is a  
671 consensus that crown clade placentals can be historically and geographically defined by four  
672 major groups: Xenarthra, Afrotheria, Euarchontoglires (further divided into Euarchonta; featuring  
673 Primates; and Glires) and Laurasiatheria (Rose 2006). These in turn may be resolved, with  
674 somewhat less consensus, into 19 crown clade “orders” (Fig. 7) (O’Leary et al. 2013). In two of  
675 these orders, the afrotherian clade Sirenia and the cetacean branch of (Cet)artiodactyla  
676 (laurasiatherian clade), extant members have extensively reduced or absent hindlimbs and thus  
677 lack skeletal knee structures, including an osseous patella. In contrast, the bony patella is retained  
678 among the aquatic seals and sea lions in Carnivora, although unlike Sirenia and Cetacea these  
679 animals still display some terrestrial habits and thus presumably still employ the gearing  
680 mechanism that the patella is involved in at the knee. An ossified patella is documented as present  
681 in at least some members of all other 17 placental “orders” (e.g. Figs. 4G,H,7,S1-S3; Table S1)

682 (de Panafieu & Gries 2007; De Vriese 1909; Dye 1987; Herzmark 1938; Lessertisseur & Saban  
683 1867; Rose 2006).

684 The evolution of the Cetacea presents an interesting scenario regarding patellar evolution (Fig. 7).  
685 Cetaceans evolved from a common ancestor with other (cet)artiodactyls (Spaulding et al. 2009;  
686 Thewissen et al. 2007). Early artiodactyls (including cetaceans), such as *Diacodexis* and  
687 *Indohyus*, shared morphological similarities with both extant groups of Cetacea (toothed and  
688 baleen whales) and yet retained an osseous patella (Rose 1982; Thewissen et al. 2007), much as  
689 stem Sirenia did (Domning 2001; Zalmout 2008). Patellar status in *Pakicetus*, a presumptive  
690 early cetacean with full hindlimbs, remains uncertain based on the primary literature, but  
691 presence is likely considering the presence of a bony patella in its closest relatives. *Rodhocetus*  
692 and *Ambulocetus*, probably semi-aquatic early cetaceans, still had large hindlimbs and ossified  
693 patellae (Madar et al. 2002). The pelvis and hindlimbs are greatly reduced in the later cetaceans  
694 *Dorudon* and *Basilosaurus*, but a bony patella is still present in these animals (Gingerich et al.  
695 1990; Uhen 2004). It is not clear exactly when the patella was lost altogether in later cetaceans  
696 with increasingly reduced hindlimbs.

697 Bats present another interesting case of patellar evolution (Fig. 7; Table S1). An osseous patella is  
698 generally present in bats (Pearson & Davin 1921b). A bony patella is also reported in a well-  
699 preserved hindlimb of an early Eocene bat, *Icaronycteris*, of intermediate form but proposed to be  
700 a microchiropteran (Jepsen 1966). However, in studies of multiple genera of modern bats  
701 including members from both of the major subgroups Megachiroptera and Microchiroptera  
702 (which is possibly paraphyletic), a bony patella was noted as absent in four species of the  
703 megachiropteran *Pteropus* (flying foxes of various sizes), and a few individual species of  
704 *Cephalotes*, *Epomophorus* and *Vespertilio* (De Vriese 1909; Lessertisseur & Saban 1867; Smith  
705 et al. 1995). No obvious lifestyle distinction was noted for the *Pteropus* genus as compared to  
706 many other bats, hence the loss of the ossified patella in members of this particular subgroup (and  
707 others) remains mysterious. In general, bat hindlimbs are highly derived, adapted to hanging and  
708 pulling rather than pushing. A few bats such as the vampire bats are actively quadrupedal (Adams  
709 & Thibault 2000; Riskin & Hermanson 2005). Bat hindlimbs are articulated in abduction, so that  
710 the knee faces dorsally; as in the original ancestral orientation for Tetrapoda (Fig. 2) (Neuweiler  
711 2000; Schutt & Simmons 2006). There remains a need for a comprehensive study of the patella in  
712 bats (Smith et al. (1995) only studied 31 specimens of 13 species), but this is challenging due to  
713 the existence of >900 extant bat species (Jones et al. 2002). The microstructure of the “patelloid”  
714 in *Pteropus* is generally similar to that in many marsupials (e.g. deep layer of fibrocartilage;  
715 superficial layer of dense connective tissue contiguous with the quadriceps/patellar tendon)  
716 (Smith et al. 1995). This also raises the question of whether the patella only ossifies later in  
717 adulthood in *Pteropus*, rather than not ossifying at all.

#### 718 *General evolutionary patterns and ambiguities*

719 Considering the above distributions of patellar presence/absence in Mammalia (Figs. 5-7; Figs.  
720 S4,S5) and our data matrix (Table S1), the simplest interpretation of the evolutionary record of  
721 the patella in mammals (by parsimony and maximum likelihood mapping of presence/absence) is  
722 that this structure arose (i.e. ossified) independently at least four times (but possibly up to six),  
723 mostly during the Mesozoic era: 1, in Australosphenida ancestral to modern monotremes; 2, in  
724 Multituberculata (later than *Rugosodon*); 3, in Symmetrodonta (specifically in Spalacotheroidea  
725 that were ancestral to *Zhangheotherium* but not *Akidolestes*); 4-6, in early Theria (including  
726 Eutheria, Metatheria, *Eomaia* and related stem groups; depending on topology between one and  
727 three times in this clade). Conceivably, a single common patelloid precursor may pre-date the

728 origins of the bony patellae, or the bony patella may have arisen fewer times and undergone loss  
729 (and re-gain) in some lineages, similarly to the pattern in Metatheria. Each of these scenarios  
730 remain difficult to test purely with fossil evidence, however, due to the typical lack of  
731 preservation of cartilaginous or fibrous structures.

732 Once the bony patella evolved in Eutheria, it was highly conservative in its presence (Fig. 7).  
733 There are very few examples of fossil or extant Eutheria in which the hindlimb remains intact but  
734 the patella is unossified in adults (e.g. *Pteropus*). A caveat is that many fossil specimens are not  
735 sufficiently complete for a definitive rejection of patellar ossification in those taxa. Still, the  
736 evolutionary stability of the osseous patella in Eutheria stands in contrast to its general variability  
737 across mammals, and suggests some conserved functional requirement and/or ontogenetic  
738 mechanism that remains to be determined.

739 Although an ossified patella is absent in the majority of Metatheria, it is reported in several  
740 groups (Figs. 6, S5). This likely represents some loss and regain(s) of the early metatherian bony  
741 patella. Importantly, in this case the presence of a fibrocartilaginous “patelloid” in most  
742 marsupials shows a clear evolutionary polarity from an ossified patella to a non-ossified  
743 patelloid, and back again in the case of the secondary gain of ossification, in each case within  
744 Metatheria (Reese et al. 2001). This “patella to patelloid” transition suggests the reverse may also  
745 be possible – that a soft tissue patelloid may represent the evolutionary precursor to an ossified  
746 patella – but it has yet to be clearly documented. There is no obvious lifestyle or biomechanical  
747 correlate among all four groups of osseous patella-bearing Metatheria: the notoryctid moles are  
748 underground burrowers, and bandicoots may dig for insects, but *Tarsipes* is a nectar feeder and  
749 the borhyaenoids/sparassodonts were largely terrestrial carnivores. In contrast, other Australasian  
750 carnivorous marsupials including the recently extinct thylacine, and the extant quoll, numbat and  
751 Tasmanian devil are not reported to have a bony patella.

752 The large size of the patella in the monotreme platypus might be related to its aquatic (and partly  
753 fossorial) lifestyle. The other monotremes, the echidnas, also burrow and the long-beaked species  
754 (*Zaglossus*) lives in underground dens-- further suggesting an association between fossorial  
755 habits and the presence or enlargement of a bony patella in Monotremata, as well as in some  
756 fossil Mammaliaformes (multituberculates?) but curiously not in other fossorial stem taxa (e.g.  
757 the docodont *Docofossor*). Reduction of the patella in the Cetacea and Sirenia is not intrinsically  
758 correlated with their aquatic lifestyle, but with the reduction of the hindlimbs as part of their  
759 particular adaptations. Elsewhere in groups with aquatic adaptations, for example in various  
760 diving birds, an unusually large patella is found. It seems premature to weave detailed scenarios  
761 around the high degree of convergent evolution of the osseous patella in mammals until the  
762 biomechanical function and genomic control of the patella are better understood, and improved  
763 phylogenetic sampling improves resolution of when it evolved in particular lineages.

#### 764 *Patellar developmental genetics*

765 Molecular phylogenomics provides a potential independent or synergistic approach to resolving  
766 issues of patellar evolution. If specific genomic sequence signatures could be associated with  
767 patellar status, then comparison of the genomes of the various extant but widely separated groups  
768 with a bony patella might indicate whether these represent convergence events or a common  
769 ancestral event (i.e. identified via shared evolutionarily transmitted genetic markers required for  
770 patellar development). For example, it has recently been shown that the ability to taste sweet  
771 carbohydrates in hummingbirds represents a trait convergence. Hummingbirds diverged from the  
772 insectivorous swifts, in which the sweet taste receptor is inactivated by mutations in the receptor

773 coding gene. In hummingbirds, the ability to taste sweet has been re-acquired, apparently through  
774 molecular adaptation of the umami receptor to detect sweet molecules (Baldwin et al. 2014). It  
775 would be helpful to understand the (developmental) genetics of the patella as a step toward the  
776 identification of such sequence signatures. Developmental genetic studies in two mammals,  
777 humans and mice, have identified genes required for correct patellar specification. The known  
778 functions of some of these genes are informative regarding their requirements.

779 There are currently approximately 12 human genetic disorders with identified molecular bases  
780 that regularly include abnormal, reduced or absent patellae (hypoplasia or aplasia) as an  
781 important aspect of the phenotype (reviewed by Bongers et al. (2005), see also Warman et al.  
782 (2011) and Table S2 for details). There are also several genes whose genetics in mice indicates  
783 relevance to patellar development at least in rodents. A detailed discussion of all these syndromes  
784 and genes is beyond the scope of this study. However, the known patella-related genes can be  
785 broadly organized according to three major developmental processes: limb specification and  
786 pattern formation (transcription factors such as *LMX1B*, *TBX4*, *PITX1* and mouse *Hoxaaccdd-11*,  
787 *SOX11*, and signalling factor *WNT7A*); bone development, biochemistry and regulation (*GDF5*,  
788 *CHRNA2*, *SLC26A2*, *COL9A2*, *AKT1*); and genes involved in DNA replication and chromatin  
789 (*ORC1*, *ORC4*, *ORC6*, *CDT1*, *CDC6*, *GMNN*, *CDC45*, *RECQL4*, *KAT6B*, *ESCO2*). Of these, the  
790 genes of replication and chromatin are the most unexpected, and potentially of the most interest  
791 for evolutionary studies. Patellar ossification may be dependent on the timing of DNA replication  
792 in particular cells, or else may be affected by aberrant gene regulation resulting from mutations in  
793 replication and chromatin factors. In either case, the target genes mis-regulated in these  
794 syndromes, if they can be identified, may provide useful evolutionary markers to distinguish  
795 convergent from homologous patellar status.

796 Developmental studies in mouse or chick embryos, sometimes with induced paralysis, document  
797 the additional importance of local environmental factors in patellar ontogenesis (Hosseini &  
798 Hogg 1991; Mikic et al. 2000; Nowlan et al. 2010a; Nowlan et al. 2010b; Osborne et al. 2002;  
799 Rot-Nikcevic et al. 2006). Similarly, embryonic development and hindlimb activity in the case of  
800 particular marsupials may be important in understanding the diversity of patellar states in this  
801 group. A better understanding of these environmental processes will also be helpful to disentangle  
802 genomic versus epigenomic regulation of patellar development, and hence evolution.

## 803 CONCLUSIONS

### 804 *How “the mammalian patella” evolved*

805 The widespread, repeated evolution of the bony patella across evolution argues for an important  
806 role in locomotor biomechanics. In animals lacking an ossified patella (e.g. Lissamphibia,  
807 Testudines, Crocodylia; as well as many extinct lineages of tetrapods), the consequences of this  
808 ancestral absence for hindlimb function remain mostly unstudied. This mystery is striking, in  
809 particular, within Mammalia where most marsupials lack an ossified patella, as did numerous  
810 fossil stem-mammals, despite seeming to share common ecological niches and the associated  
811 locomotor requirements. This sporadic occurrence in marsupials and stem mammals contrasts  
812 with its near universality and evolutionary stability in the Eutheria as noted above.

813 The exact number of independent origins of a bony patella among mammals remains unclear, but  
814 we have estimated at least four convergent episodes inside Mammaliaformes, and several  
815 instances of patellar “loss” (with apparent re-gain in some marsupials). The pattern of acquisition

816 and loss will require revisiting as new fossil material is discovered, as our evolutionary  
817 reconstructions are dependent on single specimens for many ancient taxa. Moreover, patellar  
818 status has not been verified for all >5,000 eutherian and >330 metatherian species (Wilson &  
819 Reeder 2005), so it is possible that additional placental species (other than the fully aquatic  
820 forms) may be found lacking, or marsupials having, a bony patella. A recent evolutionary study  
821 documented many apparently independent evolutionary origins of the caecal appendix in  
822 mammals; thus the convergent evolution of unusual anatomical structures like the osseous patella  
823 has precedent (Smith et al. 2013). Similarly, blue coloration among tarantula spiders apparently  
824 involved at least eight independent evolutionary acquisitions, among different microscopic  
825 anatomical structures affecting spectral reflectance and hence general external colour (Hsiung et  
826 al. 2015). A better understanding of the genomic signatures required for development of such  
827 novel structures should be very helpful to deconstruct the observed complex patterns of  
828 evolution, distinguishing between convergent evolution (homoplasy) and shared inheritance  
829 (synapomorphy/homology).

830 Given that the patella evolved, and was also lost, multiple times in mammals and other Tetrapoda  
831 (Fig. 3), one thing is clear. Much as we have referred to “the patella” throughout this study, there  
832 is no such thing—perhaps not even a single “mammalian patella”. The story of patellar evolution  
833 is one of many (bony) patellae; a story of diverse evolutionary origins as well as forms, functions,  
834 ontogenies and perhaps even diverse underlying genetics. Mottershead (1988) wondered if the  
835 patella is “not typical of its kind” for a sesamoid bone (Mottershead 1988). Yet even patellae are  
836 not necessarily typical for patellae, let alone other sesamoids-- there are double or fatty patellae  
837 in some birds (Regnault et al. 2014), proximal suprapatellae and/or fibrocartilaginous patelloids  
838 in many marsupials, no ossified (or even other forms of) patellae in many species, and even  
839 amongst those animals that have patellae, there are numerous shapes and sizes of patellae (Figs.  
840 4,S1-S3), suggesting still-unappreciated lifestyle constraints in patellar (and knee joint)  
841 mechanics.

842 While we have provisionally used the terms “patelloid” and “suprapatella” for non-ossified  
843 tissues near where the patella is or might be found, the validity of these terms needs further  
844 inspection in a broader context. Certainly, patellae exist in non-ossified forms in younger animals  
845 before endochondral ossification completes, and where such ossification does not initiate at all  
846 during ontogeny it may be best to apply the term “patella” to such tissues rather than invoke new  
847 terms for the same organ that simply underwent different tissue development; as above, a case of  
848 divergent character state transformation rather than distinct characters (i.e. new organs). This is  
849 not simply a semantic issue as the implications for evolutionary novelty, adaptation and “evo-  
850 devo” of patella-like structures will depend on the decisions made about homology of these traits  
851 in organisms, and how those decisions are communicated by the choice of anatomical  
852 terminology.

### 853 *Future prospects*

854 Our discussion of patellar evolution in Mammalia has identified several areas where key  
855 questions remain unresolved, in addition to uncertainties about the amount of  
856 convergence/parallel evolution in origins of the osseous patella and about specific roles of (and  
857 interactions between) genetic/developmental factors in bony patellar formation/loss. Considering  
858 that mechanical loads are known to play an important role in the development of sesamoid bones  
859 (in particular in early ontogeny), studies linking these loads to genetic/developmental control as  
860 well as broad evolutionary patterns could prove very insightful, especially in explaining the  
861 seemingly large amount of patellar homoplasy in mammalian evolution. Mammals may be less

862 sensitive (i.e. more genetically assimilated (e.g. Vickaryous & Olson 2007)) than birds in terms  
863 of the relative influence of mechanical loads on bone (including sesamoid) ontogeny (Nowlan et  
864 al. 2010b) -- this idea deserves better testing as insight into load-based influences improves.  
865 Furthermore, indications that some bones within an organism may be more responsive to their  
866 loading regime (Nowlan et al. 2010a) may be of great relevance to interpreting patellar biology  
867 and evolution, but at present strong inferences cannot be drawn about how variable the patella's  
868 responsiveness to mechanics is within or among organisms. There is clearly much room for  
869 further study of the patellae of mammals and other tetrapods, and here we have noted directions  
870 in which these might most beneficially be directed.

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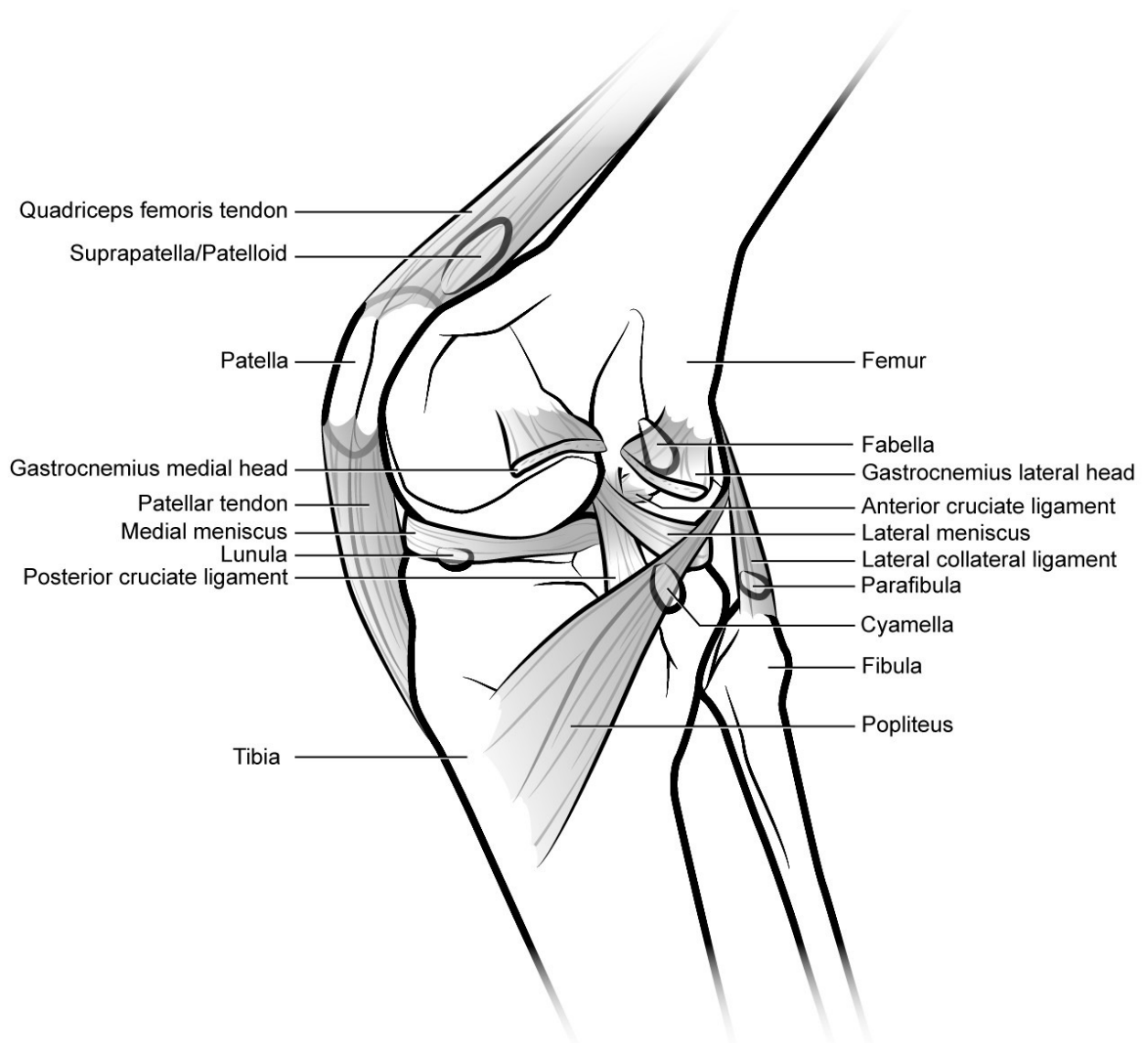
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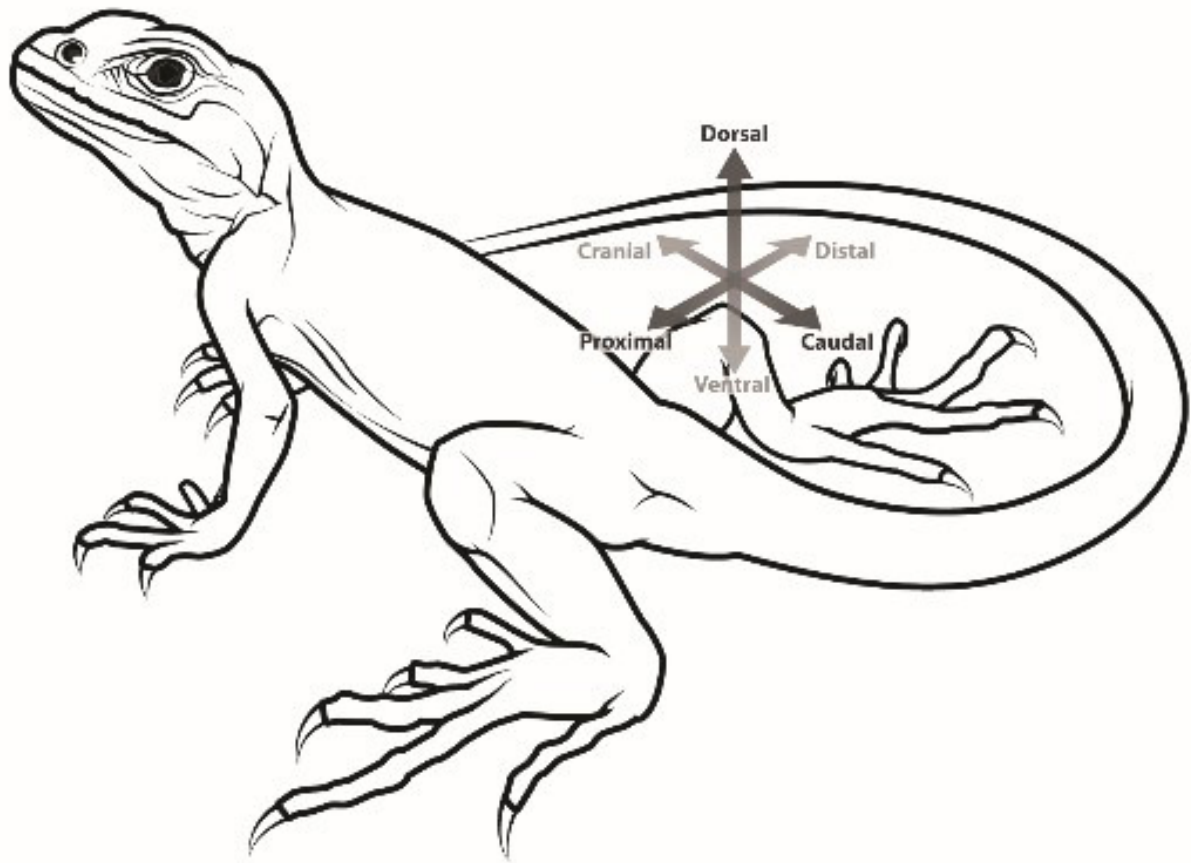
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## 1459 FIGURES

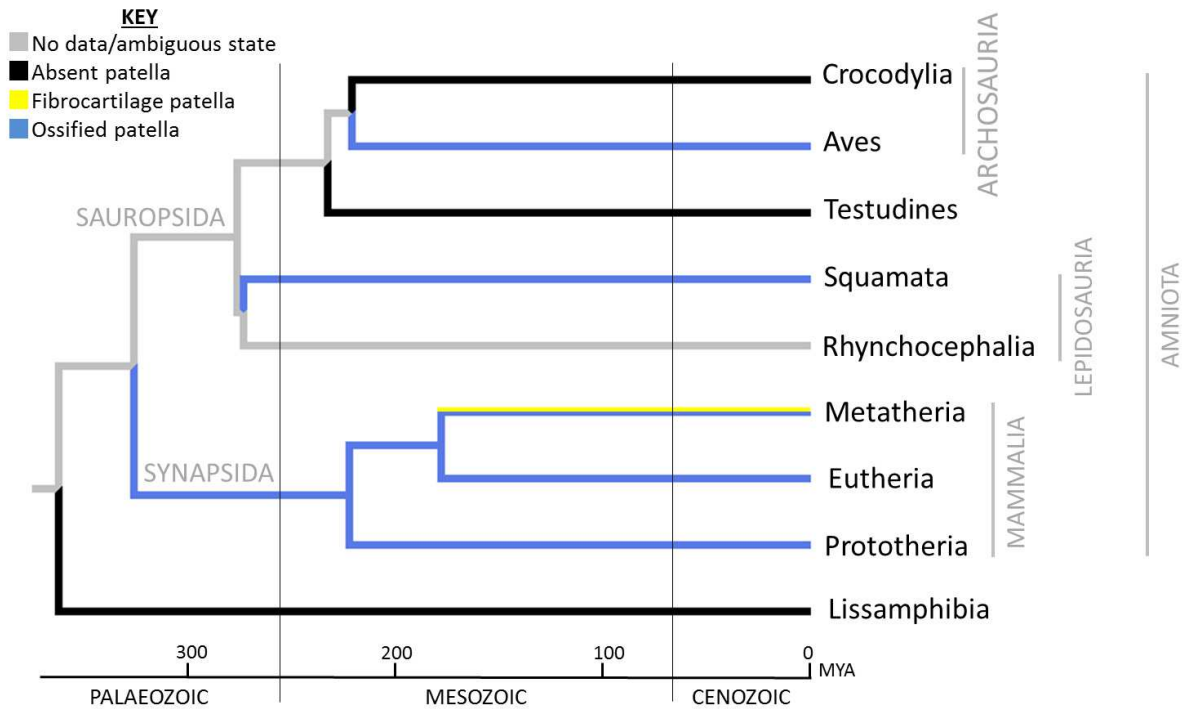
1460 Figure 1. Generalized knee showing sesamoid bones found in various mammals, although  
 1461 possibly no species includes all of these (patella, lunula, cyamella, fabella and parafibula). Also  
 1462 shown are relevant muscles, ligaments and other anatomical elements that lie close to the  
 1463 sesamoids of the knee joint. The knee is in medial view and the medial collateral ligament has  
 1464 been removed. Illustration: Manuela Bertoni.



1465 Figure 2. Generalized tetrapod with anatomical/developmental axes defined for the hindlimb:  
1466 cranial/caudal (towards the head/tail respectively), proximal/distal (toward/further from the trunk  
1467 respectively), dorsal/ventral (towards the back/belly respectively). Illustration: Manuela Bertoni.



1468 Figure 3. Reconstruction of ancestral patellar states in Tetrapoda, showing the major extant  
 1469 clades. Reconstruction was performed using Mesquite's parsimony algorithm and unordered  
 1470 character states, where 0 (black) = absent patella, 1 (yellow) = soft tissue patella/patelloid, and 2  
 1471 (blue) = ossified patella; see Methods for further details. The distribution of the ossified patella  
 1472 among extant clades has been interpreted as three occasions of independent evolution (in Aves,  
 1473 Squamata, and Mammalia) (Dye, 1987, Haines, 1940), a conclusion strongly reinforced by  
 1474 specific fossil evidence (absence or equivocality of a patella in all outgroups). Reconstruction  
 1475 within Mammalia is explored in more depth in Figures 5-7. MYA= millions of years from  
 1476 present.



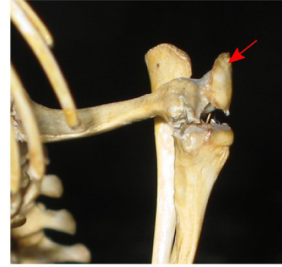
1477 Figure 4. Examples of tetrapods with or without patellae. Red arrows denote the patella. A, B.  
1478 *Ornithorhynchus anatinus* (Monotremata: duck-billed platypus, Redpath Museum specimen  
1479 2458). C, D. *Tachyglossus aculeatus* (Monotremata: echidna, Redpath Museum specimen 2463).  
1480 E, F. *Didelphis virginiana* (Metatheria: North American opossum, Redpath Museum specimen  
1481 5019). G, H. *Procavia capensis* (Eutheria: Afrotheria: Cape hyrax, uncatalogued Horniman  
1482 Museum specimen, London, United Kingdom). I, knee of patient with Meier-Gorlin Syndrome  
1483 (Guernsey et al. 2010). For more images of mammalian patellae (or lack thereof in some  
1484 marsupials), see Figures S1-S3.



A



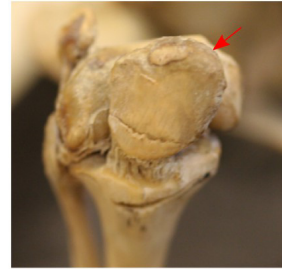
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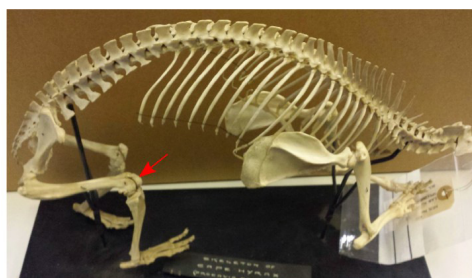
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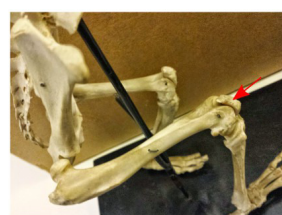
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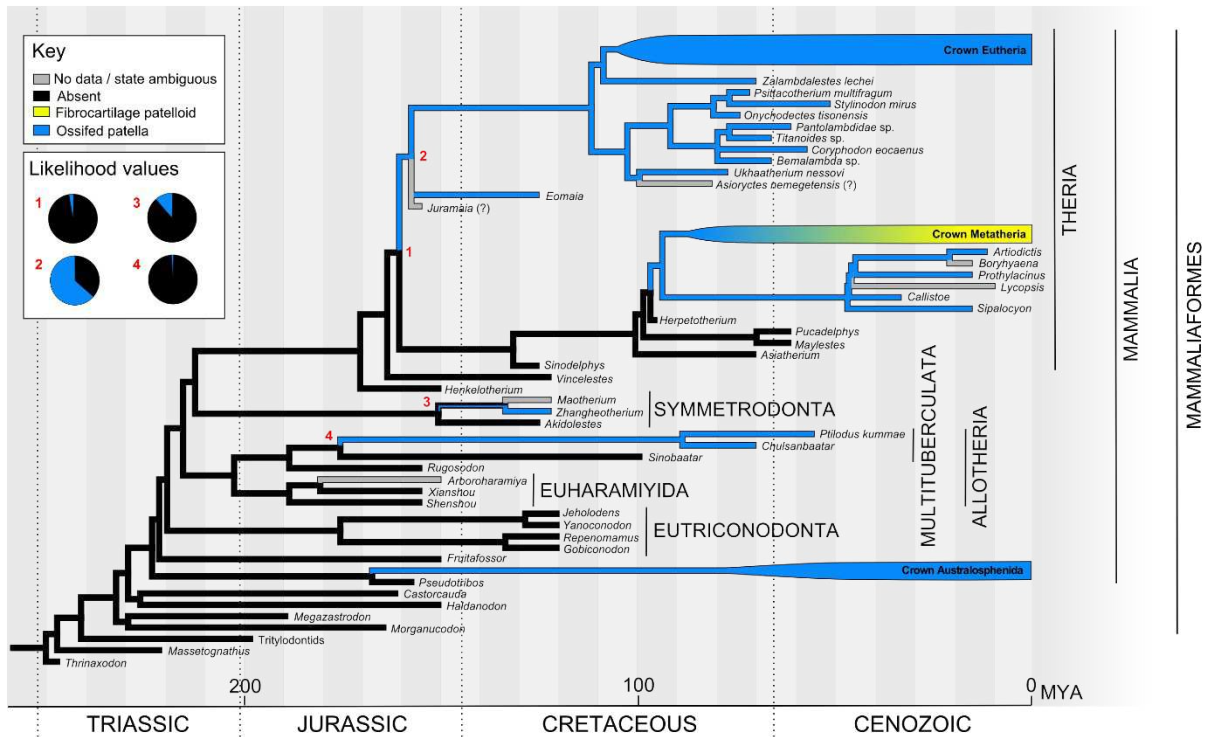
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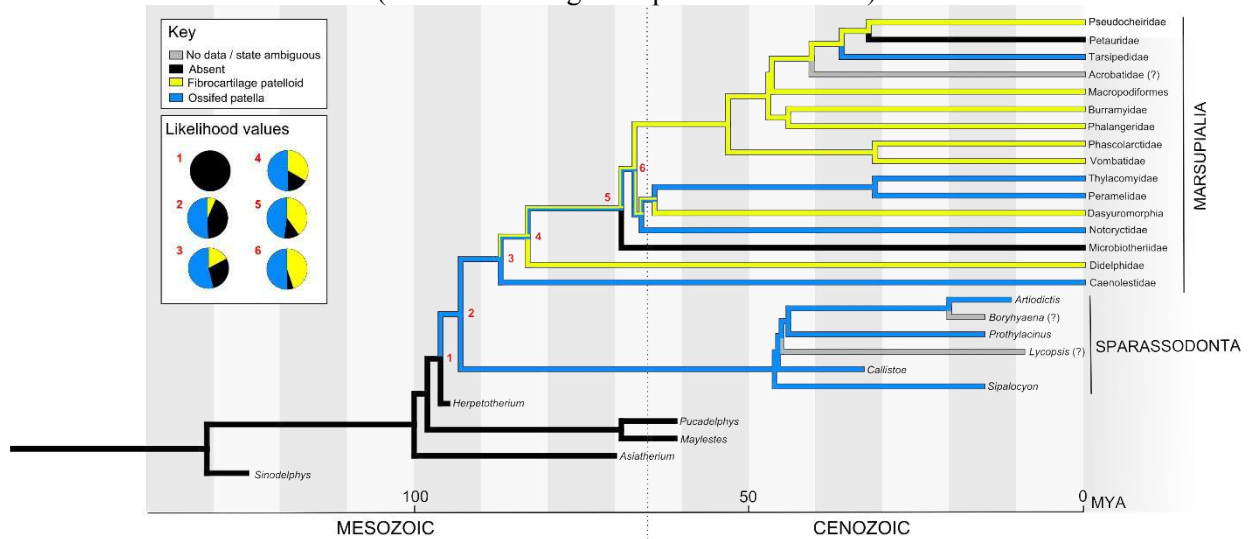
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1485 Figure 5. Ancestral state reconstruction of the patella in Mesozoic mammals (see Fig. S4 for alternative  
 1486 tree topology). Key fossils with hindlimb material are denoted by †. The main tree shows a parsimony  
 1487 reconstruction using unordered character states, where branch colour indicates reconstructed state.  
 1488 Maximum likelihood gives similar results to parsimony, and likelihood values for numbered nodes are  
 1489 displayed (inset). Crown Metatheria and Eutheria are further explored in Figs. 6 and 7. Our results suggest  
 1490 that the ossified patella has evolved at least five times within Mammaliaformes.



1491 Figure 6. Ancestral state reconstruction of the patella in Metatheria and related taxa. Key fossils with  
 1492 hindlimb material are denoted by †. The main tree shows a parsimony reconstruction using unordered  
 1493 character states, where branch colour indicates reconstructed state. Likelihood values for the numbered  
 1494 nodes are shown (inset). Our results suggest that the ossified patella evolved once in Metatheria, with  
 1495 instances of loss and reversion (to a fibrocartilaginous patelloid and back).



1496 Figure 7. Ancestral state reconstruction of the patella in Eutheria. Key fossils with hindlimb material are  
1497 denoted by †. The main tree shows a parsimony reconstruction using unordered character states, where  
1498 branch colour indicates the reconstructed state. Our results suggest that the ossified patella evolved only  
1499 once within Eutheria and (as far as is currently known) has only been lost by the bat genus *Pteropus* (not  
1500 counting groups which have lost hindlimbs; e.g. *Trichechus manatus*/crown Sirenia, *Tursiops*  
1501 *truncatus*/crown Cetacea).

