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Dance of the Cave Bear: Honouring the Scientific Legacy of Björn Kurtén

Methods of preparing palaeontological display models: three case studies

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Life reconstructions are a popular way for natural history museums to inspire and educate the public about the prehistoric world. Palaeontological display models combine the results of scientific research and apply this knowledge to a three-dimensional piece. No single model-making technique is optimal for all palaeontological subjects. We compare here traditional taxidermy techniques, sculpting with polymer clay, and 3D printing with resin or a filament printer to produce animal reconstructions. Using four extinct animals, the Eurasian cave lion (*Panthera spelaea*), a theropod dinosaur (*Carnotaurus sastrei*), a lobe-finned fish (*Gyroptychius*) and a sea scorpion (*Eurypterus remipes*) as examples, we study the advantages and limitations of each method and document the process of translating the results of palaeontological studies into accurate scientific models.

Introduction

Scientific reconstructions aiming to capture the appearance and behaviour of prehistoric animals are among the most popular museum exhibits and an important component in communicating scientific ideas to the public. They can inspire future generations of scientists and new avenues of research, and sometimes they can be directly used to test scientific hypotheses (Vinther *et al.* 2016, Peterman *et al.* 2019).

Life reconstructions of extinct organisms consistent with palaeontological evidence are known as palaeoart (Witton *et al.* 2014, Witton 2018). As covering the whole field of palaeoart is beyond the scope of this paper, we focus here on three-dimensional models and sculptures of animals. Such reconstructions can be life-size, scale models, or partial figures (e.g. Hangay & Dingley 1986, Debus & Debus 2002). Recreations and reconstructions are figures made without any natural parts from the species portrayed (https://www.taxidermy.net/wtc/rules-and-regulations/), which is almost always the case with prehistoric animals (though for mounting the skin of a mummified Alaskan steppe bison with conventional taxidermy techniques *see* Guthrie 1990). Extinct species are usually known from the incomplete fossilised or subfossil remains of hard body parts, as well as coprolites and tracks. A substantial amount of background work, preferably in cooperation with experts, is necessary to produce rigorous life reconstructions (Paul 1987, Paul & Chase 2003, Antón & Sánchez 2004, Witton 2018).

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Few publications cover the whole process of making palaeontological models. Technical papers on palaeoreconstructions typically discuss the theoretical background of the process (Bryant & Seymour 1990, Witmer 1995, Antón *et al.* 1998, Titov *et al.* 2021) or treat the process at a general level (Paul 1987, Antón 2003, Paul & Chase 2003, Antón & Sánchez 2004, Witton 2018). The existing literature on natural history techniques focuses on the practical side of modelmaking, either demonstrating a specific method (Hangay & Dingley 1986, Munns 1993a, 1993b, 1993d, 1993e, 1994, Cooper 1994) or documenting a specific project (Jones 1993, Munns 1992, 1995, Lucas 2007a, 2007b, Walker 2007, Luke 2011), yet often overlooks the scientific background to it (though *see* Franzen 2021). The construction of a three-dimensional model of a prehistoric animal is a process that requires both theoretical knowledge of the organism's anatomy and practical skills in manufacturing the piece. Perhaps due to the dualistic nature of the process, the existing literature rarely documents the interaction between palaeontological research and hands-on modelmaking. The limited number of articles on modelmaking is unfortunate both for museum technicians creating palaeontological reconstructions as well as scholars interested in the history of palaeoarts. At worst, entire techniques of producing natural history models may be lost due to secrecy and must be reverse engineered later (e.g. Leopold and Rudolf Blaschka, glass artisans famous for their contemporary botanical and invertebrate animal models, *see* van Giffen & Astrid 2017).

Recreating extinct animals in a highly conservative manner has been the norm for a long time, but increasingly scholars criticise the methodology (e.g. Conway *et al.* 2012). However, while portraying speculative anatomy, details or behaviour in reconstructions is possible, they should be deduced from palaeontological or phylogenetic evidence and remain biologically credible (Bryant & Russell 1992, Witton *et al.* 2014). Museum exhibitions are a place where the main engagement should be a pedagogical one. Scientific models in a natural history museum should be held up to the same high standards as the whole institution when disseminating information. Good reconstructions may create highly recognisable, even iconic, portrayals of prehistoric life. The same is unfortunately true for faulty reconstructions: physical models can promote inaccurate, outdated or fringe ideas long after they have been discarded by most in the scientific community (Munns 1993c, Naish 2012).

In Finland, the fossil record is quite scarce and very few original fossils are available for public display. Thus, Finnish palaeontological displays benefit greatly from the addition of scientific models and reconstructions. One of the earliest examples of a palaeontological life reconstruction at the Finnish Museum of Natural History LUOMUS (FMNH) is the melanistic scimitar-toothed cat (*Homotherium serum*; *see* Fig. 1). Chief Taxidermist Eirik Granqvist created it in 1984–1985, under the supervision of Professor of Palaeontology Björn Kurtén (Kurtén 1984, Anonymous 1985). This model was inspired by the titular beast in Kurtén's 1978 palaeofictious novel *Den svarta tigern* (literally 'The Black Tiger', the title of the 1980 English translation being 'Dance of the Tiger') (M. Fortelius pers. comm.), and it is still on display. New reconstructions have later been added in the Finnish Museum of Natural History's exhibitions at several stages, notably during the opening of the two permanent exhibitions, the renewed *History of Life* in 2008 (Hiisivuori 2009) and *Change is in the Air* in 2016.

Here, we present three case studies on creating accurate and lifelike reconstructions of prehistoric animals.

Ari Puolakoski: Eurasian cave lion life-size reconstruction

Many consider large mammals the pinnacle of taxidermy (e.g. Hangay & Dingley 1985), and the same challenges are certainly present and even accentuated when reconstructing them (e.g. von Kleinschmidt 1951, Walker 2007, Franzen 2021). Here, I describe the process of reconstructing a Eurasian cave lion or steppe lion (*Panthera spelaea*). It should be noted that the taxonomic status of cave lions is a controversial subject. Some authors treat the different Pleistocene forms as subspecies of the modern lion (e.g. Turner 1984, Kurtén 1985), whereas others suggest that the differences between various lion taxa are sufficiently great to justify species-level distinctions (e.g. Sotnikova & Nikolskiy 2006, Barnett *et al.* 2016). Some researchers even consider it a tiger rather than a species of lion (Groiss 1996).

While Eurasian cave lions of the Middle Pleistocene period were significantly larger than their contemporary relatives, the size of Late Pleistocene animals matches quite well the overall dimensions of a full-grown modern lion (Marciszak *et al.* 2014). The skin used in this piece came from a deceased zoo specimen of a male Asian lion (*Panthera leo persica*). The animal was a typical representative of the subspecies, with a weight of 190 kg, a body length of 174 cm and a tail length of 93 cm. The animal previously resided in Korkeasaari Zoo, Helsinki, in a moderately cold climate, and it acclimatised by growing a long and thick winter coat, making it ideal for the recreation of a Pleistocene Eurasian cave lion. Moreover, since the animal was a zoo specimen, its skin was not as valuable as a scientific material as a wild individual's, and using it for reconstruction was considered appropriate. I preserved the skin in the standard fashion: pickled with formic acid, shaved to a thickness of 1–3 mm, tanned with Novaltan AG (Zschimmer & Schwarz Chemie GmbH, Germany) and insect-proofed with Eulan SPA 01 (Tanatex chemicals BV, Netherlands).

I planned the reconstruction as part of a diorama: a lion hunting wild reindeer. I studied reference photos and video footage of modern African lions running to best encapsulate the animal in motion. I then made the artificial body, the manikin, in several sections. I carved the body and the tail out of a block of polyurethane, while I modelled the limbs and the head on top of a skeletal frame. I roughly cleaned the original limb bones, strengthened with wire, and used them as the armature while sculpting the soft tissues of limbs. I modelled the muscles and arteries using custom-made modelling clay and cast them in rigid polyurethane foam. Compared to modern lions, Eurasian cave lions had slightly shorter legs, especially the most distal segments, the zeugopodium and autopodium (M. Antón, pers. comm.), and so I modified the polyurethane casts accordingly (Fig. 2). For the front limbs, I chose to extend the upper arm instead of shortening the distal elements to achieve the correct proportions and to attain the front-heavy appearance of Eurasian cave lions. I cut the cast in sections, poured polyurethane foam between them and refined the surface. For the hind limbs, I shortened the metatarsals instead. Note that the thinned and tanned skin of a large animal can be stretched a few centimetres, even in the limbs; larger deviations from the measurements of the original animal may require a different approach.

Fig. 1. Model of the melanistic Scimitar-toothed cat (*Homotherium serum*), photographed during the construction of the original *History of Life* exhibition; the skin of a modern lion, dyed black, was used to create this piece (photo: P. Palmgren, archives of FMNH).

The head of the animal is the natural focal point for the viewer, and thus, the most important single part of the reconstruction. The cranial characteristics of cave lions differ notably from those of modern lions (Sotnikova & Nikolskiy 2006). Of the several possible deviations in the proportions of the skulls of the two animals, the most important regarding the life reconstruction must be the ones associated with housing the larger and more powerful jaw-closing muscles of the Eurasian cave lion as well as the more rounded top profile of the cave lion's skull. I acquired a replica skull of a Eurasian cave lion that was the size of the original lion skull from Bone Clones Inc. (the original skull is in the collections of the Babiarz Institute of Paleontological Studies, USA). I modelled the soft tissues of the head on top of this skull with the oil-based modelling clay Roma Plastilina (Chavant Clay, United States; Fig. 3) and cast the head of the

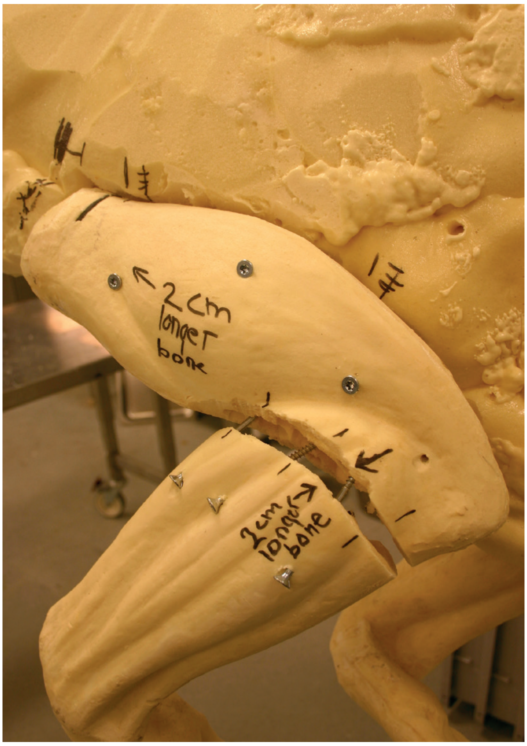

Fig. 2. The left front limb of the manikin is modified to match the dimensions of an Eurasian cave lion: the original cast was cut in sections and the space between them filled with polyurethane foam to increase the length of the limb segments (photo: Ari Puolakoski).

manikin in polyurethane foam just like the limbs. I fine-tuned details of the nose and other anatomical minutiae using a death mask of a modern lion as a reference.

The existing literature discusses the similarities and differences between Eurasian cave lions and modern lions in detail (e.g. Yamaguchi *et al.* 2004). An especially interesting detail regarding the life appearance of male animals is the question of whether they had a mane, as most populations of modern lions do have one. In the case of the cave lion, contemporary eyewitness depictions of the animal in the form of cave paintings serve as an important source of information. Cave paintings, for example those in Chauvet Cave, France, depict obviously male animals without visible manes (L. Werdelin pers. comm., M. Antón pers. comm.). Thus, I decided to reconstruct the animal without a long mane. After mounting the skin, I mostly shaved the mane, yet left tufts of long hair in places to retain natural variation in the hair length. Finally, I added faint patterns to the pelt with an airbrush and diluted acrylic paint (Fig. 4).

Vili Koskinen: *Carnotaurus sastrei* scale-model bust

Gigantic, exotic or even alien-looking, dinosaurs always fascinate the public. The popularity of dinosaurs is evident also in museum reconstructions. In this section, I describe the techniques employed in sculpting a carnivorous dinosaur, *Carnotaurus sastrei*, using polymer clay. *Carnotaurus* is an exceptionally well-known dinosaur due to a remarkably preserved fossilised speci-

Fig. 3. Soft tissues of the head modelled on top of the replica skull. The skull (brown parts) is partially visible among the modelling clay (photo: Ari Puolakoski).

Fig. 4. Finished Eurasian cave lion reconstruction in the diorama (photo: Salla Mehtälä).

men, revealing detailed imprints of the animal's scaly skin. Studies of the *Carnotaurus* fossil and details of the skin impressions (Paul 1988, Bonaparte 1990, Hendrickx & Bell 2021), as well as the general anatomy of the animal (Bonaparte 1985, Paul 1988: 284, Snively & Russel 2007, Mendez 2014, Hendrickx & Bell 2021), make it easy to produce relatively accurate reconstructions of this dinosaur species. Recognizable by its distinctive blunt snout and frontal horns, *Carnotaurus* tends to feature prominently in popular culture, though often with significant amounts of artistic license.

To accommodate the heat-setting requirements of polymer clay and the size limitations of the electric oven, I created a 1:4 scale bust, focusing solely on the head and neck of the animal. *Carnotaurus* was a large animal, eight metres long from head to tail with a skull 69 cm long (Paul 1988, 2010). At a 1:4 scale size, the bust is approximately 300 mm in length from the snout to the terminal end of the neck and 60 mm wide at the base of the neck.

A high-quality skeletal reconstruction done by Paul (2010: 82) was the natural starting point for the reconstruction. Prints of the animal's head and neck in a lateral and dorsal view served as a basis for crafting a silhouette using plywood and wire. I then filled in the silhouette with crumpled, food-grade aluminium foil, affixed with a hot glue gun (Kreator tools VARO, Belgium; Fig. 5).

Around this framework, I then shaped the animal's skull and musculature using the heat-curing polymer clay Super Sculpey (Polyform Products, USA). I consulted technical literature on predatory dinosaur musculature as well as oral and nasal tissues (Paul 1987, 1988: 90,

Fig. 5. Proportionally accurate armature of *Carnotaurus sastrei*, made from plywood, iron wire and aluminium foil (photo: Vili Koskinen).

Fig. 6. Sculpting process was carried out adding small pieces of coloured polymer clay to achieve a mottled appearance. Individual scales were later carved onto partially cured clay (photo: Vili Koskinen).

2010: 25, Witmer 2001, Sampson & Witmer 2007, Snively & Russell 2007, Mendez 2014, Delcourt 2018, Cullen *et al.* 2023) before the sculpting process. I cured the sculpted model in an electric oven at 130 °C for 15 minutes.

For the model's gums, nostrils, lips and jaw muscles, I used the translucent polymer clay FIMO (Staedtler, Canada), tinted with pink-coloured powder from the artist's pastels (Conte à Paris, United Kingdom). This approach resulted in a light-absorbing, organic appearance for the soft tissues because the colour pigments were within the modelling material. I individually sculpted the teeth from the same translucent polymer clay, tinted with white pastel powder. I attached the teeth to the model's gums using quick-drying cyanoacrylate glue.

I cast 50 mm resin eyes (Stamperia International, Hungary) using Silcolan NV silicone moulds (Creartec, Germany). I coloured the irises with acrylic paints (Amsterdam Acrylic, Netherlands) and set the eyes in place using polymer clay, ensuring symmetry with the help of a mirror. I based the size and shape of the eyes on a study of theropod dinosaur orbits (Chure 2000).

To achieve an organic appearance with the skin of the animal, I sculpted it with coloured polymer clay, mixing various shades of brown. I covered the head and neck with small, 5 mm × 5 mm pieces of clay, creating a brown mosaic. I achieved a counter-shaded and mottled appearance by applying darker shades of clay to the top and concentrating it in certain desired areas (Vinther *et al.* 2016, Brown *et al.* 2017, Witton 2018).

I applied clay in small lumps to create skin folds and vertical wrinkles (Paul 2010: 32, Hendrickx & Bell 2021) in the neck, throat region and under the jaw and sculpted a keratin covering for the horns and a rough keratin texture on the nasal area, as described by Sampson and Witmer (2007) and Delcourt (2018). I smoothed the clay skin with isopropyl alcohol and a soft brush to eliminate fingerprints and unintended rough spots.

I cured the polymer clay sculpture briefly in the oven, for approximately one minute at 130 °C, to harden the outer surface and carved individual scales into the partially hardened clay with needle-like sculpting tools, following the descriptions by Hendrickx and Bell (2021). I chose to create the scales individually instead of using rubber stamps with a scale texture, as the pattern created with stamps tends to become repetitive and unrealistic (Fig. 6). After the scales were ready, I brushed them thoroughly to smooth the edges of the individual scales and clean them of any polymer clay crumbles. Lastly, I baked the sculpture in an electric oven for seven minutes at 130 °C to cure the clay completely.

To finalise the model, I applied a water-diluted acrylic lacquer mixed with 10% acrylic-coloured burnt umber (Amsterdam Acrylics, Netherlands). I applied the mixture with a brush to highlight the darker areas, using the colouration of a Komodo dragon's (*Varanus komodoensis*) scales as a reference for a realistic tone and shine. For added realism, I brushed powdered clay (Kerasil, Finland) onto the top area of the model, wiping excess clay off with a moist cloth. In this way, a small amount of clay remained between the scales, creating the illusion of accumulated dirt (Fig. 7).

Fig. 7. Bust of *Carnotaurus sastrei*, which was finished with a thin layer of clay powder, giving the impression of a large animal that had been exposed to dirt and elements (photo: Vili Koskinen).

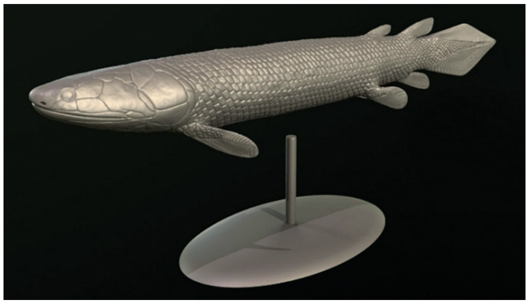

Fig. 8. Digital model of *Gyropthychius*, including the stand (not printed) (model by Elena Egorova).

Janne Granroth: 3D printing of mid-sized aquatic animals

Natural history museums relatively recently added 3D printing technology to their repertoire of ways in which they produce display specimens (e.g. Illek *et al.* 2022, Pereszlényi & Müller 2023). At the Finnish Museum of Natural History, 3D printing technology has previously been used to replace elements that were missing from skeletons of Recent animals, e.g. Javan tiger (*Panthera tigris sondaica*) claws (skeleton in Heino *et al.* 2018) or Javan rhinoceros (*Rhinoceros sondaicus*) teeth. An equivalent structure from the other side of the animal was scanned with a Planmeca PlanScan Lab structured light scanner, the resulting digital surface model mirrored and replicas printed at a commercial 3D printing service (Shapeways).

While fossils can be scanned (*see*, e.g. Morphosource, https://www.morphosource.org/ or DigitalMorphology, https://digimorph.org/index.phtml) and printed, life reconstructions require either a combination of traditional sculpting and scanning or the use of design software. I used models available at commercial online platforms and chose 3D models designed by Elena Egorova for printing (Fig. 8). I chose two aquatic animals, a sea scorpion (*Eurypterus remipes*), printed 19.5 cm in length, and a lobe-finned fish (*Gyroptychius*), printed 25.5 cm in length, for life-size reconstructions. Animals with exoskeletons or with naked or scaly integuments lend themselves quite well to 3D printing. *Eurypterus remipes* is remarkably well known for a Palaeozoic animal (Kjellesvig-Waering 1958, Andrews *et al.* 1974). The exterior surface of eurypterids was covered by a chitinous exoskeleton that is often well-preserved in fossils, some even retaining their three-dimensional shape (Copeland & Bolton 1985). Scientists' view about the life appearance of *Gyroptychius* has evolved during the years (Newman 2010). Our model is most likely based on the reconstruction by Jarvik (1948) rather than earlier work done by Pander (1860), Traquair (1895) or Watson (1935).

I printed the reconstruction of *Eurypterus* using a personal desktop filament printer (Original Prusa MINI+) and a PLA filament. While filament printing is widely available and scales well for printing even relatively large objects, conspicuous layer lines make this technique less suitable for scientific models (Fig. 9). These horizontal ridges are not part of the model; they are artifacts of the printing process. They can be countered somewhat with a combination of sanding and filling. I treated the *Eurypterus* print with steel wool, a fine-grit sanding block and a special Mr. Surfacer primer (Gunze Sangyo, Japan). However, the process is tedious, the final result may be unsatisfactory and fine details of the model may be lost, forcing the technician to recreate them manually. The paddle-like swimming extremities of the sixth prosomal append-

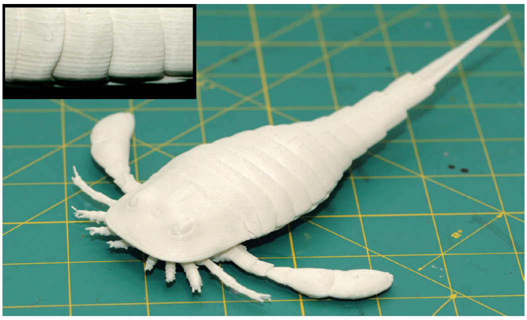

Fig. 9. Printed *Eurypterus* model; the grid of the cutting mat shown is in inches. Insert: closeup of the print lines on the side of the model (photo: Janne Granroth).

Fig. 10. Finished model of *Eurypterus remipes* (photo: Janne Granroth).

age of *Eurypterus* are relatively thin, and I had to sand down the ones in the model post-print to correct the shape.

I outsourced the printing of *Gyroptychius* to Markonator Props, a small Finnish company that operates UV-resin printing units. Resin printers provide excellent print quality; however, the small size of the printer's built plate usually limits the size of the object that can be printed. Many resins are toxic in liquid form, and operating the printer requires good ventilation and personal safety gear. Many of the resin prints are also brittle, and care should be taken when transporting or handling them. The finished print was washed of uncured resin in Isopropyl alcohol and cured in UV-light. The print was hollow and lightweight and required minimal post-print cleaning. I dealt with remains of the scaffold with using a scalpel and brushed faint, fingerprint-like layer lines easily with steel wool. Note that the resin particles may be harmful and a dust extractor or respirator should be used while sanding and polishing the print. I fitted the *Gyroptychius* model with a pair of 4 mm glass eyes (KL Glasauge, Germany). Due to their three-dimensional structure, acrylic or glass eyes are preferable to painted-on eyes.

I airbrushed the finished models with black Vallejo surface primer (Acrylicos Vallejo, Spain) and white ink from above to produce a volumetric sketch on the model. I did most of the painting using acrylic paints (Vallejo, Citadel, Pro Acryl, Wildlife Colours). I airbrushed major blocks of colours with diluted paint and did the detail work with a brush. I also increased the tonal variation and depth of colour by stippling the acrylic paint with sponges and large brushes.

In addition to standard acrylic paint, I also used highly diluted oil paints to colour the models. Oil paints are diluted with mineral spirits and applied with a brush. Before the oil paints had entirely cured (1–24 h after application), I removed some of the paint with a cotton swab or make-up sponge dampened with mineral spirits. This re-activated the paint, and careful swiping left a tinted surface, while some paint remained in the deep crevices of the model. After thoroughly curing them, the oil paints are quite durable and difficult to remove.

Eurypterids belong to the subphylum Chelicerata. Their closest living relatives are horseshoe crabs (Schultz 2007), which are relatively large marine arthropods. *Eurypterus remipes* lived in marine or brackish habitats, similar to its modern relatives. Many of the *Eurypterus* fossils are deep amber brown, which quite possibly was its original colour (Copeland & Bolton 1985). The chosen colour scheme was inspired by the modern horseshoe crab, leaning towards the red end of the spectrum (Fig. 10).

Among the modern close relatives of *Gyroptychius*, scholars have long considered coelacanths (*Latimeria*), a 'window into the past' (McCosker & Lagios 1979). Contemporary coelacanths are, however, specialised deep-water forms (Fricke & Hissmann 2000) and unlikely to be a good analogue to their Devonian relatives. Modern lungfish (class Dipnoi) are adapted to murky, oxygen-deficient, shallow freshwater habitats. *Gyroptychius*, too, was a creature found in lacustrine environments (Dineley & Metcalf

Fig. 11. Finished model of *Gyropthychius* (photo: Janne Granroth).

1999). Ancestral sarcopterygians had heavy, diamond-shaped, cosmoid scales, while those of modern coelacanths and lungfish have thinner, elasmoid scales (Sire *et al.* 2009). Ganoid scales present in some primitive actinopterygians (gars, *Lepisosteus*) and brachiopterygians (bichirs, *Polypterus*) may be better analogues for the integument of *Gyroptychius* (Jarvik 1985). For this reconstruction, I based the colouration and sheen of *Gyroptychius* on the features of lungfish and bichirs (Fig. 11).

Discussion

The three methods described in this paper are applicable to a great many situations and different kinds of animals. Each technique can be used to achieve good results, yet they all have their inherent limitations. Neither polymer clay nor 3D printing is ideal for animals with feathers or hair. These integuments are complex and difficult, if not impossible, to convincingly create from hard materials, while flocking and other types of artificial hair lack the natural structure of a mammalian pelt. Mastery and application of conventional taxidermy techniques can produce some of the finest reconstructions of mammals and birds. For many extinct animals, however, there are no good candidates for a single-piece taxidermy mounting. The woolly mammoth (*Mammuthus primigenius*) and woolly rhinoceros (*Coelodonta antiquitatis*) reconstructions on display at FMNH have been made using pieces of musk oxen (*Ovibos moschatus*) skin obtained from multiple individual animals. The FMNH has also successfully reconstructed the pterosaurs *Dimorphodon macronyx* and *Anhanguera* using artificial fur for the integument. The skins of modern-day birds can be treated with hydrogen peroxide and dyes to alter the appearance of the feathers and make them better suited for creating reconstructions of feathered dinosaurs (D. Speleman pers. comm.).

The polymer-clay method demonstrated with *Carnotaurus* is a low-tech approach especially suitable for reconstructing animals with scaly or naked skin. Ease of use is one of the main advantages of polymer clay; it is readily available in different colours and levels of hardness. Polymer clay sets in high temperatures. Traditional oil- and wax-based clays stay soft and are only suitable for sculpting. They require mould-making and casting to produce a durable finished product. Usually, the final cast is made from either plaster or epoxy resins. With polymer clay, there is no need to make a mould and a cast.

The downside of using polymer clay is the need to evenly temper it with heat to ensure solidity of the finished model. The limiting factor is typically the size of the oven used to temper the model. Reconstructing animals larger than a house cat may require cutting the model into smaller pieces for curing and assembling them together later.

3D printing is relatively fast and inexpensive compared to traditional modelmaking. Excluding printing of the model and the drying times of paint, a high-quality reproduction can be made in 1–2 working days when using a resin printer. The availability of models limits what animals can be recreated with 3D printing; making or commissioning the original file would increase both the cost and duration of the project substantially. However, working together with an expert is highly recommended with existing models, since a detailed and attractive appearance is no guarantee of scientific accuracy. While anatomical errors in a model can be amended either pre- or post-print, making major changes to the model may negate most of the advantages of 3D printing.

3D printing is an excellent way to make reconstructions of small animals, which can be printed in one piece. The cost of 3D printing usually depends on the volume of the piece, providing another incentive to print small animals rather than large ones. Models of small and especially aquatic animals can be printed in clear resin to achieve the transparency natural to, e.g. the fins of fish. One advantage of 3D printing is the ability to produce multiple copies of slightly different size for a diorama instead of just one original or exact copies of a single piece. Slight changes to the model in either the pre- or post-print phase can be used to add variety. 3D printing is also suitable for producing prototypes, which can be moulded and casted in different materials with traditional modelmaking techniques. For in-house printing, the cost of electricity, resin and parts for the printer are rather insignificant. However, the cost of the printer itself, as well as paying the personnel to run, maintain and troubleshoot the printer, may make outsourcing this particular step an attractive alternative. All told, 3D printing is a valuable new method to add to one's toolkit when doing natural history exhibition work.

Regardless of the method used to create the physical model, the animal portrayed must feature a naturalistic colour scheme. Plenty of new research exists on the colouration of fossil animals (Vinther 2015, Roy *et al.* 2020), yet phylogenetic bracketing remains an invaluable tool for determining the colouration of many extinct organisms. For reference purposes, observing and recording a live, dead or preserved specimen is preferable. Signs of wear caused by exposure to elements in nature can greatly enhance the realism of the piece.

Models are sometimes displayed by themselves, but more often together with other exhibition pieces. The Eurasian cave lion diorama, which at the time of writing is on display in the FMNH permanent exhibition *Change is in the Air*, is part of a wider cross-cutting narrative juxtaposing 'winners and losers' of the Pleistocene megafaunal extinction. To emphasise this message, a replica skull of the extinct Eurasian cave lion was included as part of the diorama, covered in snow and visible through the hole in the front panel, while the other animals in the diorama, reindeer, still survive. The in-depth, publicly accessible materials on the diorama include a brief making-of section on the cave lion reconstruction.

Scientific models typically require substantial investment in materials and working hours, and so they are often on display for a very long time. They reflect the knowledge and techniques available at their time of production, but also conscious and subconscious ideas of what to display. Since they are usually not part of the scientific collection, administrators often give reconstructions little more than instrumental value for the public outreach of the institution. Old reconstructions may be seen primarily through the lens of a shortage of storage space (cf. old taxidermy mounts; *see* Morris 2010), ridiculed for their shortcomings and rarely discussed as products of their time (though *see* Naish 2016). Of the animals discussed in this paper, a full-size model of the *Carnotaurus sastrei* was made in the mid-1990s by the sculptor Stephen Czerkas (Czerkas & Czerkas 1997). New studies on the details of the animal's skin (Hendrickx & Bell 2021) make this model somewhat outdated. This is perhaps the fate of every reconstruction: to become outdated and replaced by later, more accurate or technically better ones. Even when models are entirely retired from displays, they remain monuments to the constantly evolving human understanding of the prehistoric world. Without museum-quality reproductions, the very human need to imagine prehistoric animals in life is filled with commercial or amateur depictions at varying degrees of accuracy. Carefully made models stand as ambassadors for the science behind creating them.

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