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Author(s): Larkin, N. R., Dey, S. & Hutchinson, D.

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Mounting the type specimen of *Pliosaurus carpenteri* Benson *et al.*, 2013, an 8m-long fossil pliosaur skeleton, including the 3D-printed 1.8m-long replica of the skull for Bristol Museum & Art Gallery

Nigel R. Larkin[1*], Steven Dey[2] and Deborah Hutchinson[3]

[1]*Natural-History-Conservation.com & Affiliated Researcher, Cambridge University Museum of Zoology, Downing St, Cambridge CB2 3EJ, UK.*

[2]*ThinkSee3D, 10 Swan St, Eynsham, Witney, Oxfordshire, OX29 4HU, UK.*

[3]*Bristol Museum & Art Gallery, Queens Rd, Bristol BS8 1RL, UK.*

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**Corresponding author: nrlarkin00@googlemail.com*

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Abstract

The type specimen of *Pliosaurus carpenteri* Benson *et al*., 2013 from Westbury in Wiltshire, UK, is the most complete skeleton known of this extinct species, with an estimated body length of 8m. The skeleton was mounted for a temporary display at Bristol Museum & Art Gallery in 2017 for the first time since it was excavated in 1994. The fossilised skull is 1.8 m long, very heavy and consists of many very fragile pieces. Mounting the real skull in position would have required a large amount of unsightly supporting metalwork that also would have obscured some very interesting pathology on the palate inside the mouth. One option was to CT scan the individual pieces of the skull and use the subsequent digital models to 3D-print replicas. This method of making a lighter replica skull would present less risk to the specimen than traditional moulding and casting and would be quicker, cheaper and safer for the duration of the exhibition. Importantly, the process would also provide detailed 3D morphological data of the skull's internal anatomy for the first time, which would be invaluable to ongoing research. The pieces of the 3D-printed skull were mounted with internal steel armature and painted to match the real specimen. However, there are many ethical and practical issues to consider when replacing missing bones with replicas, including: making clear to the public what is real and what is not; and using appropriately stable and tested materials where possible.

Keywords: pliosaur, skeleton, display, mounting, CT scanning, 3D printing.

Introduction

The work described below was undertaken for an 8-month temporary family-orientated exhibition 'Pliosaurus! face to face with a Jurassic beast' displayed at Bristol Museum & Art Gallery (BMAG) from 17th June 2017 to the extended date of 18th February 2018. The skeleton (BRSMG Cd6172) that formed a centrepiece of the exhibition is the 'type specimen' of *Pliosaurus carpenteri* Benson *et al.,* 2013, a large pliosaur (marine reptile) skeleton that was found in Lower Kimmeridge Clay sediments at Westbury in Wiltshire in 1994 by Simon Carpenter who donated the material to Bristol Museum (Sassoon *et al*., 2010; Sassoon *et* *al.*, 2012). The specimen is significant not just because it represents a new species, but because it is one of the most complete specimens of its kind known. It is also huge, about 8 m long (Figure 1) with a skull that is nearly 2 m long. Elements preserved include approximately half of the vertebrae, part of the gastralia, fewer than half of the ribs, a selection of phalanges and one shoulder girdle. The taxonomically important areas - the skull and mandible - are complete and many large teeth were found with the skeleton. Other more fragmentary elements of Cd6172 remained in store and did not go on display.

Accompanying the mounted skeleton on display were other fossils including marine reptiles and invertebrate fossils from the Southwest of the UK, showing visitors how fossils are preserved, collected, curated and interpreted. The exhibition included skulls of modern animals (a crocodile, a gharial, a false killer whale and a tiger shark), highlighting how diet affects the shape of teeth, and there was also information about the discovery of the pliosaur skeleton and its excavation.

A life sized, fleshed-out reconstruction of *P. carpenteri* was commissioned for the exhibition from model maker Tony Hitchcock (Figure 2). The model incorporated features and pathologies (based on evidence from the fossil) that were designed to show the specimen as a living individual. The model had moving eyes that tracked visitors as they walked close to her head; a reptilian heartbeat; halitosis; a flipper pathology (complete with pus); and a low rumble when visitors got too close. To generate interest in the project and to give a sense of ownership to the people of Bristol (as the specimen was found less than 30 miles from the museum), members of the public were asked to help choose a name for the specimen. A shortlist of names was drawn up by museum staff for the public to vote on: Brizo (a Greek goddess that was a protector of mariners, sailors and fishermen); Doris (a sea nymph from Greek mythology); Chompy; and Pip. Doris was chosen by the public and the specimen was often referred to as '#DeadlyDoris' on social media and in museum displays, and advertising literature.

The exhibition was divided into three main sections: 'Back to the Jurassic' where visitors were invited to step back in time to Jurassic Bristol; 'Meet the Beast' where visitors came face to face with the life sized reconstruction of Doris and

Figure 1. The fossil skeleton (BRSMG Cd6172) of Pliosaurus carpenteri *Benson* et al.*, 2013 laid out next to Roger Vaughan (1948-2015), the conservator (later curator) who prepared the fossil at BMAG in the back hall at BMAG. Note: only elements composing one limb are preserved - although this is fairly complete – and about half of the vertebrae and fewer than half of the ribs. The taxonomically important areas - the skull and mandible - are complete. Image © Bristol Museum & Art Gallery.*

Figure 2. Visitors appreciating the ability to get up close and personal with the life size fleshed-out model of Pliosaurus carpenteri *Benson* et al.*, 2013 (also known as 'Doris') by model maker Tony Hitchcock. Image credit: NRL.*

were encouraged to investigate her story hands-on; and 'Scintillating Science' where visitors could see the real skeleton on display and learn about Doris and the science behind her story through a series of interactive stations. This included learning about her many pathologies, investigating colour in the fossil record, what was on the menu for Doris and who she was sharing her Jurassic marine world with. Visitors were finally signposted to other areas of the museum and further afield where they could see more fossil material and develop skills and interest. The exhibition attracted over 76,000 visitors.

Materials and methods

Designing the pose and the fossil mount

At the start of the project the conservator and museum staff studied all the bones and teeth of the skeleton in the museum stores to work out the various ways they might be mounted and how the whole skeleton might be displayed in terms of its pose. A structured light scanner was used to record the three dimensional morphology of every bone. From this data a low resolution 3D digital model of each bone was created, and an anatomically accurate virtual skeleton assembled with the support of museum designer Simon Fenn and the palaeontologist Dr Judyth Sassoon, who had originally described the fossil material. This enabled all involved in the project to visualise how the bones of the specimen articulated together, what the different poses would look like on display and, crucially, how much space it would take up (Figure 3). The skeleton is only partially complete and it would have been possible to take more detailed scans of some bones (through CT scanning or photogrammetry) and mirror the data to 3D print missing elements, such as making a complete right forelimb based on the data captured from the complete left forelimb and/or mirroring ribs to make up replicas of some of the missing ones. However, it was decided to keep the specimen as original as possible. This work would have also added substantially to the cost of the project.

Mounting the postcranial material

BMAG created various detailed CAD plans of the skeleton and a method of safely mounting the skeleton was devised by the project's conservator. The steel armature would have to support over 100 kg of fossil bones to millimetre precision, constructed in a fashion that would allow easy assembly and dis-assembly as the mounting work would be undertaken in an offsite conservation studio in Shropshire and the mount and the fossil would need to be transported back to Bristol in sections.

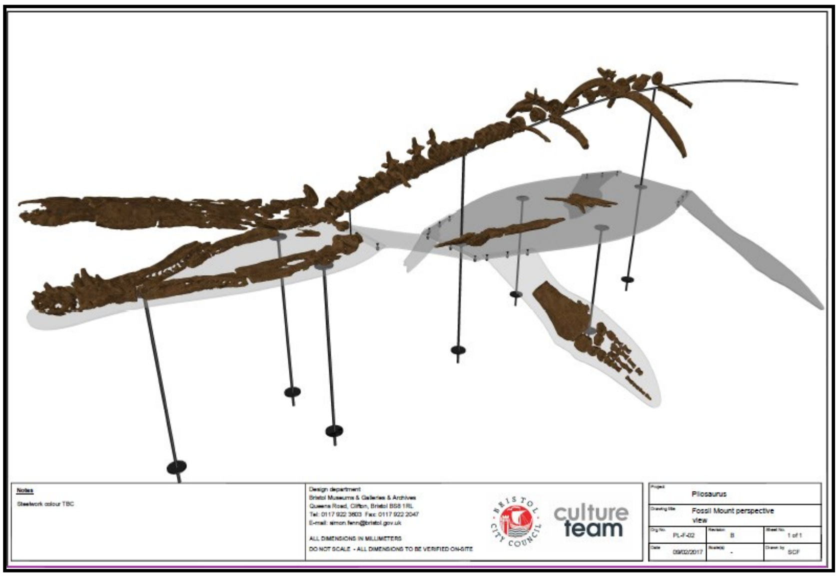

Figure 3. The detailed design using the 3D digital models made from data captured by the structured light scanner scans of the bones, articulated in discussion with the palaeontologist Dr Judyth Sassoon. Image © Bristol Museum & Art Gallery.

A sturdy base (488cm x 122cm) was made for the armature using four sheets of 30 mm thick MDF. These were arranged in two pairs, with several 45mm batons separating the sheets in each pair, screwed together after all the MDF had been sealed with two coats of clear Dacrylate® varnish. Adjustable feet were added to the underside of the base, as the gallery floor of the temporary exhibition space in Bristol was known to be slightly uneven.

The main metal armature (8m long and 2.5m high) required to support all the bones in articulation was made from steel tubes and flat steel strips that were heated and bent to shape according to the CAD drawings and the morphology of the bones. The armature was MIG welded together (Figure 4). The armature had to be made in sections not only so that it could be dismantled and transported to Bristol within a Luton van but so that it could be carried into the exhibition space through the various doors and corridors. The vertebrae of the spine and the various small ribs, gastralia and limb bones were held in place with rods and/or strips of brass shaped to the outline of the bones (Figure 5) and brazed to one another (brazing joins two metals by soldering with an alloy of copper and zinc at a high temperature). Where required, the metalwork was lined with black inert Plastazote® foam (thickness 2mm and 5mm, depending on the weight of the bone) to protect the bones from the metal. The armature for the postcranial material was supported by two upright steel tubes cut to the appropriate height. A floor plate was welded near one end of each which would sit on top of the wooden base but the end of the pole would insert through a hole drilled right through the base, under which it would be secured with nuts and large spring washers (threaded bar had been inserted into the lower end of the tube and welded in place).

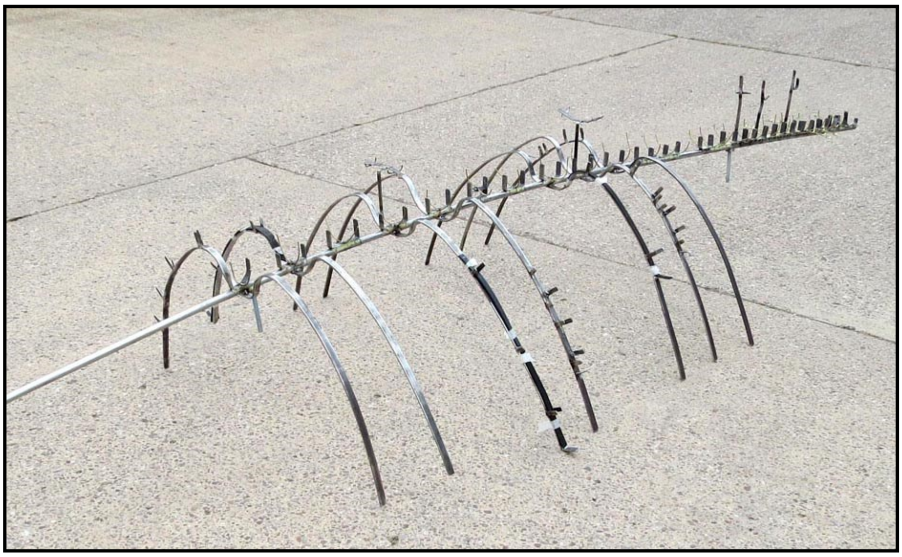

Figure 4. The steel frame made to hold the larger ribs and vertebrae in place, not yet positioned on the upright supports. Image credit: NRL.

Figure 5. Brass strips and rods brazed together to hold smaller ribs in place. Image credit: NRL.

The main sheet of Perspex that had been cut in the outline of the fleshed-out body was held in place in a horizontal aspect by more floor plates that were welded to each of the main uprights at the appropriate height. As the four sheets of Perspex indicating the size and shape of the fleshed-out limbs (Figure 3) were to be securely attached to this main sheet of Perspex that represented the body (using nuts and bolts through pre-drilled holes), further upright supports were needed to hold the horizontal Perspex in place so that it did not sag with the extra weight. These supports and the Perspex sheets themselves added extra rigidity to the whole structure. The gastralia bones were simply laid on the Perspex of the body outline. The composite limb bones were located on a steep slope so brass rods brazed to the brass armature that held the bones in association were inserted through the Perspex through small holes drilled in place (Figure 6). All the metalwork was painted a dark grey colour to the specification of the designer before the black Plastazote® foam was adhered in place as required with double-sided tape.

Mounting the skull and mandible

The skull and mandible of any skeleton are always important. Not only are they usually the most significant part of the animal in terms of identifying the species, but they are the elements people most want to see on display, especially when it is a large predator with large teeth (Figure 7). The skull and mandible of this pliosaur skeleton are particularly well preserved. Both are almost totally complete although dorso-ventrally compressed. There is interesting pathology on the palate of the skull and in the jaw where elements were fractured in life

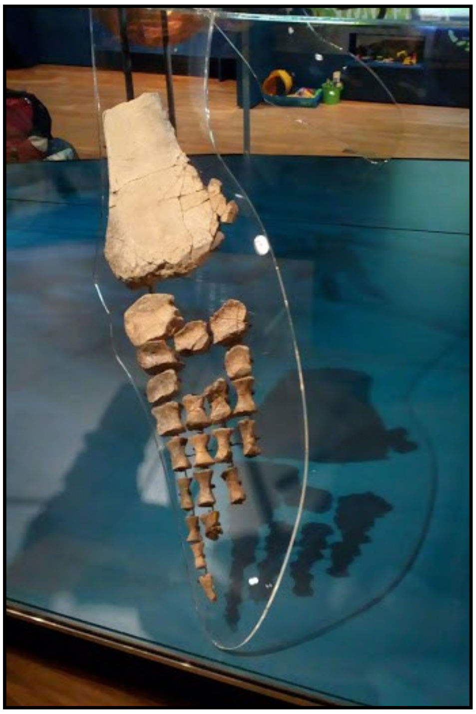

Figure 6. The bones of the composite forelimb held in place with the brass armature on Perspex shaped to the size of the fleshed-out limb. Image credit: NRL.

then healed, plus evidence of overbite tooth depressions from misalignment of the jaw (Sassoon *et al.*, 2010) and a flipper pathology. However, the skull was excavated in about 20 pieces, is about 1.8m long and weighs over 25kg. To have mounted this original material would have required a large amount of intrusive supporting metalwork which would have obscured the interesting pathology, and also have been a risk to the specimen while on display for a significant length of time. Therefore, suitable methods of replicating the skull were explored so that a replica skull with replica teeth could be mounted and articulated with the real mandible and the rest of the skeleton, with the interesting pathology visible for visitors to examine more easily.

A replica skull could have been made by carefully moulding the individual pieces of the original skull to make resin casts but this would not have been without risk. Many of the original skull fragments are quite thin and fragile. They could have been broken during the moulding process. Also, making moulds of a specimen can be invasive due to the consolidants, rubber, water soluble putty and other products that have to be used in the process, so the material can end up adulterated (Goodwin and Chaney, 1994). An alternative solution was to

Figure 7. Three of the large teeth of BRSMG Cd6172 with a (large male) hand for scale. Image credit: NRL

either 3D scan the bones using photogrammetry or to CT scan the bones, then build detailed 3D digital models from either set of data and 3D print the bones in a suitable medium. CT scanning would require the bones to be taken to a suitable facility, involving road transport and therefore some risk to the material. Photogrammetry could have been undertaken on site with less risk involved. However, the bones had to undergo road transport anyway to get to the conservation facility in Shropshire where the mounting was to take place, so suitable sturdy protective bespoke packaging had already been manufactured by the conservator. Despite being such an important specimen, the skull had not yet been CT scanned and therefore CT scanning the skull for this project would provide current and future researchers with an accurate morphological model and data about the internal structure of the specimen for the first time: a lasting legacy for science from the project. For similar reasons, although the mandible did not need to be scanned for replication purposes it was decided that this would be CT scanned at the same time as the skull as there would be no extra cost for scanning this in the same session.

Therefore, both the skull and the mandible were taken to the Royal Veterinary College, London. To minimise any risks involved in the process a risk assessment was undertaken and as a result the project conservator packed and unpacked the bones, transported them carefully and handled them throughout the CT scanning session. It is possible that CT scanning may damage some DNA in museum specimens (Grieshaber *et al.*, 2008), especially if a specimen is scanned multiple times, although some studies have found this is not the case (Hall *et al.*, 2015) and specimens as old as the pliosaur are unlikely to have any DNA within them to damage. Nonetheless, specimen exposure to CT scanning should be minimized - such as scanning it just the once in this case - and all such procedures should be recorded in the museum's specimen database.

A GE LightSpeedPro 16 CT scanner was used to scan the bones at 100 kV and 10 mA in 1.25mm slices (Figure 8). The scan resolution could have been finer but because the material was so dense and there was so much of it, had it been scanned at a higher resolution the scanner would apparently have overheated. However, this resolution still gave superb results partly because there is no matrix on the bones at all and the resolution of the eventual 3D print was more than adequate for display and research purposes.

The output of the CT scans were TIFF image files of large sets of x-ray cross-sectional images through the various skull fragments and mandible. 3D printers require digital 3D mesh surface models as input so the first digital preparation job was

Figure 8. CT scanning the anteriormost tip of the pliosaur skull (BRSMG Cd6172) at the Royal Veterinary College London. Image credit: NRL.

to extract the outer surface from these 2D CT images and convert them into appropriate digital models (Figure 9). The software used to do this conversion was 3DSlicer (version 4). 3DSlicer is an open source CT application designed for human clinical uses but also suitable for animal bone and fossil specimen scans.

Once the 3D surface models were extracted, they were converted into 3D print ready closed hull digital models. The software used in this process was Blender version 2.6, which is a multi-purpose 3D mesh modelling and animation application. The skull fragments were to be reconstructed into a whole skull so to assist in this process some holes were digitally created through the sides of many of the fragments for the insertion of steel supports later. This was done using a Boolean operation to remove cylinders of material from the internal structure. Doing this digitally allowed for accurate placement of these internal structures ensuring they went through the thickest parts of the skull walls and avoiding thinner structures and holes like the teeth sockets. This was not possible on every fragment, however, as some parts were very thin. The 3D printer being used to recreate the bones was an industrial colour jet gypsum 3D printer. Although the replica skull bones could have been 3D printed in full colour it was decided to 3D print them in a base colour and paint the replica skull by hand after it had been assembled on its armature to ensure a good and consistent match with the real material. The 3D print volume in this printer was limited to 38cm x 25cm x 20cm but fortunately all the fragments except one fitted into this volume. The only exception needed to be partially split on a corner and reconnected once 3D printed.

The 20-plus 3D printed pieces of skull (Figure 10) were articulated by adhering the smaller pieces together with Jesmonite acrylic resin which bonds well to the gypsum, and using the lengthwise holes through the thicker pieces for two long thin steel rods that held them all in articulation together. The thinner pieces had channels cut into them with a mixture of angle grinders, chisels and scalpels, in which the steel rods could sit. Any gaps left from this process were filled with Jesmonite acrylic resin bulked out with hollow plastic microspheres to lessen the weight and to make the filler more easily carved and worked. The 3D-printed gypsum was then painted to match the real bone of the skull with artists' acrylic paints (Figures 11, 12 and 13).

The skull itself was quite dorso-ventrally flattened but some of the teeth (preserved separately from the skull during burial) were robust and were not

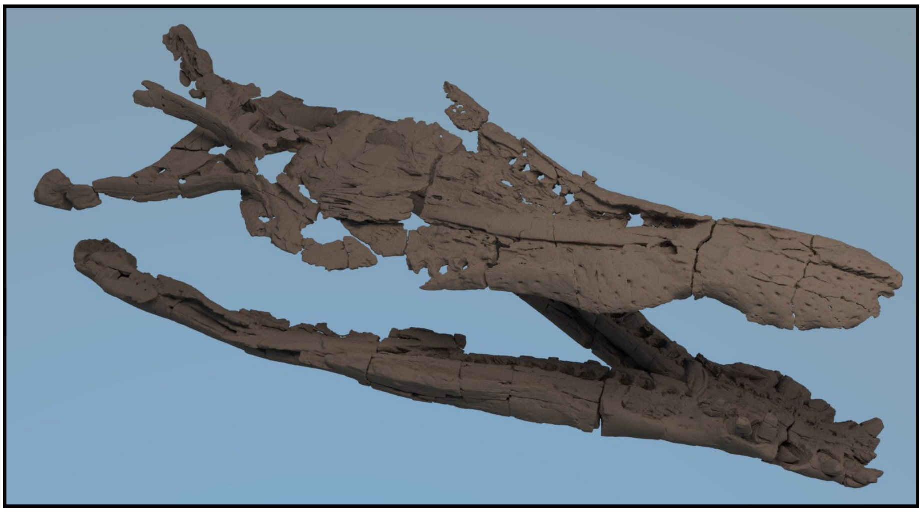

Figure 9. The high-resolution 3D digital model of the skull and mandible of BRSMG Cd6172 generated from the CT scans. Image credit: SD.

Figure 10. All the pieces of the pliosaur skull freshly 3D printed in gypsum at ThinkSee3D (with a single replica tooth placed temporarily in a socket). Image credit: SD.

significantly crushed. These had to be replicated and then the roots of the replicas trimmed so that they could be inserted into the empty tooth sockets of the flattened skull to recreate tooth placement as in life. Because of the way different aspects of the project were funded, and because of timing issues, the teeth were replicated by moulding them and making casts. They are very robust so were unlikely to be damaged during the process, unlike some pieces of the skull, and they were first protected by a reversible layer of consolidant (Paraloid B72 in acetone at 5%). The silicone rubber used for moulding the teeth was Silastic 3481 base cured with 81F catalyst and the replicas were cast in Jesmonite AC100 acrylic resin with woven glass fibre matting then painted to match the original material with artists' acrylic paints. They were adhered in the sockets of the skull with Jesmonite acrylic resin. Extra copies of the teeth, without the rods trimmed off, were made for display purposes and handling sessions.

The heavy, real, sections of the robust mandible were held together with Plastazote®-lined bespoke metal brackets. These were made by heating and bending strips of steel to the shape of the mandible when it was positioned in articulation upside-down, cooling-down the metal first each time before offering it up to the bone to check the shape. The pieces of the mount were welded together away from the fossil material and then the fit was checked. The mandible in its bracket was positioned on the horizontal piece of Perspex shaped to the size of the fleshed-out skull. The painted 3D skull model was mounted above this, with a large enough gap so that all the teeth could be appreciated and the palate seen, but stability of the structure was not compromised. It was held in place with a single upright steel tube within the mouth and two small-steel rods at the rear.

Discussion and conclusions

Aimed at families with children aged 3 to11 years old, the exhibition focused on Bristol Museum's spectacular 8-metre-long holotype fossil *Pliosaurus carpenteri*. Using an imaginative family focused approach, the exhibition took visitors on a journey that brought Doris the pliosaur 'back to life' and engaged them with the history and science behind her story.

CT scanning has been used for decades to image human anatomy. More recently, the technology has aided anatomical descriptions in zoology and palaeontology (Porro *et al.,* 2015) by enabling the digital preparation of small or fragile specimens (Butler *et al*., 2010), the visualization of internal anatomy (Lautenschlager *et al*., 2012), and the capture of morphology for shape and biomechanical analysis (Porro *et al*., 2013). Only recently have the benefits of CT scanning for conservation, exhibitions and education begun to be explored. CT scanning combined with 3D printing, although expensive on a large scale, can be a powerful tool for museums and educators in natural history (Tembe and Siddiqui, 2014). CT data may be used to produce 3D models and animations, such as cut

Figure 11. The 1m long painted 3D printed skull positioned above the real fossil mandible, lying on a Perspex sheet, on display. Image © Bristol Museum & Art Gallery.

Figure 12. The mounted partial skeleton of the 8m-long fossil pliosaur skeleton (BRSMG Cd6172) with the Perspex sheets indicating the 'flesh outline' of the animal. The specimen was displayed behind Perspex panels. Image © Bristol Museum & Art Gallery.

-away sequences, which may be incorporated into museum exhibits and educational settings and provides increased access to rare or delicate material without increasing risk to these specimens (Kuzminsky and Gardiner, 2012; Tembe and Siddiqui, 2014).

However, there are many ethical and practical issues to consider when mixing 3D printed models or other replicas with real specimens. Firstly, the public should be aware of what is replicated and what is real either immediately and obviously as in the case of the Quagga skeleton recently remounted at the Grant Museum of Zoology (Figure 13) whose missing bones were replicated in a matt black colour to differentiate them from the real bones (Larkin and Porro, 2016), or by noting it within the display text or labels as was the case with the display of Cd6172 discussed in this paper. Also, freshly 3D printed materials and resins used for casting can 'off-gas' which could affect nearby specimens. Ideally, the stability and likely longevity of all the materials used would be known but very few 3D printing materials have been tested and the results published. White nylon 3D printed models may "yellow" over time due to oxidation (Martyn Carter and Richard Beckett, University College London, pers. comm.) but most have been in use for such a short time that little is known about their stability. Therefore, the authors are actively testing the stability and longevity of the most commonly used 3D printing materials with colleagues including Gabrielle Flexer in Wiltshire through undertaking Oddy tests (Robinet and Thickett, 2003). In the meantime, when 3D printing replicas for use in museum displays our preferred material is gypsum using water based inks. This is surely the least problematic 3D printing material for long term use in museums as there is a long history of gypsum being used in museums in the form of plaster of paris. Replicas made out of plaster (gypsum) have been used in museums for hundreds of years. Therefore gypsum is a known entity for long term use in museums unlike all other materials currently used in 3D printing. SLA 3D printing (the most commonly used replication process in industry) is entirely different and produces replicas in cynoacrylic, a relatively modern material known to be far less stable and which will off-gas.

This pliosaur display in Bristol was only temporary and the skeleton was not sealed in a display case with the gypsum 3D prints. Also, there were

Figure 13. The UCL Grant Museum of Zoology quagga skeleton LDUCZ-Z581 on display after cleaning, conservation, remounting and installing the 3D printed models of the left hind limb and right scapula. Image courtesy of UCL Grant Museum of Zoology. Image credit: NRL.

several months between 3D printing the skull elements and putting them on display with the real material, allowing off-gassing to take place. However, in other exhibitions real specimens may be mounted with elements that are 3D printed from less benign and placed in display cases with no precise knowledge of how the material will age over time nor how it may affect the specimens around them. Until these materials are proven to be safe, the use 3D printed objects in direct association with real specimens should be minimal, ideally temporary and such products should not be in direct contact with original material nor be enclosed in sealed cabinets with them. All 3D printed materials used for long term projects in museums should be checked regularly (i.e. once a year) for signs of ageing such as change of colour and embrittlement.

Although this exhibition was only temporary, the project required several months of scanning, digital model making, designing, blacksmithing, welding, grinding, brazing, 3D-printing and painting. The steel, brass and Perspex® armature has been kept by BCMAG, as well as the 3D printed skull enabling the specimen to be put on display again relatively easily in the future. The temporary exhibition therefore has a fourfold permanent legacy: many thousands of people will have been inspired by the exhibition containing the massive skeleton and model; funds were raised during the exhibition for the life size model of Doris to be suspended permanently in the rear hall of BCMAG after the temporary display was over where she is mounted today; the 8m-long skeleton could be displayed again in the future with relative ease; and the data from the CT scans of the massive skull and mandible will allow researchers to investigate the internal anatomy of this unique material for the first time.

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