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From bone to pixel—fossil restoration and reconstruction with digital techniques

Fossils represent the only physical evidence for the existence of extinct life, and hold a vast potential to reconstruct organisms and ecosystems vanished a long time ago. Yet fossils are not as complete as they might appear in museum exhibits, documentaries or Hollywood blockbusters. Millions of years of fossilization have left their marks on the fossils, which might no longer resemble the condition of the organism when it was alive. A key challenge in palaeontology is therefore to restore and reconstruct the morphology of fossils. Luckily, novel digital visualization and reconstruction techniques offer powerful tools to bring extinct organisms back to life in unprecedented detail.

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Although only a small part of the vast number of extinct organisms has actually been fossilized, palaeontologists can gain a wealth of knowledge from those preserved in the fossil record. This ranges from the anatomical description and characterization of a single species to the formulation of evolutionary hypotheses (e.g. how different species were related) as well as large-scale palaeoecological studies. However, one problem for scientists has persisted since the first fossil was described: preservation and taphonomy.

Taphonomy describes all processes occurring from the time of an organism's death to its burial and eventual fossilization, such as decay, decomposition, fragmentation, transport and re-mineralization. These and other processes affect how—and how much of—an organism is preserved. Taphonomic processes are so ubiquitous that every fossil shows some kind of preservational artefact. The most obvious and common one is the decay of soft-tissues before or during burial. As a consequence, all that palaeontologists are left with are—with a few rare exceptions—hard parts: bones, teeth, shells and so on. However, these hard parts are in themselves rarely immaculate or even complete. Tens or even hundreds of millions of years of fossilization may have resulted in a number of taphonomic artefacts. In the best case, these artefacts may present themselves simply as small breaks or cracks, leaving the fossil otherwise intact and therefore changing little of its appearance. However, far more often, fossils are incomplete due to broken-off pieces (fragmentation) or missing whole elements within skeletons (disarticulation). Furthermore, fossils can be distorted or deformed during fossilization, resulting in a change of the overall morphology. In addition to these taphonomic artefacts, damage can occur in fossils after fossilization during excavation, preparation or subsequent handling. As a result of all of these processes, the preserved fossil may be considerably different from the original organism just before it died. As a consequence, the challenge palaeontologists are faced with is to restore the original *in-vivo* (during life) morphology of extinct organisms.

In the past, the restoration of fossils and the reconstruction of soft tissues have mostly been performed as two-dimensional drawings. In other cases, and often in the context of creating museum displays and exhibits, fossils have been restored using a combination of casts of the original specimen with clay or similar materials being used to supplement missing parts. However, this approach is time-intensive and laborious. It requires access to the original specimens and includes the risk of damaging the fossils during casting and handling.

Within the last twenty years, digital technology has revolutionized nearly every aspect of life—and palaeontology is no exception. The past decade has seen a surge of digital methods and computational analysis techniques in the study of fossils, often

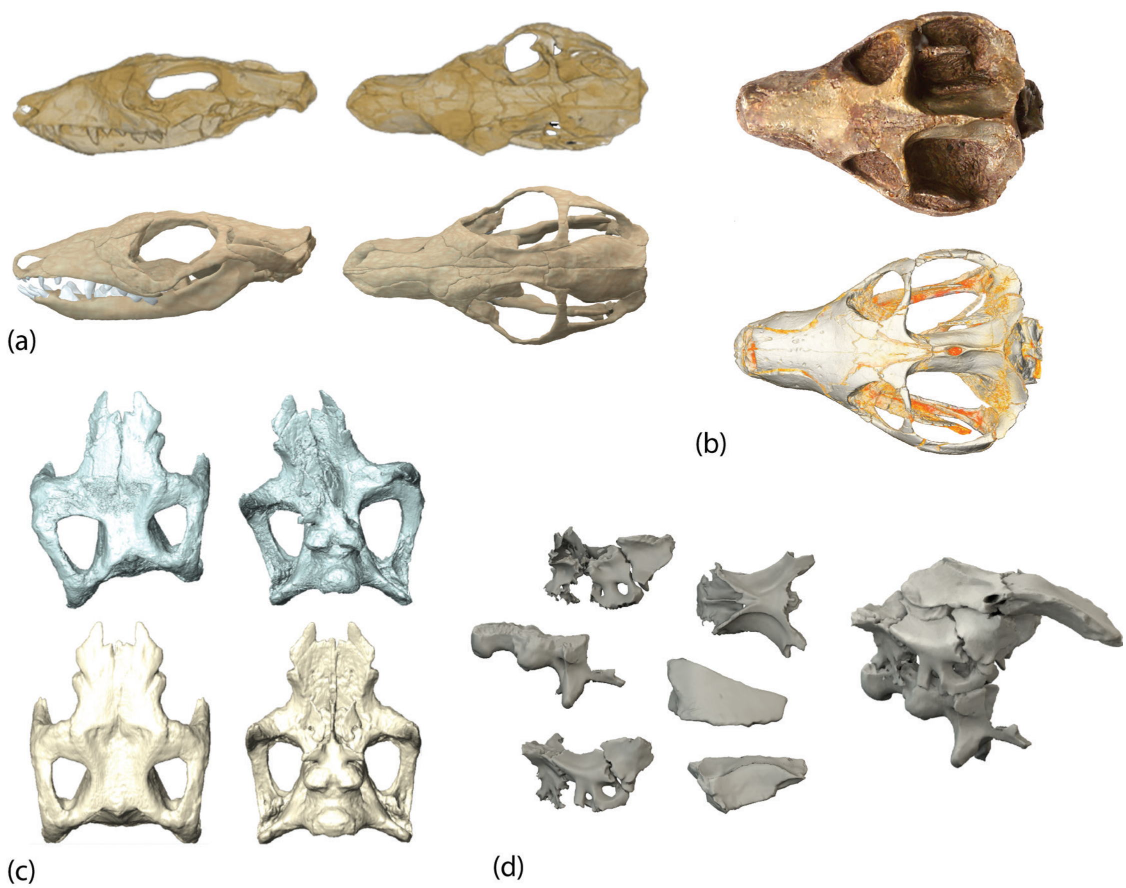

Fig. 1. Examples for digital fossil restoration. **a.** Digital models of the original (top) and restored (bottom) specimen of the Triassic cynodont *Probainognathus*. **b.** Original specimen (top) and digital model (bottom) with sediment digitally removed in the Triassic cynodont *Thrinaxodon*. **c.** Digital models of a stegosaur braincase deformed (top) and retro-deformed (bottom) in dorsal (left) and ventral (right) view. **d.** Digital models of individual bones rearticulated into a dinosaur braincase.

summarized under the term ‘virtual palaeontology’. Such new methods now allow researchers to create digital copies of fossils using computed tomography (CT) scanning (the same technology used in hospitals to identify bone fractures and other internal injuries), laser scanners, or even a series of photographs (a technique known as photogrammetry). CT scanning can also be used to look inside fossils, revealing internal structures and insights, which would not be accessible otherwise, or which would require destructive sampling by cutting open specimens. Digital models and data obtained from these methods are often used further for morphological and functional studies. However, despite the variety of applications offered by virtual palaeontology, the problem of preservational and taphonomic artefacts in fossils still exists. But here, the same digital techniques can provide a versatile solution.

The bare bones—restoration of hard tissues

To restore the morphology of a fossil, be it an ammonite, a dinosaur skull, or the limb bone of a mammoth, a digital model of the physical specimen is required. As mentioned in the beginning, different technologies are available to digitize fossils. The most accurate is CT scanning and its various subsets, such as synchrotron scanning. CT scanners come in many shapes and sizes, and with them different capabilities in terms of scanning resolution, specimen size, scanning time and associated costs. For example, medical CT scanners can accommodate large specimens and may be even used for free in some hospitals, but the resulting resolution can be very coarse for smaller fossils. In contrast, micro-CT scanners, such as those found in many research institutions and engineering companies, can offer higher resolution, but are limited in the size of the specimen (unusually around 20–30 cm) and their use can incur further costs, either for scanning or the acquisition of the scanner itself. Alternative options include surface scanning technologies, such as laser or structured light scanners. Here a laser beam or light is emitted onto the specimen to scan its morphology. The biggest caveat here is that only the external surface can be digitized. However, for many fossils with a simple morphology, such as limb bones or mollusc shells, it is often just the external morphology that is required.

Once the fossil has been digitized, using one of the methods above, the actual restoration process can begin. There are no strict protocols how to perform this, as every fossil shows a unique combination of taphonomic artefacts and may require different restoration steps. The simplest step is to remove small breaks, cracks and fractures. In most cases, these tiny imperfections do not alter the morphology of the fossil, so it might appear as if this is a purely cosmetic procedure. However, if the final restored model is used for functional analyses, such breaks could introduce analytical artefacts and therefore create wrong results. Removing these breaks can be done using CT data (if available), where their full extent is visible, or surface models. In both cases, material is digitally added to fill in cracks and fractures and to create a smooth surface (Figs 1a, 2). This step is usually very quick and requires only little interpretation.

Simply filling in breaks might not be possible in some cases, in particular if parts on one or both sides of a break have been offset and displaced. In such cases the fragments have to be isolated digitally and recombined. What would be a very laborious and often difficult—if not impossible—task with physical specimens, is just a slightly more sophisticated way of ‘cut-and-paste’ with digital specimens. It can, however, become more complicated if many fragments have to be aligned—essentially forming a Jurassic jig-saw puzzle (Fig. 1d). What if some of the pieces are missing from that puzzle? Luckily, many organisms show some kind of symmetry (bilateral or radial). So when dealing with a bilaterally symmetrical fossil, for instance a dinosaur skull, the missing elements may be replaced by exploiting this symmetry. If a particular bone element or region is missing on one side, the corresponding part on the other side can be isolated, duplicated and digitally reflected to supplement the missing portion (Figs 1a, 2). And although vertebrate skeletons may show a tiny amount of asymmetry due to functional demands, this step allows the restoration of missing parts of a fossil without too much inference.

However, not all fossils and skeletal elements are necessarily symmetrical or preserved well enough to allow the duplication and reflection of more complete parts. In such cases, information on how to supplement the missing elements has to be obtained from other fossils. Additional specimens of the same species might have preserved the respective region, which can then be used to fill in the missing parts in the to-be-restored fossil. This is where things become more complicated. The second specimen might not be the same size or could be a juvenile individual, showing a distinctly different morphology. Or even more problematic, it might be that a second specimen of the same species does not exist—something that happens more often than one would think, in particular for vertebrate fossils. In these cases, palaeontologists have to look for closely related species. The obvious caveat here being the fact that a different species might show a different morphology. However, the morphology of some skeletal elements can be very conservative, meaning that there are no significant differences between related species (think, for example, about theropod dinosaur teeth, which generally share the blade-like recurved morphology in many different species).

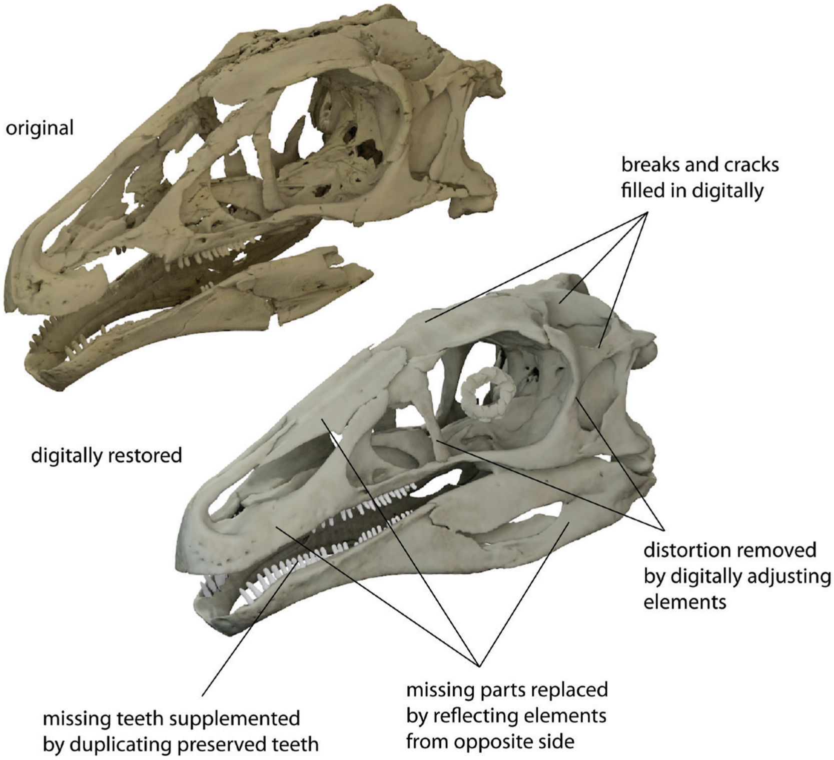

Fig. 2. Digital model of the original (back) and digitally restored (front) skull of the Cretaceous dinosaur *Erlikosaurus* with restoration steps shown.

Two types of deformation can occur during taphonomy and fossilization: brittle and plastic deformation. Brittle deformation leads to breaks, cracks, fragmentation and loss of morphology, but can be restored with the methods outlined above. In contrast, plastic deformation results in permanent changes of shape and dimensions without causing breaks. A typical result in fossils is often compression (e.g. flattening) or shearing (e.g. the left side is transformed in the opposite direction compared to the right side). Removing artefacts from plastic deformation is probably the most challenging task when restoring fossils. Again, bilateral symmetry can help here. Using characteristic points (so-called ‘landmarks’) on both sides of the fossils, the plane of symmetry, and with that the direction of deformation can be calculated by a computer program. Based on this information, a retro-deformation can be applied, transforming the fossil in the opposite direction (Fig. 1c). This might not work, though, for flattened fossils in which the deformation is symmetrically identical. In this case, other criteria have to be consulted. For example, the shape of the eye socket is circular in many vertebrates and this information can be used to un-deform a fossil in a single direction to result in a circular morphology. In other cases, information from other specimens or related species has to be gathered to remove the effects of plastic deformation.

Applied individually or in combination, these and

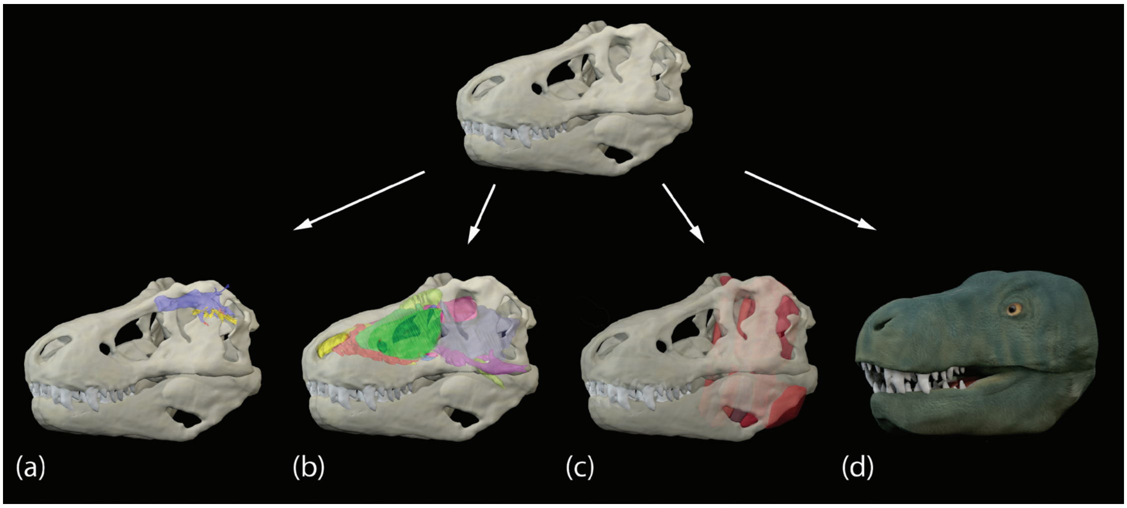

Fig. 3. Different types of digital soft-tissue reconstructions exemplified by a skull of *Tyrannosaurus*. **a.** Endocranial anatomy (brain and inner ear). **b.** Cranial sinuses. **c.** Jaw closing musculature. **d.** Life reconstruction.

other techniques allow the digital restoration of fossils in a relatively time-efficient and accurate manner. Although some interpretation and subjectivity is introduced during the process, digital restoration offers a number of advantages. For example, models can be adjusted, should new information in the form of fossil findings come to light and the digital nature of the process prevents damaging original specimens. In addition, the reconstructions can be used for further analyses and applications.

Soft-tissue reconstruction

In contrast to hard parts, soft tissues are rarely preserved in extinct organisms (a few remarkable exceptions aside) and have to be reconstructed. Similar to the restoration of fossils, digital techniques have revolutionized soft-tissue reconstructions. In particular CT scanning now allows the identification and visualization of internal structures, which form the basis for the reconstruction of soft tissues (Figs 3, 4).

The endocranial anatomy, which includes the brain, the inner ear and associated nerves and blood vessels, is now routinely reconstructed in vertebrate fossils. In nearly all vertebrates, these structures are located within internal cavities in the skull and partially or completely enclosed by bone. Although the soft tissues have withered away, the bony cavities have been preserved. To restore the anatomy once housed within these cavities, a digital cast is created using tomographic datasets. In these, the internal cavities can be identified and digitally highlighted in each of the tomographic slices—a process which can essentially be regarded as the scientific equivalent of children's colouring books. Once all structures of interest have been highlighted in this way, a computer program aligns the two-dimensional outlines to create a three-dimensional model (Fig. 3a). The resulting model can then be used for quantitative measurements and to identify function. For example, the relative and absolute size of the brain has traditionally been used to infer intelligence and cognitive capabilities, whereas the size of the inner ear allows the calculation of the possible range hearing frequencies. Although mostly applied to the reconstruction of brain anatomy and related structures, this technique can also be used to reconstruct other soft-tissues, such as sinuses—cavities within skeletal elements—which are often lined with soft tissues or air-filled (Fig. 3b).

Aside from the endocranial anatomy, muscles are commonly reconstructed in fossils using digital techniques. Although rarely preserved, muscles are essential for feeding, locomotion, breathing and other physiological activities. Detailed knowledge about the anatomy and arrangement of an extinct animal's musculature can therefore offer important insights into fossil behaviour and ecology. However, unlike internal soft-tissue structures, muscles are only partially enclosed by bone or lie external to skeletal elements. The reconstruction of muscles is therefore not as straightforward, but can be performed similarly with digital methods. For that purpose, muscle attachments are identified on the bones and/or the corresponding digital model. This is done on the basis of characteristic surface features, such as ridges or depressions, indicating that a muscle was once attached to these structures. Connecting corresponding attachments is the simplest form of reconstructing the musculature, and although it is still a very coarse technique, it already provides the gross anatomy and dimensions of a muscle. Using further information, this preliminary reconstruction can be refined. For example, multiple muscles may attach to the same bones or may be closely packed within one region, such as the skull. As muscles cannot intersect each other, but still have to fit within the skeletal structure, this offers a set of packing constraints, which limit the possibilities of how the muscles can

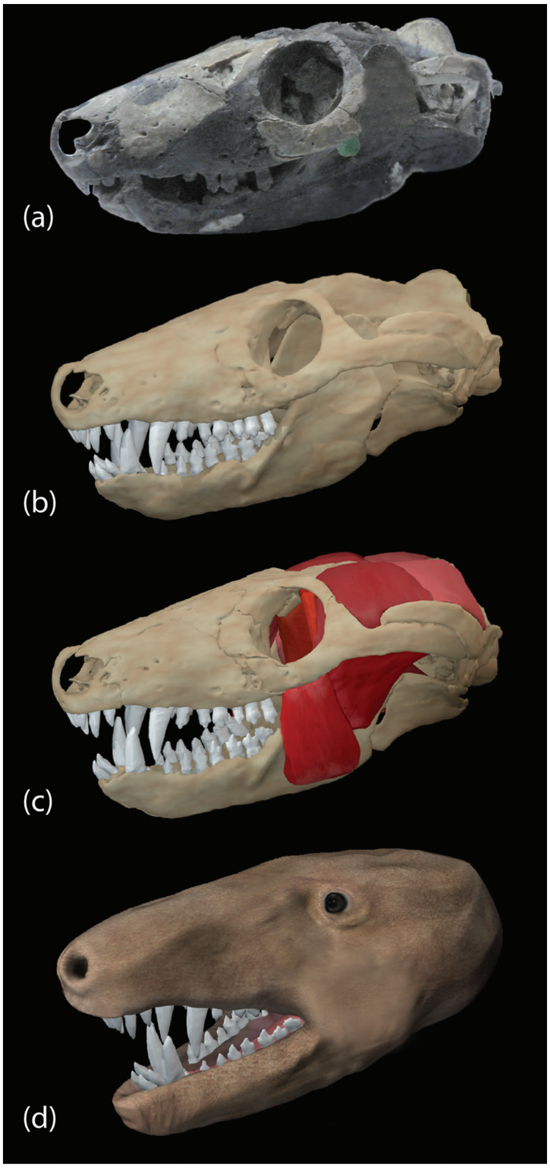

Fig. 4. Fossil restoration and soft-tissue reconstructions of the Triassic cynodont *Thrinaxodon*. **a.** Original specimen. **b.** Restored skull model. **c.** Reconstructed jaw closing musculature. **d.** Life reconstruction.

be arranged (Figs 3c, 4c). Additional criteria, such as maximum muscle stretch, the presence of other soft-tissues occupying the same region (e.g. the eyeball) or comparisons with extant animals can help to further improve muscle reconstructions and to increase their accuracy.

In recent years, soft-tissue reconstructions have focused on specific anatomical features, as for example those outlined above. However, there is also great potential to use this information in creating life reconstructions of the whole fossil organism (Figs 3d, 4d). Life reconstructions tend to be performed in a largely artistic context, to provide an idea about an extinct animal's appearance. Using digital models, the scientific accuracy of such reconstructions can be improved greatly. Similar approaches have been used in anthropology and forensic science to reconstruct the appearance of hominid fossils or, in a more serious context, crime victims.

The future of reconstructing the past

Digital visualization, analysis and reconstruction techniques have significantly changed palaeontological research in the last decade and it is very certain that these techniques will become even more widely used, as hardware and software become increasingly available and affordable. One of the biggest advancements will lie in automating these processes. At the moment, some of the introduced reconstruction and restoration techniques are time-consuming and user-dependent. Algorithms designed to speed up and automate the reconstruction process will not only reduce the level of interpretation but could also pave the way for broad, large-scale studies. Furthermore, the vast number of available digital models will certainly find their way into museum exhibitions, popular science publications and outreach activities.

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Suggestions for further reading

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