VIRTUAL REPAIR OF FOSSIL CT SCAN DATA

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X-ray micro-tomography (XMT) and 3D image-based modelling software has unlocked the ability to digitally repair distorted or broken fossil specimens, thus permitting interpretation of previously unusable finds in finite element analyses (FEA). A fossilized terminal ungual phalanx from the manus of the dromaeosaur *Velociraptor mongoliensis* (Manchester Museum, University of Manchester, specimen LL.12392) was scanned at the Henry Moseley X-ray Imaging Facility. Inspection of radiographs revealed the *Velociraptor* manual ungual was broken in several places, previously going unnoticed due to cement repair of the fossil. After conducting a high resolution scan of the ungual the increased sensitivity of the apparatus enabled separation of areas of differing density, in this case the fossilized bone and cement. Image-based modelling software produced by Simpleware (Simpleware Ltd, Rennes Drive, Exeter, EX4 4RN, UK.) allowed slice-by-slice repair in three planes, resulting in a complete, fully stitched 3D digital model of the ungual, whilst maintaining internal cavities and the micron resolution reconstruction of trabecular bone architecture. This software also has the capability to digitally re-inflate specimens that have been compressed during fossilization, restoring skeletons to their original shape and dimension. 3D dissections on geometrically precise reconstructions allow the interpretation of previously unusable specimens and reinterpretation of already described fossils. Further, use of Simpleware software to convert repaired fossils into microstructurally-faithful finite element meshes enable the biomechanical testing of these repaired structures. Testing of fossil structure and function is already underway at the University of Manchester and is adding to our knowledge of the mechanical behaviour of extinct animal biomaterials.

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Introduction

X-ray micro-tomography (XMT), image-based modelling and finite element analysis (FEA) is utilised by evolutionary biologists interested in the relationship between form and function (Moreno *et al.* 2008; Kupczik *et al.* 2009). XMT and image-based modelling coupled with rapid prototyping techniques can also be used by museum curators to generate museum displays and teaching aids of rare specimens.

Previous work (Manning *et al.* 2006) proposed a further study of the function of a Dromaeosauridae (Matthew and Brown 1922) terminal ungual phalanx, utilising the technique of finite element analysis (FEA) to consider the mechanical capability of these biological structures.

A manual terminal ungual phalanx of *Velociraptor mongoliensis* (Manchester Museum, University of Manchester, specimen LL.12392) was computed tomography (CT) scanned to provide a 3D dataset for the finite element (FE) mesh. Initial examination of the radiographs (Figure 1) showed that this specimen was fractured in two places and had been skilfully repaired with cement. Radiographs were inspected first as a quick step of checking the quality of the sample before more detailed scrutiny of the reconstructed dataset.

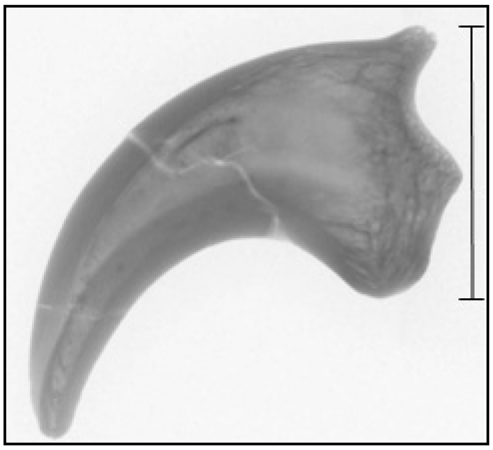

Figure 1. Radiograph of **Velociraptor** *manus claw (LL.12392) (Scale bar= 10mm)*

Closer inspection of the reconstructed volume revealed that the repair of the larger crack had left the two halves misaligned. The alignment posed a problem as specimens of dromaeosaur claws are rare in collections, and FEA of this specimen would not be representative of the true structure, thus rendering the fossil unusable. The novel solution was to digitally repair the fossil by using image based modelling software from SimplewareTM to align the claw and "heal" the fractures.

Material

Fossil Material

A manual ungual of *Velociraptor mongoliensis* (Manchester Museum, The University of Manchester, specimen LL.12392) (Figure 2Figure 2). *V. mongoliensis* is known primarily from the Djadokhta Formation (Campanian) of Mongolia (Osborn, 1924) and was a small (˜15 kg) bipedal predatory dinosaur (Paul, 1988).

Figure 2. Manual terminal ungual phalanx of **Velociraptor mongoliensis** *(LL.12392) (scale bar in cm and mm)*

Methods

X-ray Micro-tomography

X-ray micro-tomography (XMT) is a non-destructive evaluation technique that allows the internal structure of an object to be imaged by reconstructing the spatial distribution of the local linear X-ray absorption coefficients of the phases contained within (Elliott and Dover, 1982). This provides a virtual 3D representation of the internal architecture of an object from which two-dimensional (2D) cross-sectional slices can be extracted along the three orthogonal planes of the object (Mummery *et al.*, 1994; Babout *et al.*, 2005).

Data was acquired using a HMX-ST CT 225 X-ray micro tomography (XMT) scanner from Metris X-Tek Systems Ltd., capable of tube potentials up to 225 kV. The scanner used a fast CT collection method recording 2735 projections at 1 frame per second, resulting in a voxel size of 19.1μm3. The radiographs were collected using a tube potential of 136kV, current of 146μA, and with a silver anode. All of the x-ray projections were saved as images in .tif file format. The data were reconstructed using proprietary software utilising the filtered back-projection reconstruction algorithm.

Digital repair

Following reconstruction, data was imported in RAW format to ScanIPTM. The fossilised bone was segmented as a mask from the background by thresholding grey values corresponding to the specimen only and not the surrounding air. The proximal and distal parts of the fossil separated by the fracture were identified and assigned as two distinct masks. Manipulation of the distal portion of the claw by rotating and translating the image based mask allowed the two parts to be realigned by visual inspection in 3D and in the three orthogonal planes.

An alternative approach would have been to align the two masks by first exporting them as point clouds, importing them to a commercially available package such as PolyWorks, and using the point cloud registration and alignment capability of the software. PolyWorks is able to align point clouds in two ways: if there is overlap between the two point clouds it can automatically detect this and correlate the two point clouds; Alternatively the user can manually pick a minimum of three points that correspond on both fracture surfaces and PolyWorks will align the two point clouds using this reference points. Using PolyWorks was not possible with our sample as there was no overlap between the two masks and the two fracture surfaces were not from a clean break, the result being material had been lost so suitable registration marks could not be assigned. The best option available was to align the data within ScanIPTM manually and determine the quality of the alignment by eye.

Within ScanIPTM dilation and erosion algorithms were used to heal the fractures on a data set downsampled to 10% of the original resolution and at this resolution the technique worked effectively. On a low resolution data set the use of global filters has a minimal effect on features as the data has already been smoothed. However on the 100% high resolution data the fidelity of the entire data set was compromised by the use of global filters as the kernal required to "heal" the fractures also removed many of the internal voids and trabeculae. To keep the data faithful to the original specimen it was necessary to manually paint large areas of the data set to completely fill in both cracks. Painting was carried out utilising all three orthogonal view and review of the 3D preview function. Following this all masks were merged and a recursive gaussian filter with a kernal of 0.0192 (the length of one pixel) was applied to smooth the surface features. This approach maintained the fidelity of the entire data set.

Depending on the requirements of the investigator both methods are suitable, for example if all that is required is a model for measuring claw curvature then the 10% model would be adequate. However as the intended use of this model by the authors is to perform FEA then the latter approach is required.

Re-inflation and morphing

During the fossilisation process it is common for biological structures to be flattened and distorted due to post-depositional controls. A crude two-stage method to digitally re-inflate/morph this specimen was investigated. First, the medial line of the claw was aligned with one of the orthogonal axis in ScanIPTM. Then, by increasing the pixel spacing in the direction perpendicular to this axis, thereby changing the aspect ratio of the voxels, the claw was dilated.

Results

Figure 3 illustrates the original and realigned position of the claw tip. Digital realignment of the specimen ensures that any further work on this dataset will yield results based on the true geometry of *Velociraptor*'s claw.

Following realignment the two fractures were "healed" by manually painting in the missing material. Figure 4 outlines this process. Figure 5 illustrates that the internal microstructure of the claw is retained throughout the fixing process.

A Finite Element mesh was generated to test the effect of loading this biological structure (Manning *et al.* 2009).

The results of digitally re-inflating the claw are presented in Figure 7. This was a purely a demonstration of how to re-inflate a specimen, no criteria as to how compressed the specimen was known.

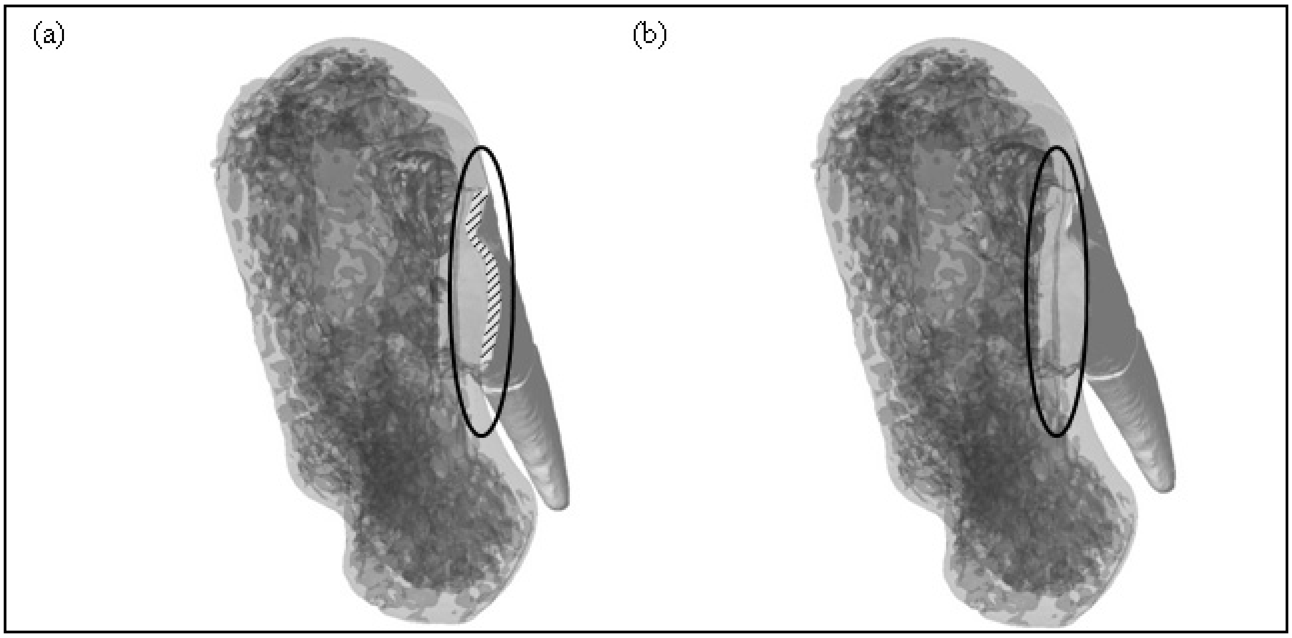

Figure 3. (a) 3D rendering of claw showing the original position of the claw tip and the proximal portion of the claw. The shaded area indicates the offset between the two pieces. (b) 3D rendering of claw showing the two pieces of the claw realigned.

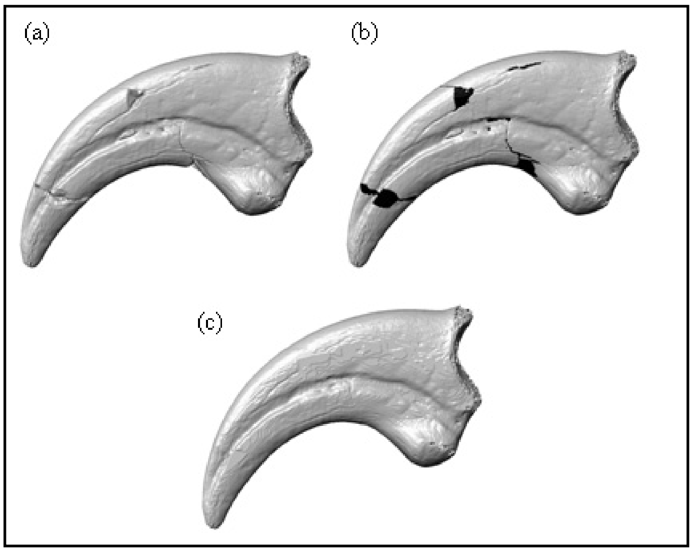

Figure 4. (a) realigned claw, (b) repaired regions shown in black, and (c) final rendering of aligned and "healed" claw.

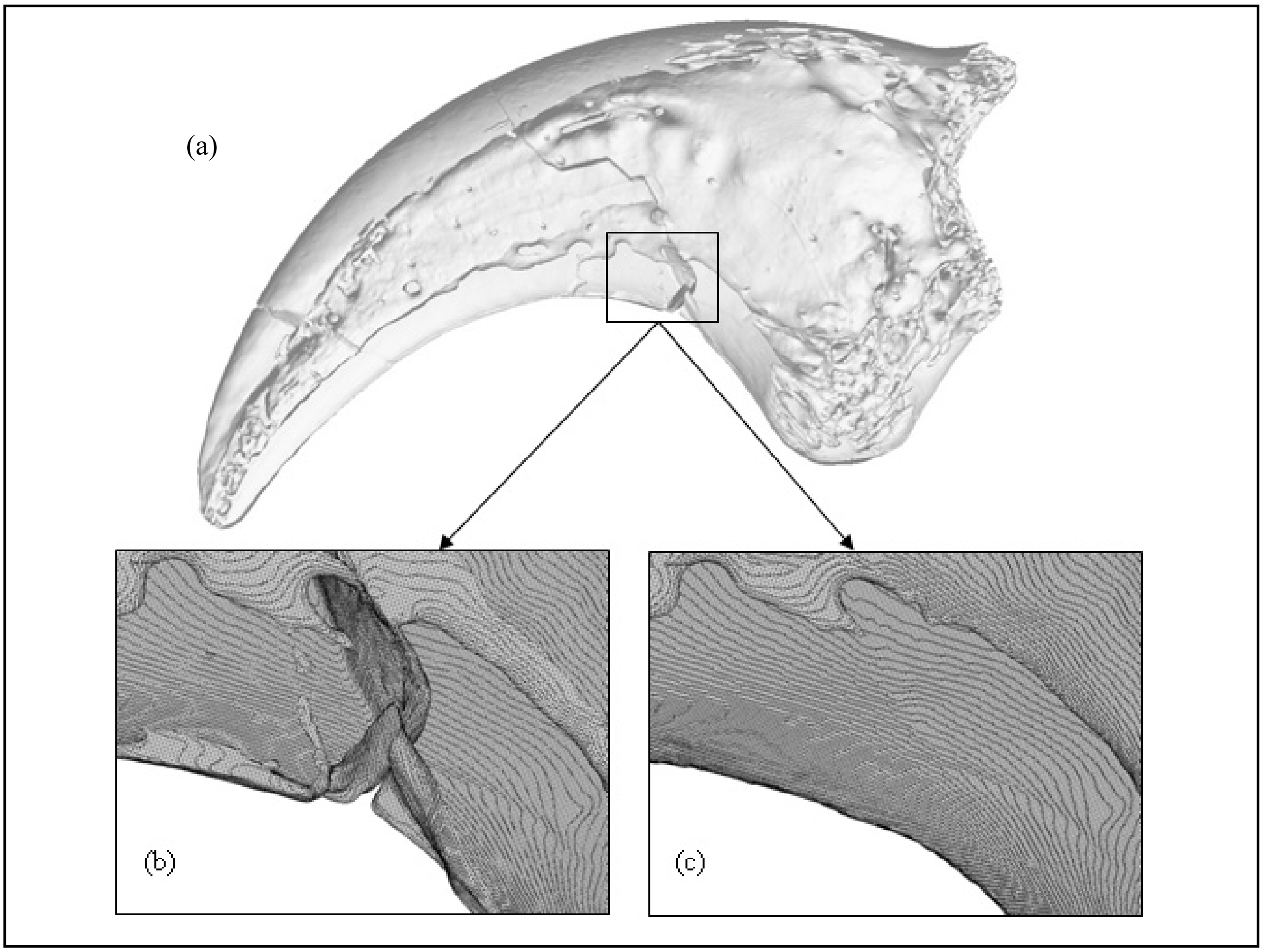

Figure 5. (a) Slice through image based model of claw, (b) close-up of FE mesh detail along crack, (c) close-up of FE mesh detail after repair

Discussion

Significant repair was needed for the *Velociraptor* claw specimen and was conducted using image-based modelling software from Simpleware. This required manual segmentation, manual alignment, and manually painting in material to "heal" the fractures and restore missing material.

Reconstruction and repair of damaged fossil specimens with image-based modelling has much value in palaeontology as it increases the usable fossil record. This is especially significant when studying rare, incomplete specimens. XMT and image-based modelling are particularly useful techniques when studying ill-prepared specimens, still bound in matrix. Matrix material can be digitally removed without risk of damaging the fossil, allowing the quality of the fossil to be assessed without the need for traditional, and somewhat lengthy manual preparation techniques. Once digitised, fossils can be studied by several scientists working in different locations, accelerating collaborative projects.

Once a fossil has been digitised it can be used as a

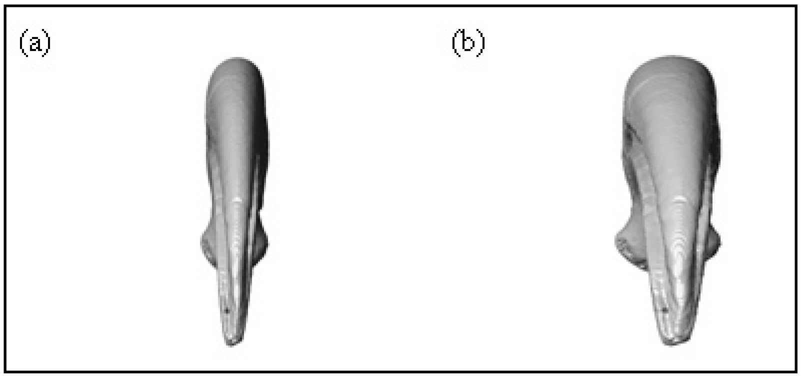

Figure 6. (a) reconstructed claw (b) re-inflated claw.

template structure and morphed to extremes to see what affect that would have on different structures, potentially revealing key evolutionary trends. Pierce *et al.* (2008) explored the patterns of variation in crocodilian skull morphology and the functional implications of those patterns. Morphing those skulls to extremes beyond the observed morphospace would have conclusively shown there is no mechanical advantage to be gained by increasing snout width.

Demonstrated within this paper is a method for morphing specimens captured by XMT. Further development of this technique could be of interest to evolutionary biologists who wish to test hypothetical forms. A possible FEA study for the *Velociraptor* would be to create variations upon the original claw and determine the effect of changing a range of parameters on the claws ability to perform various functions.

This paper covers only FE model preparation, and not any subsequent analyses. However, FEA within palaeontology can be used to test biomechanical hypotheses non-destructively and repeatedly with differing boundary conditions and material properties. Being able to analyse the biomechanical capability of a fossilised biological structure allows greater understanding of extinct form and function.

Conclusions

A finite element mesh of the digitally repaired *Velociraptor* claw was successfully created utilising image processing techniques within Simpleware software. The 3D digital model captured internal cavities and trabecular bone architecture on the micron scale.

This work indicates the potential of XMT and image-based modelling to other discounted specimens, opening the possibility of studying previously unusable material. This will lead to new research possibilities and further FEA studies of poorly preserved fossils, with the prospect of revealing the mechanical behaviour of extinct animal structures and their viable functions.

Demonstrated within this paper is a method for morphing specimens captured by XMT. Further development of this technique would provide the capability to digitally re-inflate specimens compressed during fossilisation, and could also be of interest to evolutionary biologists who wish to test hypothetical forms.

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