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DISCOVERING DINOSAUR FOOTPRINTS

Studying extinct animals is important, as it can help to further our understanding of evolutionary biology and provide a wider context to our knowledge of animals alive today. Learning more about the history of our planet and its previous inhabitants can provide us with more details about how animals evolved – and potentially what evolutionary pressures may have caused these changes.

▲ Using biplanar X-rays (XROMM), 3D motions of the bones can be reconstructed from the living animal, even when the foot is buried beneath the substrate.

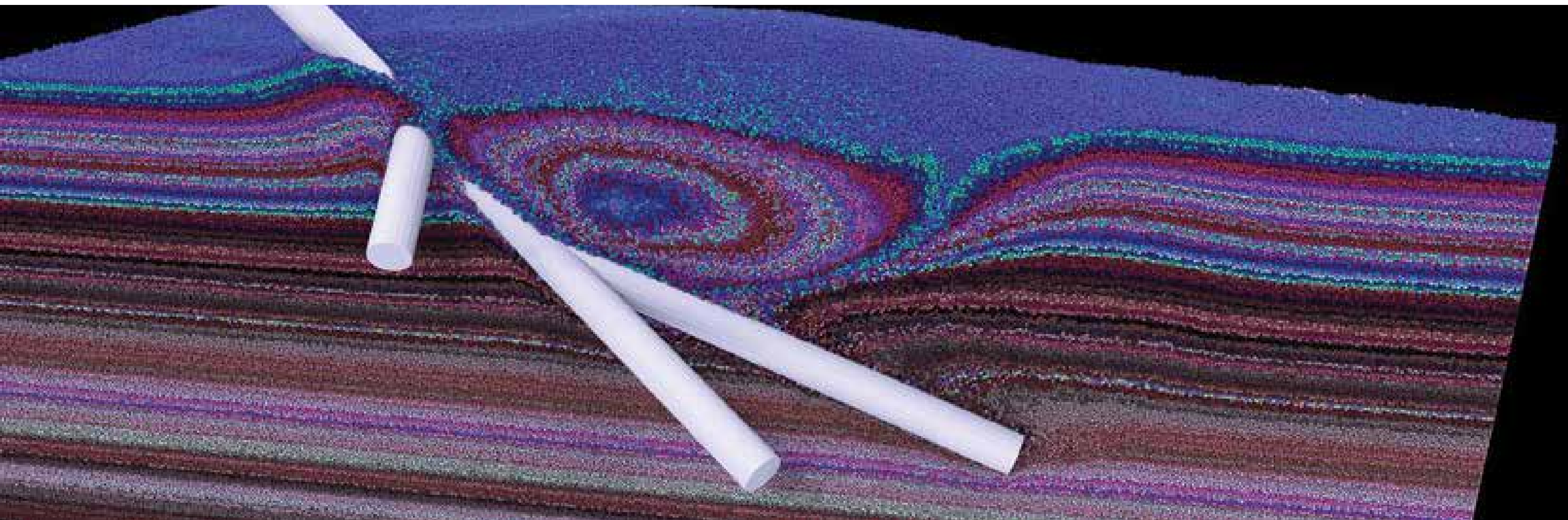
▼ A cross section through a simulated footprint using a simplified foot. The virtual sediment can be cut, coloured, and viewed in any way, exposing the internal structure of the footprint as it is formed.

Studying long-extinct animals can be very difficult, as we cannot observe them directly. In the cases of species that were already extinct long before the emergence of modern humans, fossils are the only historical records we have. While the bones of an animal are often well-preserved in fossil form, soft tissues such as muscles can be incomplete or missing entirely. This makes it much more difficult to predict how an animal may have moved, as we might not know exactly how big the muscles were or how they attached to the dinosaur's bones.

The task becomes even more complex when considering long-extinct animals that were far bigger than anything alive today. Large dinosaurs such as *Tyrannosaurus rex*, an eight-ton carnivore that moved on two legs, have no modern equivalents, and thus we have no way to approximate how they may have moved.

The fossil record can tell us that *T. rex* moved on two legs, but it cannot tell us exactly how it walked, or ran. However, the fossil record also includes preserved dinosaur footprints, which is as close as we can get to a direct observation of how these animals moved. We can understand more about how *T. rex* and other large, extinct animals moved by investigating how their footprints were formed.

Confidently interpreting how footprints form requires a detailed understanding of how a foot interacts with the ground as it touches it – how the foot flexes and moves, and how the ground changes around it. In order to gain this understanding, scientists in the UK and US have been combining high-speed X-ray video with computer simulations on ARCHER to recreate the footprint forming process virtually. The closest relations to dinosaurs alive today are birds, so studying how bird feet form footprints can provide vital information as to how the dinosaur footprints formed, and thus, how the dinosaurs may have moved.

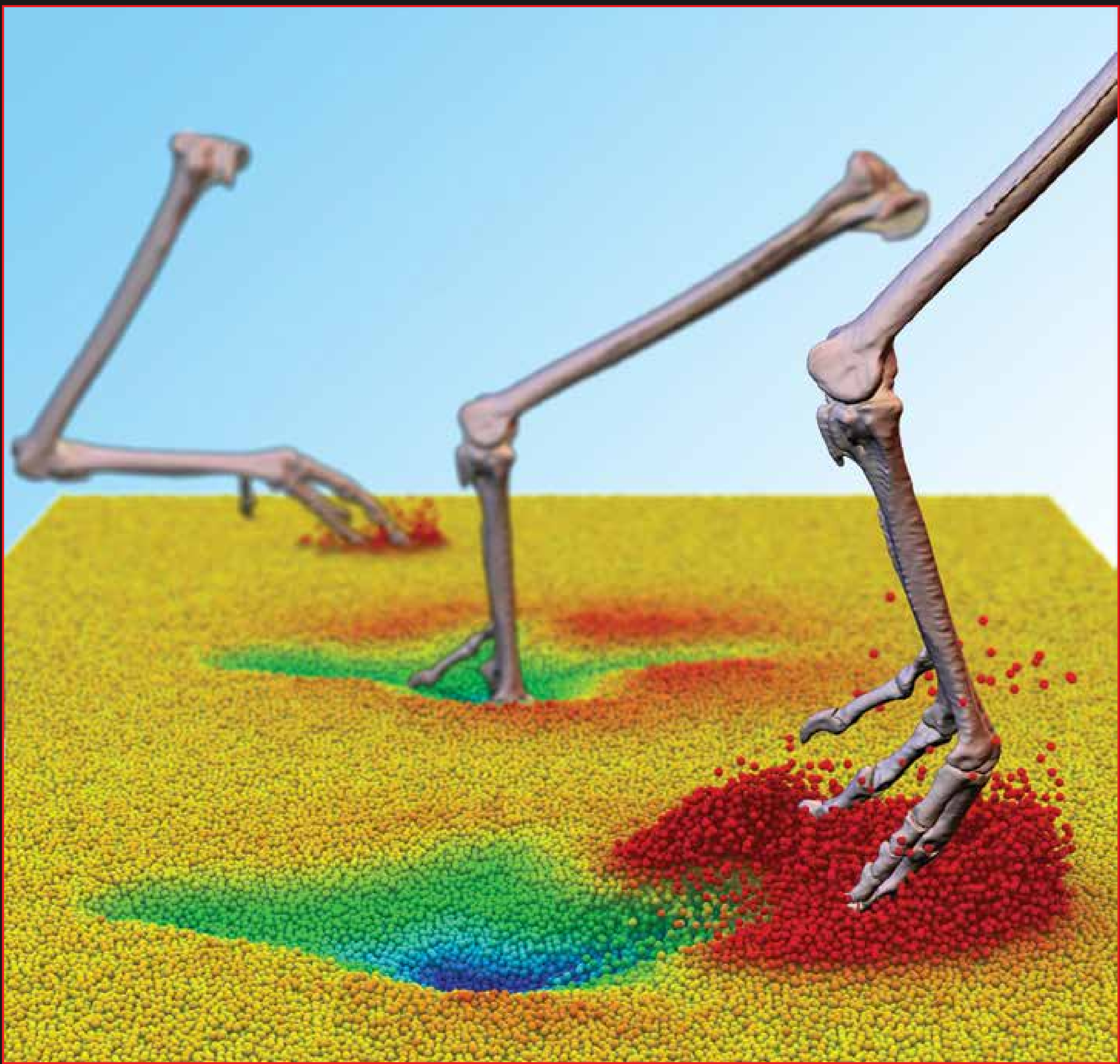


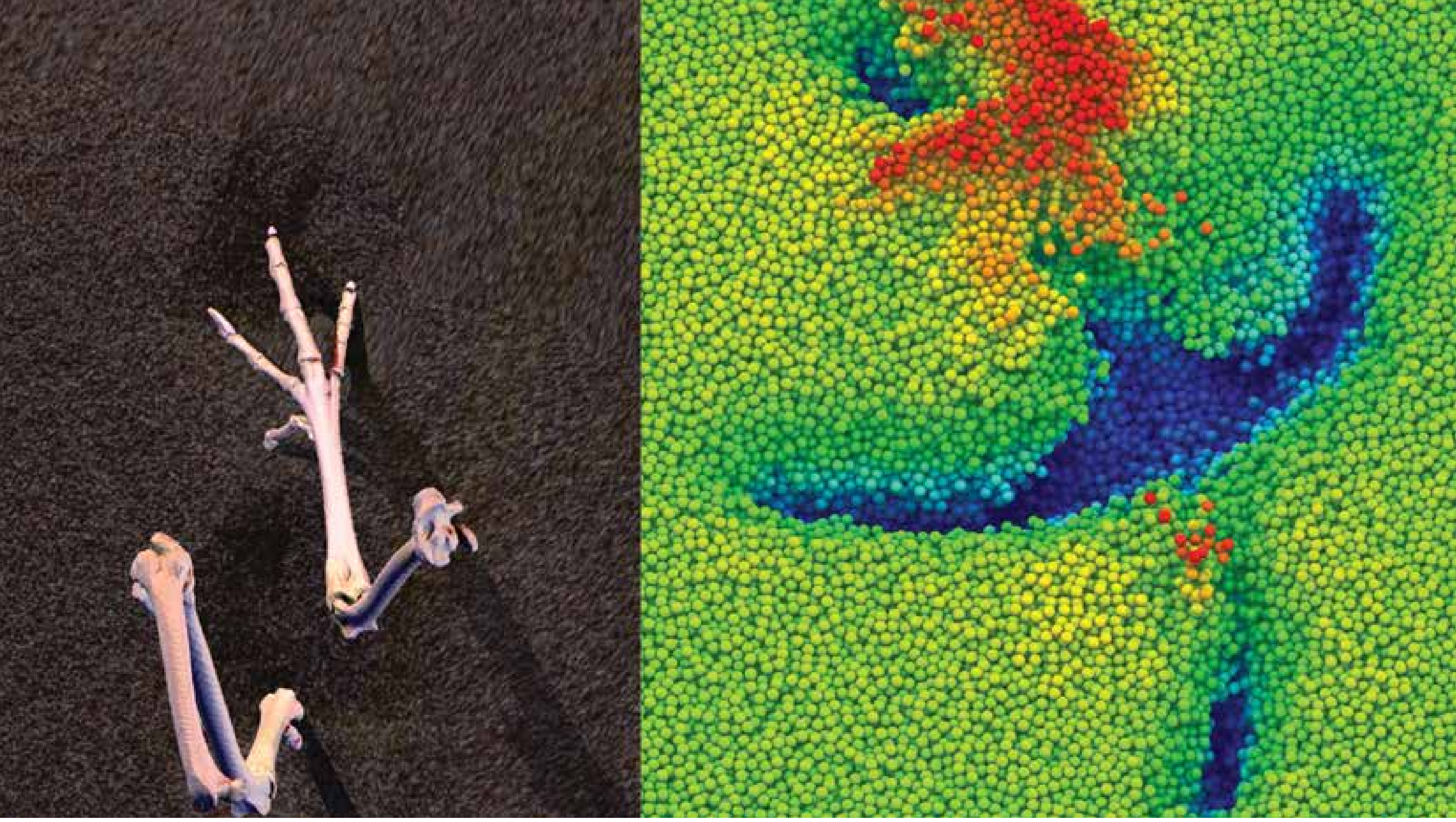
In this case, in order to better understand how dinosaur footprints were formed, the researchers first recorded the movements of a bird as it walked over a soft surface – in this case, a guinea fowl (roughly the size of a chicken) moving through a bed of poppy seeds. These birds have a foot which is somewhat similar in form to that of a *T. rex* and other bipedal dinosaurs.

This was done using X-Ray Reconstruction of Moving Morphology (XROMM, www.xromm.org). Previously, when studying skeletal movement, it was only possible to do so using indirect technique such as video capture of marker points placed on skin. However, skin movements do not always correlate to bone movements, and in some cases, bones are too deep to get even a rough idea of their movements. XROMM is much more accurate than these other methods, as it directly observes skeletal movements using biplanar X-ray video. Using this technique, the scientists were able to reconstruct the 3D motions of the bird foot as it left footprints, even though the foot itself was buried by the sediment out of sight.

Once the researchers had accurately recorded footprints, they could work from this to simulate how the sediment changed and moved when the footprints were being formed. To do this, they simulated the 3D motion of the foot in sediment using the Discrete Element Method. This was done using LIGGGHTS (www.cfdem.com) on ARCHER. LIGGGHTS is a fully open-source software for handling particle simulation using the Discrete Element Method, which is a mathematical method for computing the motion of a large number of small particles. In order to fully capture the behaviour of the sediment, they had to simulate millions of particles the same size as individual grains of sand. Even for a relatively small bird, simulating the positions and forces for every grain of sand in and around the footprint is a massive task, and is only possible with the resources of a supercomputer like ARCHER.

▼ The winner of the 2016 ARCHER image competition, showing the simulation of a footprint using XROMMM data of a guineafowl.





▲ On the left, the guinea fowl making a footprint in a loose sand-like substrate. Right, the same footprint simulated, but from 2 cm beneath the surface - The shape of subsurface tracks differs considerably from that at the surface.

These simulations provide a completely new way of looking at how footprints form.

The virtual footprints that the researchers have produced provide an unprecedented view of the way footprints form. Once the simulation has completed, the foot and the sediment can be viewed at any point in the footprint forming process, allowing them to understand how a footprint is created, and which motions of the foot are linked to which disturbances of the sediment. This was the first time that anything like this had been done with dinosaur footprint formation (or indeed any footprint formation).

With the new knowledge they have gained by using ARCHER, the researchers are now hoping to go back and re-analyse dinosaur footprints that have already been found. Knowing how the footprints of the bird are formed will allow the researchers to work backwards and apply these principles to fossilized dinosaur footprints. By comparing the fossil footprints to those of the bird, the movements which formed the fossil footprints can be inferred and applied to the dinosaur they belonged to. They have already started matching previously unexplained features in the fossils with particular foot motions – fossil specimens that were collected over 150 years ago and are yet to be fully explained.

Although this research concerns theropod dinosaurs, a group of largely bipedal dinosaurs that includes *T. rex*, the techniques developed could be used for different types of dinosaurs that have differently-shaped feet. Theropod dinosaurs were chosen because they had similar foot and limb structures to modern birds, making validation of the work much easier. The method could be applied to any dinosaur (or any extinct animal for that matter) but as many extinct animals lack a sufficiently similar living ancestor, it would be more difficult to confirm the results of a comparison.

This research will inform our understanding of how dinosaurs moved. The similarities and differences between theropods and birds – as expressed in their footprints - can tell us a lot about the evolutionary processes that occurred over 150 million years.

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About ARCHER

ARCHER is the UK National Supercomputing Service. The service is provided to the UK research community by EPSRC, UoE HPCx Ltd and its subcontractors: EPCC and STFC's Daresbury Laboratory, and by Cray Inc. The Computational Science and Engineering (CSE) partners provide expertise to support the UK research community in the use of ARCHER. The ARCHER CSE partners are EPSRC and EPCC at the University of Edinburgh.

The eCSE Programme

The Embedded CSE (eCSE) programme provides funding to the ARCHER user community to develop software in a sustainable manner to run on ARCHER. Funding enables the employment of a researcher or code developer to work specifically on the relevant software to enable new features or improve the performance of the code.

The Case Study Series

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