# The science of 'Walking with Dinosaurs'

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The biggest science documentary series ever, 'Walking with Dinosaurs' (WWD) was first shown in Britain in October, 1999, in the United States in April, 2000, and in most other countries around the world during that interval. By late 2000, some 200 million people had seen the series (25 million in Britain, of whom 19 million watched it the first time round). The spin-off programme, 'The Ballad of Big Al' attracted similar attention when it was aired at Christmas, 2000.

These viewing figures are what is expected for a cup final football match, a royal wedding, or an especially hyped episode of a soap opera, but not for a documentary about palaeontology. But was WWD a scientific documentary, as I suggest, or was it a media stunt, as a (small) group of critics claimed at the time? I'd like to explore this idea, and relate it to the wider question of how palaeontologists operate, and indeed what science is all about.

## The gestation and making of WWD

I was involved in the series from its early days, as palaeontological consultant for the first programme. Several of my colleagues from Bristol were also involved: David Unwin (now in Berlin) was main consultant on pterosaurs (the leathery flying ones), Donald Henderson (now in Baltimore) offered expert advice on the biomechanics of dinosaurian locomotion, and Jo Wright (now in Denver) was employed by the BBC full-time for a year as their in-house palaeontological consultant.

Tim Haines, the producer of WWD, conceived the idea of a fully animated wildlife series about dinosaurs in 1997. He knew that the technology for this kind of animation existed. After all, Steven Spielberg had used it to spectacular effect in 'Jurassic Park' in 1993. (Equally, Haines knew that Spielberg had spent untold millions of dollars on what was then extremely novel and difficult computing to achieve only 11 minutes or so of true computer animation. The rest was animatronics — models — and chaps in rubber suits.)

But, by 1997, the costs had come down. It was possible at last to do this work on a desktop PC, using software packages that were available commercially. The animation technology had become reasonably commonplace in advertising. But, for a wildlife documentary, Haines needed 25 minutes of animation for every half-hour programme. No room for rubber suits, although animatronic models were used for close-up shots in WWD.

But the BBC had to be assured that the effects would be acceptable scientifically. So Haines toured various universities in Britain and the United States, seeking opinions of a short trial film he had had made by the animation firm Framestore in London. I remember watching that first trial film, five minutes of the pliosaur *Liopleurodon* swimming around, and other underwater shots. It was breathtaking, and it had cost a minute fraction of what Spielberg had paid five years earlier. In the end, Haines raised his budget of £6 million from US, German, Japanese, and British sources, and they set to work.

It took 18 months to make the programmes. The storyboards were precise, and film crews set off round the world to film the backgrounds. Special effects had to be incorporated into these background films. Meanwhile, a team of animators at Framestore was engaged, each developing a particular animal. The consultant palaeontologists were brought in early to check and approve the clay sculptures on which each animation was based, and to look at the initial wireframe and simplified moving images. We were asked to specify how the limbs moved, how the animals ate, and any other behaviours we know they could do, based on evidence from the fossils.

The to-and-fro of consultation and development went on throughout the production period. In the end, over 100 palaeontologists and geologists were consulted. Questions were specific: not merely 'were there scorpions around in the Triassic?', but 'was this family of scorpions around in the Late Carnian of Arizona?' Jo Wright, the in-house BBC palaeontologist, of course was able to deal with innumerable daily questions, and she went out for specific advice constantly.

## Cheapening science?

Did we sell our souls? Yes, according to some (well, one). We were accused by a fellow palaeontologist of having been seduced by the bright lights, of selling our expertise cheaply, of doing anything for money. He publicly called us prostitutes in an e-mail discussion list. His message reached thousands of professional palaeontologists around the world. In an interview with Science, he claimed that he was ashamed of the profession of palaeontology after seeing the series. Strong (perhaps rather mad) words! Other critics were less harsh, and the criticism became more muted as the programmes rolled out.

A few critics adopted the pose of the cynic. They claimed that WWD was all a bit of fun, but it really needed a serious hand at the tiller to lend it some true authority. Or perhaps it should never have been attempted. Or who knows? The cynic is not obliged to be specific, merely to smile indulgently at the caperings of his fellow human beings, while muttering, 'Tut, tut.' Maybe this stance was largely sour grapes: 'why wasn't I consulted?'

Another category of WWD-haters, the fact checkers, began compiling lists of errors in the first week. These were gleefully circulated on the e-mail lists. For example, in the first programme, *Postosuchus* urinates copiously. There is no doubt that it does so in the programme, and this was a moment that my children relished. However, of course, birds and crocodiles, the closest living relatives of the dinosaurs, do not urinate; they shed their waste chemicals as more solid uric acid. Equally, though, we can't prove that *Postosuchus* did not urinate like this: copious urination is the primitive state for tetrapods (seen in fishes, amphibians, turtles, and mammals), and it might have been retained by some basal archosaurs.

The other claims of 'errors' that were identified in the first weeks fizzled out pretty quickly. The critics had found points about which they disagreed, but they could not prove that their view was correct. In matters of opinion (e.g. colours, sounds, mating behaviours), where there is limited evidence, many different views are expressed. But in making a film (or a painting) a hard choice has to be made. The nit-pickers mostly realised this and desisted: had their advice been sought, they would have suggested perhaps that *Tyrannosaurus rex* was green, not brown, and someone else would have complained.

## Excess cynicism?

I have been interested to observe, as I talk about the science behind WWD to different audiences around the country, that there has been an abiding impression of dissatisfaction about the accuracy of WWD. One or two vocal critics were reported in the press (and the press has to focus on dissension and dispute), and this has left a lingering bad taste, almost exclusively among adults, that what they were watching was technically superb, but scientifically flawed. Sadly, the healthy cynicism that most adults have for all politicians and for all the media has led many people, I think, to underestimate what they were watching.

And I think Tim Haines and the BBC underestimated this wall of cynicism that would face them. They assumed that people would appreciate that immense care that had gone into checking every detail of the animation. They assumed that the imprimatur of the BBC was enough to say, 'this has been carefully done, and with full consultation with experts.' So, any thinking person realises that colours and sounds of dinosaurs have to be imagined, but many viewers assumed also that the nests, eggs, running, walking, feeding, and other behaviours were also imagined.

This lack of appreciation of the current of cynicism was reflected in the fact that the scripts and narration by Kenneth Branagh expressed no questions or doubts. Had the narration drawn attention to the specific imaginary scenes and reconstructions, then, by implication, the viewers would have appreciated perhaps that the rest was based on sound evidence. The 'Making of WWD' programme didn't go far enough to explain the science behind the programmes: there was a certain amount of palaeobiology, but also a great deal about the technology of the animation and the film making.

I think that the narration was more carefully considered for 'The Ballad of Big Al'. And the accompanying programme, of equivalent length, went into exquisite detail on every aspect of the fossil and geological evidence that had been used in making the film. At least, after viewing both programmes, even inexpert viewers should have realised that virtually everything shown in the 'Ballad' was based on evidence (except skin colour and vocalization of course).

The current of cynicism has been positive, and it has opened up a great opportunity for educators, whether in schools, in museums or at universities. The cynicism, linked to amazement at the visual impact of the programmes, readily turns into questions: how do you know that? Tim Haines' book of WWD, and subsequent books by myself, and by David Martill and Darren Naish from the University of Portsmouth, have addressed this point head-on. The impact of the programmes has interested a huge new group of people in geology and palaeontology. At one talk I gave in Aberdeen, 400 people turned up to hear about 'the science behind WWD'. But for the programmes, I doubt that we would have attracted more than fifty.

## The science

It is useful to recall the immense range of deduction that is possible from geological and palaeontological observations. It is easy for geologists and palaeontologists to talk about the life of the past, without detailing the deductive steps that lie behind even simple statements, such as ‘Four hundred million years ago, Britain lay south of the Equator’, or ‘T. rex could not have run faster than 10 km/hr’. But we should recall that such simple declarations are startling to the non-expert, but equally that they can then be dissected into a sequence of simpler deductions from evidence.

Much of the problem revolves around the use of words. ‘It’s all speculation,’ they cry, and of course it is. But then most of science is speculation. Which geologist can put his finger on the atomic structure of montmorillonite, the core/mantle boundary, or a magma chamber? Can we prove with 100% certainty that the Earth is more than 7000 years old, that ice sheets once covered most of Britain, that there was an asteroid impact at the KT boundary? Likewise, can a chemist show us an electron, can an astronomer confirm the composition of stars that have been studied by spectroscopy, can a physicist show us a quantum of energy? So is all of science just speculation?

Clearly it is in a strict sense. Science would be rather dull if we had to restrict ourselves to what we could see and touch, to 100% certainty. It’s extraordinary that some professional palaeontologists were unable to understand that reconstructing the bodily appearance and behaviour of an extinct animal is identical in scientific terms to any other normal activity in science, such as reconstructing the nature of the atmosphere on Saturn. The sequence of observations and conjectures that stand between the bones of Brachiosaurus lying in the ground and its moving image in WWD is identical to the sequence of observations and conjectures that lie between the biochemical and crystallographic observations on chromosomes and the creation of the model of the structure of DNA. In both cases, the image of Brachiosaurus wandering across the screen, or the double helix, may be wrong — which scientist of any merit never takes risks? — but in both cases, the models reflect the best fit to the facts.

## Fact and fantasy — where to draw the line?

As in any science, there are levels of certainty in palaeontology. The fossil skeletons show the shape and size of a dinosaur, its provenance shows where it lived, what the climate was, and with whom it associated. These can be termed facts.

But what of the fantasy? Much of the speculation I would term strong supposition. For example, the bones show where the muscles went and how large they were. This gives the overall body shape. The teeth show what the animal ate, and the jaw shape shows how it fed. The limb bones show how the dinosaurs moved. You can manipulate the joints and calculate the movements, stresses, and strains, of the limbs. With care, it is possible to work out the pattern of locomotion in great detail. All the walking, running, swimming, and flying shown in WWD was based on immensely careful calculation and modelling. Fantasy? Speculation? No. I would suggest that all these behaviours are 80% accurate, or better.

The third level of certainty includes everything else: the colours and patterns, the breeding habits, the noises. However, even these, although entirely unsupported by fossil data, are not fantasy. Palaeobiologists, like any person with common sense, base their speculations here on comparisons with living animals. What colour was Diplodocus? It was a huge plant-eater. Modern huge plant-eaters, like elephants and rhinos, have thick grey wrinkly skin. So, we give Diplodocus thick, grey, wrinkly skin. The cynodonts in Programme 1 are close relatives of the ancestors of mammals. Many modern mammals pair-bond for life, and all suckle their young. So, it is not unreasonable to transfer such behaviour to the fossil forms.

## Methods of palaeobiological inference - case studies

I think it is possible to distinguish a range of approaches to determining the palaeobiology of extinct organisms. These can be divided roughly into common sense (= intuition; = uniformitarianism), biomechanics, and deduction. I'd like to illustrate these with three examples.

Common sense is the most useful tool. As an example, one might consider the giant sauropod dinosaurs. Numerous skeletons of the Late Jurassic behemoths such as Brachiosaurus, Apatosaurus, and Diplodocus are known, and these indicate enormous land-living animals, weighing at least 30-50 tonnes. Already some wild claims have crept in. 'Land-living?' '50 tonnes?' How do we know? Fossil trackways prove that the sauropods walked on land and into shallow water. The skeletons must have been clothed in flesh, and the skeletons are something like ten to fifteen times the size of the largest living elephant. However, the calculation is done, the weight comes up to 50 tonnes.

Let's go one step further. How did the sauropods live? A number of models have been presented. In the early twentieth century, some palaeobiologists decided that they must have submerged themselves deep in lakes, as a way of achieving neutral buoyancy. This seemed to make sense in that it allowed the sauropods to cope with their vast weight. But further simple consideration means that this model must be rejected. A sauropod standing in deep water has its lungs located some 3-5 metres below the surface. The laws of physics were presumably the same in the Jurassic as now (uniformitarianism), so that pressure increased rapidly with increasing water depth. So, this depth would lead to extreme difficulties in breathing, and the underwater model can be rejected.

As a kind of counterblast, Bob Bakker suggested in 1971 that the sauropods lived as scaled-up giraffes. They used their long necks to feed from high in the trees, and moved about the landscape rapidly. One image even shows a Brachiosaurus galloping. Again, this has to be rejected. At full gallop, the limb bones experience forces some ten times the normal forces experienced when at rest (in simple terms, you weigh ten times as much when running at full tilt as when standing still — think of joggers' knee, produced by endless pounding). So, a 50-tonne Brachiosaurus at full gallop is delivering a force of 500 tonnes through its legs. The leg bones would break. The strength of bones can be measured today using simple engineering crushing equipment. Modern bones have a predictable strength that depends on their cross-sectional area, and, unless sauropods had bones made from stainless steel (which the fossils show they did not), it's easy to tell when any fossil bone would break. Uniformitarianism and common sense again.

So, in WWD, the sauropods were shown ambling slowly about on land, occasionally entering lakes and rivers, but never becoming completely submerged. Boring perhaps, but very probably correct.

Biomechanics is a broad range of approaches that can be applied to any questions of movement, especially locomotion and feeding. The deductions about sauropod weights and running speeds came from biomechanics, of course. But, with the immense computing power available now, it is possible to carry out quite sophisticated biomechanical calculations that constrain the style of locomotion of any extinct vertebrate.

Donald Henderson, now at Johns Hopkins University in Baltimore, carried out his PhD research in Bristol on the locomotion of theropods, the bipedal flesh-eating dinosaurs. His aim was to reconstruct, in three dimensions, the leg movements of three theropods, the small Coelophysis, the medium-sized Allosaurus (see Figure 1), and the giant Tyrannosaurus rex. His approach was to measure the bones of the hindlimbs in detail, to fit these together in the computer, and to code in their exact ranges of movements. [All three dinosaurs are represented by numerous complete and undistorted skeletons, so Donald could manipulate the joints (hip, knee, ankle) and determine the exact ranges of movements of each] In addition, any reconstructed walking movements had to be constrained by two further factors: the feet obviously had to hit the ground each time (not land up above or below) and, more importantly, the movements had to conform to the requirements of the centre of mass.

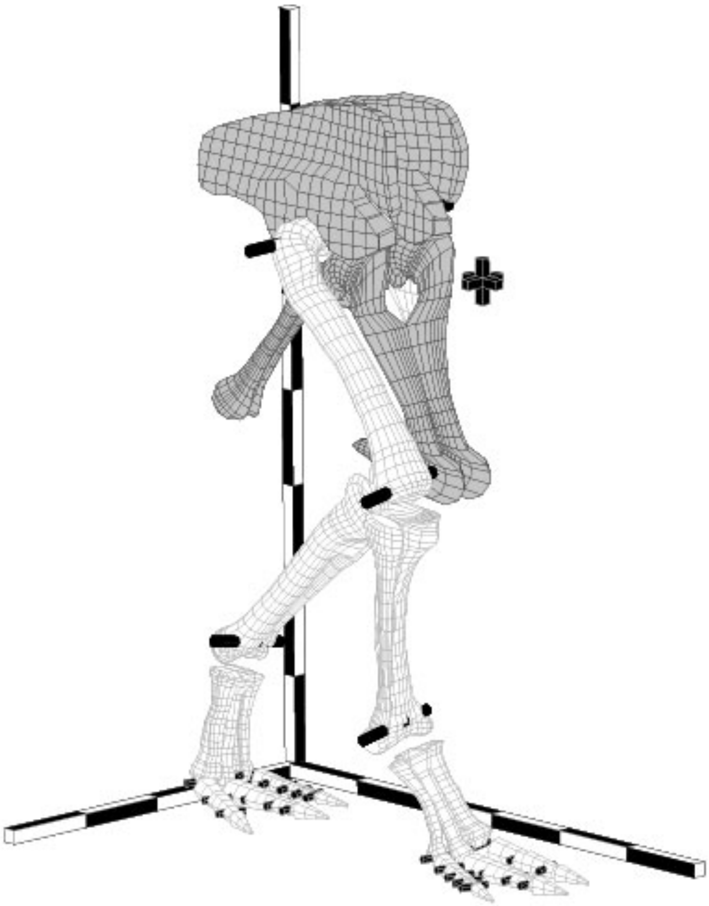

Figure 1. Oblique view of fully assembled pelvis and limbs of *Allosaurus*. Centre of gravity is shown by black cross. Reproduced by kind permission of Don Henderson.

The centre of mass is the central balance point of the body. In earlier, less sophisticated times, the centre of mass of a dinosaur would be calculated by taking a plastic model and dangling it on a string. However, Donald had to make his calculations rather more precisely. So, he reconstructed the body shape of each dinosaur, and coded in the weight differentials.

For example, the space in the mouth, and the lungs, weigh essentially nothing. Equally, the bones are distributed differently through the body, and that also affects the balance. Donald created a salami-slice model of each dinosaur, and entered the exact distribution of masses in each slice, from the tip of the snout to the end of the tail. A few calculations then gave the precise position of the centre of mass, obviously located in the midline of the dinosaur, and as it happens, just in front of the hips (see Figures 1 and 2

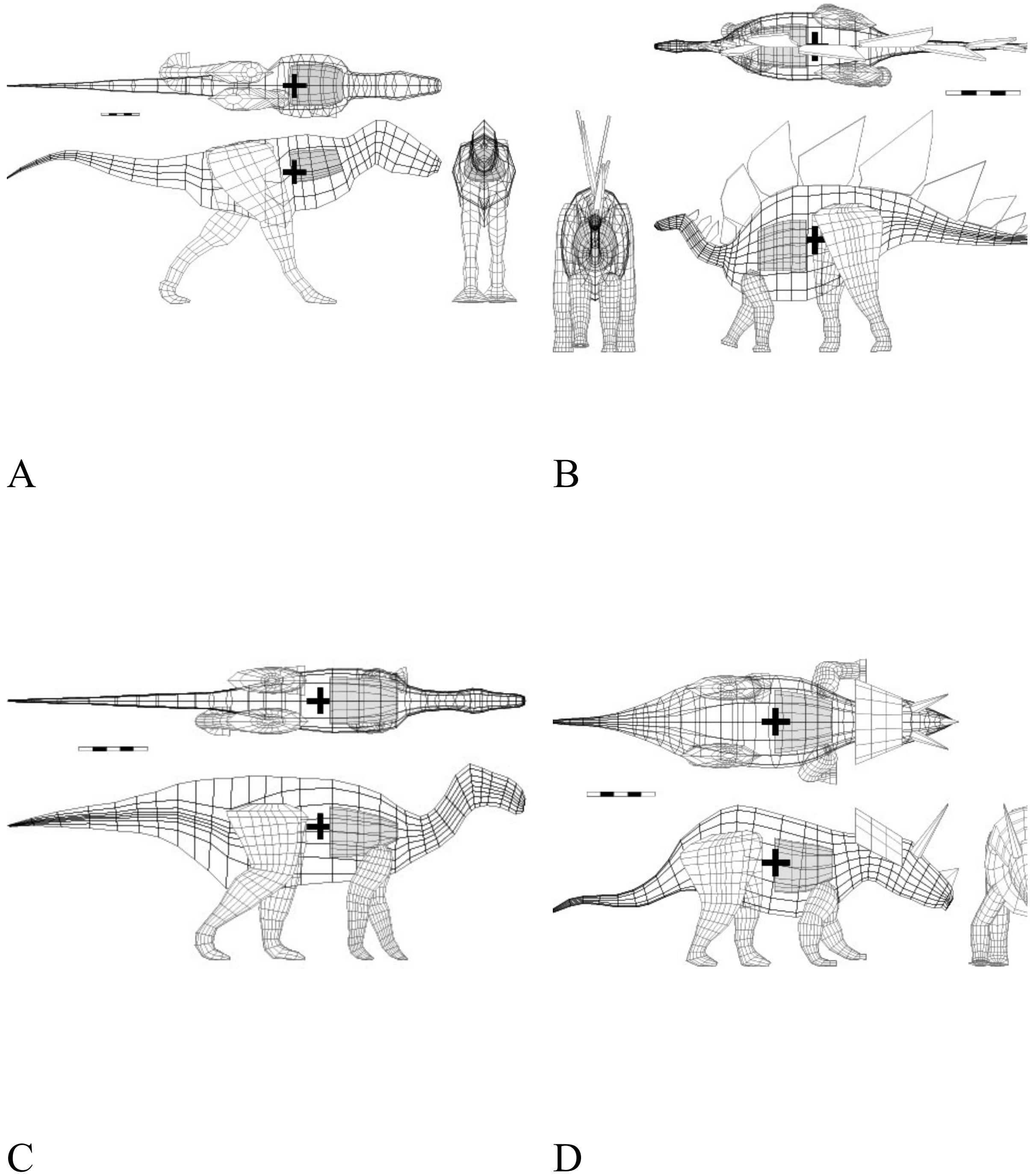


Figure 2. Dinosaur body shape reconstructions. A: *Allosaurus*, B: *Stegosaurus*, C: *Iguanodon*, D: *Triceratops*. Reproduced by kind permission of Don Henderson.

The centre of mass then summarizes the distribution of mass in three dimensions, and it tells us all we need to know about body movements during walking. Theropods were essentially like see-saws, with their backbones held pretty much horizontally, the front end balancing the back end over the pivot of the hips and hindlimbs. Lifting the left foot meant that the dinosaur had to swing its body slightly to the right. Moving one foot forward, meant that the front end had to go up, the tail down. So, during a rapid walk, the theropod was tipping up and down from fore to aft (think of a pigeon trotting at full tilt), and swinging its hips from left to right.

Donald then set about calculating the stride patterns of the theropods. Fortunately, like mammals, dinosaurs had their legs tucked beneath their bodies. Their leg movements were essentially in two dimensions, just back-and-forwards. (The ancestors of the dinosaurs, like modern lizards, had a sprawling gait, in which limb movements involve complex three-dimensional lateral curved swings of the arms and le

gs.) Donald was able to reduce the leg movements to three pendulum units: the thigh bone swinging at the hips, the shin bones swinging at the knee, and the metatarsal block swinging at the ankle. [Dinosaurs had this third crank in their legs, like horses and dogs, since they essentially stood up on their tiptoes.]

The stride was resolved, in three dimensions, by solving a set of three equations, one for each of the cranks of the hindlimb. This sounds easy, but Donald sweated over the computer for more than two years before he finally cracked it. The step cycle for each dinosaur could then be built from these calculations, and they may be inspected on the Bristol Palaeobiology Group's web site (reference below). Donald, of course, checked that his method worked by modelling the locomotion of an ostrich from its skeleton: his moving step cycles matched precisely film of a running ostrich.

This biomechanical method can lead to further, much more detailed, analytical studies: how did the step cycle change at different speeds, what was the maximum speed possible for each dinosaur, what stresses and strains acted on each bone during locomotion? Are we sure that this is how the different theropods moved? Of course, not in a mathematical sense of proof, but Donald's inferences are based on such careful consideration of how modern animals move, and such precise measurements of the fossils, that his locomotory model has to be seen to be as certain as anything in palaeobiology or Earth history.

(As an aside, Donald was pursuing his PhD project in parallel with the development of the WWD programmes. Initially, the Framestore animators based their locomotory models on their visual knowledge of modern animals. They kept tweaking the dinosaur movements until they 'looked right'. They soon found that their running Allosaurus looked horribly wooden and unrealistic if his hips didn't wiggle from side to side, his body rock up and down, and his tail whip from side to side. The human eye has an amazing intuitive ability to get things right without the complexities of physical calculations — think of catching a cricket ball. So, the animators got it right, and they were pleased to have their intuitions confirmed by Donald Henderson's intricate calculations.)

Deduction is the third approach in palaeobiology. Many examples could be given, but I shall select only one, the capabilities of pterosaurs on the ground. The classic 19th Century model showed pterosaurs as awkward, leathery creatures that walked on all fours, presumably stumbling and rolling as they went. In 1983, Kevin Padian, then a young researcher, proposed an alternative model — the politically correct pterosaur. Here he showed the small Early Jurassic form *Dimorphodon* standing upright on its hindlimbs, its front end and massive beak balanced by a long flexible tail. Its wings are folded away like a pair of neat umbrellas. Pterosaurs were reborn as sleek, fast-moving runners, and Padian's model caught on with artists and the public.

But, a number of critics kept complaining that the model just didn't work. They couldn't point to any overwhelming evidence, but they felt that his model had more to do with fashion than facts. At the very least, they asked, how could this model be applied to the giant pterosaurs of the Cretaceous, most of them with wingspans over 4 metres, and some up to 12 metres across? These later giants had no balancing tail at the back, and their wings were so wide that they could not simply be stowed away.

Three lines of evidence have now led to the unequivocal rejection of the upright pterosaur. First, new three-dimensionally preserved fossils from the Santana Formation in Brazil show that the thigh bones could not bend under the body — they stuck out to the side at an angle. So, the best hindlimb posture a pterosaur could have managed was the legs-apart stance of a gunslinger. Second, pterosaur trackways from the United States and France confirm this posture, and that the hands were used as well. Pterosaur hands were located some way along the leading edge of the wing, and they touched the ground even further from the midline than did the feet. But touch the ground they did. Third, balance calculations prove that most, if not all, pterosaurs could not have stood up on their hindlegs. Certainly, the tailless Cretaceous pterosaurs had no hope of such a posture. The models by Donald Henderson and David Unwin show exactly how a pterosaur had to walk (see web reference at the end).

## Walking with Dinosaurs — media hype or research project

I believe that WWD, far from being merely a media event, is actually a powerful piece of palaeobiological research. It shows a huge community just what the best minds in palaeobiology have been able to achieve. We should celebrate.

First, a media-related issue. Would the critics of WWD have cancelled the whole enterprise? Evidently a tiny minority of palaeontologists would. Others would allow it to happen, but with caveats. Perhaps the film-makers should have blown a puff of smoke across the screen when some speculative behaviour was shown? Or, perhaps the head of a distinguished palaeontologist should have appeared in the top right corner, and said, 'Well, we don't really know whether they copulated in this way, but...' Neither would have worked. Both ploys would destroy the illusion. More realistically, perhaps, the commentary could have been less authoritative, and could have inserted some question marks here and there.

Professional palaeontologists should rejoice. I see WWD as a natural progression from previous endeavours, both in the promotion of the public understanding of science and in the reconstruction of past life. From the time of the discovery of the first dinosaurs in the 1820s, palaeontologists have published popular accounts and illustrations. In 1854, Waterhouse Hawkins' models of dinosaurs were unveiled at Crystal Palace. These were life-sized sculptures of dinosaurs, literally in concrete form, and painted garishly. Cries of scientific anguish? Selling of souls for popular approbation? No. This may have had something to do with the fact that the models were sponsored by Sir Richard Owen, the leading natural scientist of his day, and they were backed by the Prince Consort. There were no complaints of trivialisation.

Now that we have moving pictures and computers, it is absolutely right to bring them into service as scientific tools. Sir Richard Owen would have done so, and so should we. Science is about taking risks, about making informed speculations. It's safest for a scientist not to speculate, but it's only the speculators - Newton, Darwin, Einstein - who made a mark.

Moving dinosaurs are a natural end-point of the palaeontological endeavour. When a palaeontologist has the good fortune to find a new dinosaur, the normal procedure is to remove the bones from the rock, string them together in a lifelike pose, reconstruct the muscles from scars on the bones, clothe the body in skin, and commission an artist to make a lifelike painting. No palaeontologist can afford to pay for computer animation. So, in my view, the BBC has done the palaeontological world a marvellous service, in presenting a multi-million-pound research grant to help us do this work. Roll on the next series!

## References

Further information about the themes in this article, and the WWD series, may be found in:

Benton, M. J. (2000). *Walking with dinosaurs: the facts*. London: BBC Worldwide.

Haines, T. (1999). *Walking with dinosaurs: a natural history*. London: BBC Worldwide.

Martill, D. M. and Naish, D. (2000) *Walking with dinosaurs: the evidence*. London: BBC Worldwide.

Other material referred to in this article may be pursued in:

Benton, M. J. (1997). *Vertebrate palaeontology*. 2nd edition, reissued, 2000. Oxford: Blackwells Scientific. A basic textbook account of vertebrate palaeobiology, including chapters on dinosaurs, pterosaurs, and other extinct reptiles.

Henderson, D. M. (1999). Estimating the masses and centers of mass of extinct animals by 3-D mathematical slicing. *Paleobiology*, 25: 88-106. This paper reports Donald Henderson's method for calculating centres of mass. His remaining work will be published shortly.

Donald Henderson's step-cycle reconstructions of theropods and pterosaurs may be seen here.

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