A palaeogravity calculation based on weight and mass estimates of *Acrocanthosaurus atokensis*

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Abstract

There is great interest in calculating accurate values for Earth's palaeogravity. One fundamental technique to quantify palaeogravity is to compute weight against mass estimates of ancient animals. This technique is applied to the theropod dinosaur *Acrocanthosaurus atokensis* "Fran" NCSM 14345 specimen. The results indicate that a palaeogravity of 0.54g ± 20% is a reliable estimate for 113 Ma.

Key words: Palaeogravity, *Acrocanthosaurus atokensis*

1. Introduction to palaeogravity

A more extensive introduction to the study of palaeogravity was given in Hurrell (2018). The key points identified in that publication were:

- There has been great interest in calculating palaeogravity with a number of authors speculating that ancient life might indicate palaeogravity was less than the present average of 1g (9.81 m/s^2).[1]

- The weight-mass method was identified as one of the most accurate ways to calculate palaeogravity from ancient life. It can be calculated from:

$$g_a = w_a / m$$

where g_a is palaeogravity at some predefined age, w_a is the weight at that age and m is the mass. Since mass never varies it does not need a subscript to denote its age.

- Accurate values of weight and mass are required to apply this technique. Weight can be determined from the strength of leg bones, and mass can be determined from model reconstructions and tissue density.

- The study of Hurrell (2018) observed that a wide divergence of mass estimates seemed to be mainly due to variation in the size estimates of the gut volume. Better palaeogravity estimates might therefore be obtained from studying carnivore theropod dinosaurs which should not be subject to such high subjectivity.

The dinosaur chosen for this study of palaeogravity was the *Acrocanthosaurus atokensis* "Fran" NCSM 14345 specimen.

[1] See for example: Harlé (1911), Kort (1947), Pennycuick (1992, 2008, 2016), Hurrell (1994, 2011, 2012, 2014a, 2014b, 2018, 2019), Carey (2000), Mardfar (2000, 2012, 2016), Erickson (2001), Sato *et al* (2009), Scalera (2003a, 2003b), Strutinski (2012, 2016a, 2016b), and Maxlow (2014).

2. *Acrocanthosaurus atokensis*

Acrocanthosaurus atokensis is a species of theropod dinosaur that existed in what is now North America during the Early Cretaceous. Its fossil remains are found mainly in Oklahoma, Texas and Wyoming in the USA, although teeth attributed to *Acrocanthosaurus atokensis* have been found as far east as Maryland.

Acrocanthosaurus atokensis was a bipedal predator. Its name means "high-spined lizard" in recognition of the high neural spines on many of its vertebrae. These might have supported a sail structure over the animal's neck, back and hips. *Acrocanthosaurus atokensis* was the largest theropod in its ecosystem preying on sauropods, ornithopods and ankylosaurs.

Thomas & Farlow (1997) observed that many large theropod footprints found in the area were most likely to have been made by *Acrocanthosaurus*. Farlow (2012) described the continuing work to understand these trackways. One of the best known dinosaur trackways in the area is in the Paluxy river bed, showing a chase sequence of a herd of sauropods being followed by a least one theropod. It might even record the moment the theropod attacked one of the sauropods.

Acrocanthosaurus atokensis was first described and named from partial skeletons discovered in the 1940s and 1950s. A much more complete skeleton, "Fran" NCSM 14345, was recovered from the Antlers Formation of Oklahoma by amateur collectors Cephis Hall and Sid Love. The Antlers Formation was laid down during the late Aptian to early Albian stages of the early Cretaceous, placing its age at approximately 113 million years old. The specimen was eventually purchased by Allen and Fran Graffham of Geological Enterprises in Ardmore, Oklahoma, who also financed the preparation and restoration of the specimen by the Black Hills Institute in South Dakota. The completed skeletal reconstruction was then housed at the North Carolina Museum of Natural Sciences in Raleigh.

"Fran" NCSM 14345 was scientifically described by Currie and Carpenter (2000). It had a rather high, narrow body and proved to be the largest known specimen, with a body length similar to *Tyrannosaurus*, although probably lighter. The skeleton included the only known complete skull and forelimb. The complete forelimb enabled Senter & Robins (2005) to analyse the function and range of motion of the forelimb. They concluded that the forelimbs could not have been used for locomotion since they did not make contact with the ground, but would have served a predatory function to grasp prey. Each arm terminated in three wickedly curved large claws, well designed for capturing and holding prey.

Carpenter (2016) has recently written a book with a thorough description of the five known specimens of *Acrocanthosaurus atokensis*.

3. Mass estimates from body volumes

The mass of a dinosaur can be estimated by reconstructing a model and using the calculated volume and tissue density to work out the mass of the living animal. However, as the well-known palaeontologist Paul (1988, p134) explained: "Estimating the mass of a fossil species is not an exact science." He considered that the margin of error of an accurately restored model was probably about ± 15% even when the skeletal restoration was not missing any major sections. Certainly most estimates fall within this range with only a few outliers.

For the purposes of this palaeogravity calculation we need to specify an optimal mass estimate, or a "best guess", for the specimen. A key aspect of picking an optimal mass estimate from the range of possible options is to understand why mass estimates vary. These are the key factors to consider:

- Unfortunately there is still a great deal of confusion between weight and mass and this has resulted in some palaeontologists trying to produce low mass estimates to conform to weight. Paul (1988, p130) for example explains how he used weight calculated from bone dimensions "to expose implausibly high mass estimates … so a higher mass estimate should be examined critically." All this general confusion between weight and mass has undoubtedly reduced some mass estimates to unreasonably low values.

- Conway *et al* (2013) have recently criticised "shrink-wrapped" reconstructions, arguing that many of these skinny reconstructions cannot be accurate. They note that while palaeontological artists have been keen to portray most dinosaurs as slim, sleek animals where every muscle can clearly be seen, no living mammal, reptile or bird has such "visible" anatomy. They argue that the use of modern "high-fidelity" musculoskeletal reconstructions indicates that these skinny "shrink-wrapped" reconstructions have gone too far. To illustrate just how unlikely some of these reconstructions are they used the same "shrink-wrapping" method on modern-day animals to produce virtually unrecognisable skinny versions of modern animals.

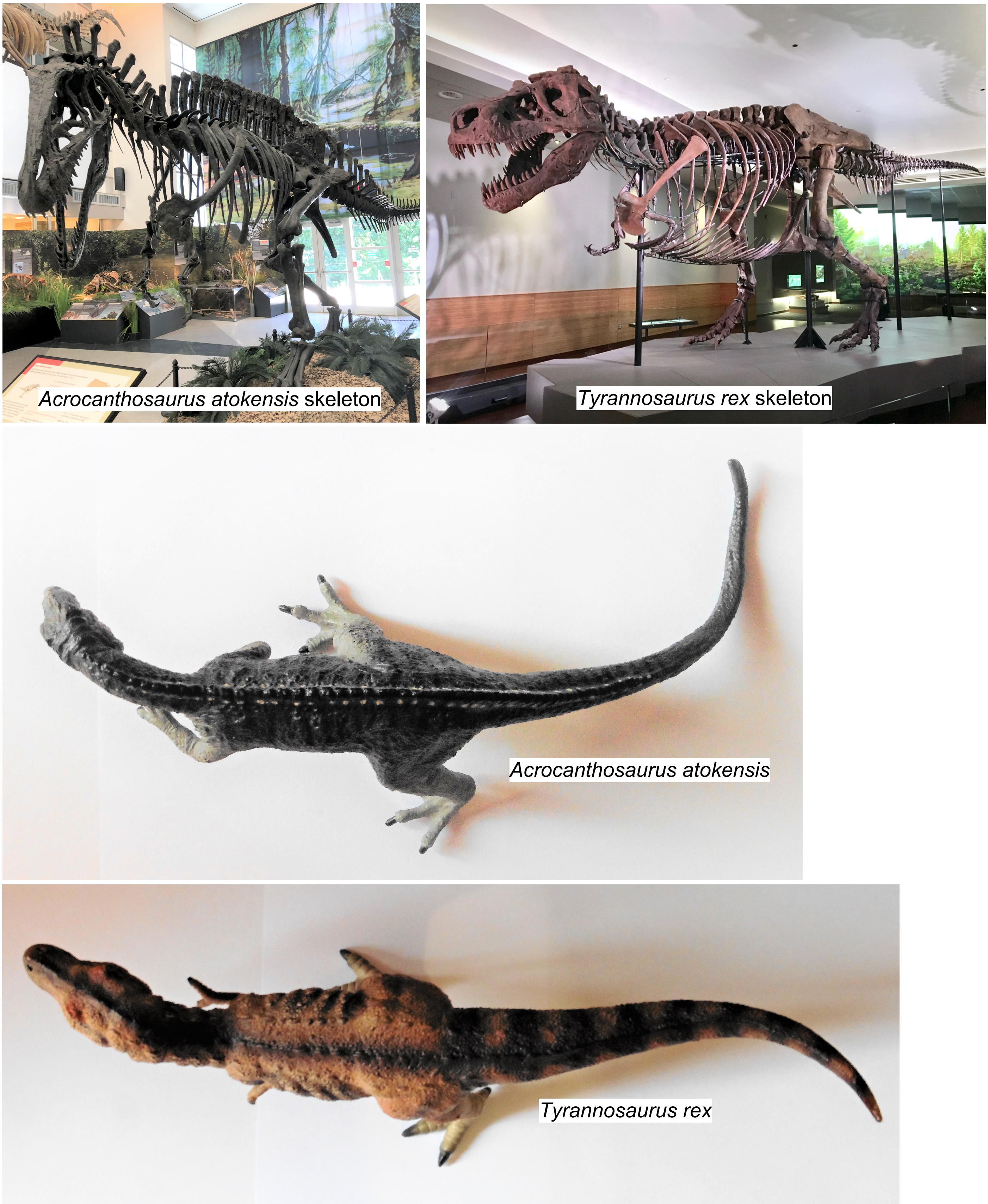

Figure 1.

Acrocanthosaurus atokensis compared with *Tyrannosaurus rex*. Although both species were approximately the same length, the body profile of *Acrocanthosaurus atokensis* is narrower than the wider *Tyrannosaurus rex* (see text for discussion). Skeleton photos © VSPYCC (2018) and © Zissoudisctrucker (2018).

- Some palaeontologists have decided to completely ignore weight estimates from bone dimensions. The differences between weight and mass estimates are so great for large bipeds that Hutchinson *et al* (2007) concluded that: "...it is almost certain that these scaling equations greatly underestimate dinosaur body masses... Hence, we recommend abandonment of their usage for large dinosaurs." This would indicate that the mass estimates of palaeontologists following this line of reasoning will not be influenced by the general confusion between weight and mass.

It is therefore expected that mass estimates that use "shrink-wrapped" reconstructions will be in the lowest range possible, providing a very useful indication of the minimum mass possible, but probably lower than reality. Palaeontologists who have decided to disregard weight estimates from bone dimensions will be more likely to provide the best mass estimates.

Many reconstructions assume the average tissue density of theropod dinosaurs was in the 0.8 to 1 tonne cu.m range and this obviously affects the mass estimates by a large amount. There clearly isn't any generally consensus on one consistent value since different densities are used even within the same study - Hutchinson *et al* (2011) for example used 0.807, 0.85, 0.87 and 0.985 tonne cu.m for different specimens of *Tyrannosaurus rex*. Life today has an average tissue density of about 0.97 tonne cu.m. This average value includes the lung volume, typically between 5 to 6 % of the total body volume for a range of life from small to large. It would seem unlikely that theropod dinosaurs would need lungs that were nearly twice the size of present-day life, so estimates of 10% allowances for lungs seem excessive. Even if we assume that lung volume is 10% instead of a more typical 6% maximum, the average tissue density would only be 0.93 tonne cu.m. Similar reasoning implies that the tissue density excluding the lungs is 1.03 tonne cu.m, not the 1 tonne cu.m often assumed for these calculations. Many studies also assume that there were additional isolated air-sacs within dinosaur bodies which would reduce their mass. However, the buoyancy effect of the lungs means that living animals can float in water because they are slightly less dense, while a drowned animal sinks in water once the lungs are full. Since dinosaur fossils are often recovered from the bottom of ancient rivers or lakes it would indicate that their tissue density was similar to today's life when they drowned. It would therefore seem unlikely that dinosaurs contained any isolated air-sacs that reduced their mass by a substantial amount. Taking all these considerations together, an average tissue density of about 0.95 tonne cu.m seems a more reasonable estimate allowing for an extra-large lung volume of about 8% (even though this is unproven) with only minimal extra air-sac structures.

Although Currie and Carpenter (2000) didn't give a mass estimate during their scientific description of the *Acrocanthosaurus atokensis* "Fran" NCSM 14345 specimen, they noted that the minimum transverse diameter of the femur was 150 mm, slightly less than the corresponding dimension in adult specimens of *Tyrannosaurus rex* (i.e. BHI 3033, MOR 555, TMP 81.12.1). The authors thought that this seemed to

Mass and weight estimates in tonne for *Acrocanthosaurus atokensis* NCSM 14345				
Mass from models tonne				
Reference	Mass	Notes	Density tonne/cu.m	Volume cu.m
Currie & Carpenter (2000)	?	"lighter than Tyrannosaurus" (6.1 tonne)		
Henderson & Snively (2004)	5.67	Between 5.1 to 6.2 for body width changes	0.90	6.30
Henderson (2008)	5.07	Personal communication to Bates *et al* (2009)	0.90	5.64
Bates *et al* (2009)	6.18	Between 5.7 to 7.25 tonne	0.91	6.78
Paul (2010, 2016a, 2016b)	4.40	Specimen identified	0.85	5.18
Carpenter (2016)	4.50	Rounded up from Paul's estimate	?	
Snively *et at* (2019)	5.47	Data source Bates *et al* (2009)	?	
Model	4.35	Acrocanthosaurus: The Carnegie collection	0.95	4.58
Best estimate	**4.50**		0.95	4.74
Weight from leg stress tonne(f)				
Reference	Weight	Notes		
Currie & Carpenter (2000)	2.41			
Bone dimensions	2.41	Bipedal calculation		
Best estimate	**2.41**			

Within ±	20%
Best gravity estimate	**0.54**
Average Age	113

Table 1.

Mass and weight estimates in tonne for the *Acrocanthosaurus atokensis* "Fran" NCSM 14345 specimen.

indicate "that *Acrocanthosaurus atokensis* was a lighter animal than *Tyrannosaurus*, even though the overall length of the body was similar."

Although Currie and Carpenter (2000) didn't quantify what a lighter animal might be it is possible to estimate this mass from their observations. The calculated bone strength of the *Acrocanthosaurus atokensis* "Fran" NCSM 14345 specimen, compared to the *Tyrannosaurus rex* specimens BHI 3033, MOR 555 and TMP 81.12.1, are 64%, 60% and 47%. If the mass of these *Tyrannosaurus rex* specimens is approximately 6.1 tonne[1] then "Fran" NCSM 14345 would be in the 3 to 4 tonne mass range. Of course this is all circular reasoning since a variation in gravity, the very quantity we are trying to calculate, would affect the results. Nonetheless it is a useful observation.

The concept that *Acrocanthosaurus atokensis* would be noticeably less massive than a similar length *Tyrannosaurus rex* seems to be confirmed by an examination of their body forms. Figure 1 illustrates how *Acrocanthosaurus atokensis* is noticeably narrower than a similar length *Tyrannosaurus rex*. Much of the body area is taken up by the narrow high neural spines on many of its vertebrae. These high spines manage to make it look larger without adding to its mass. Carpenter (2016, p56) proposes that this would help it establish its own territory by intimating intruders. The average relative body width of *Acrocanthosaurus atokensis* is approximately 20% narrower compared to *Tyrannosaurus rex*, so it would be easy to argue that an *Acrocanthosaurus atokensis* mass estimate should be lower than a similar length *Tyrannosaurus rex*.

Henderson and Snively (2004) estimated a mass of 5.672 metric tonne for the *Acrocanthosaurus atokensis* "Fran" NCSM 14345 specimen. Coordinates defining the limb and body shape were digitised from published skeletal reconstructions of Currie & Carpenter (2000) using a 'slicing' technique developed by Henderson (1999). The initial density of the entire postcervical region was set the same as water at 1 tonne cu.m. Lungs and air sacs were then modelled as hollow cavities with a volume equal to 10% of the axial body. An average tissue density wasn't given by the authors but the detail offered would indicate that it would be 0.9 tonne cu.m. The authors also altered the modelled body widths by ± 10% to estimate high and low masses as 6.171 tonne and 5.173 tonne. Bates *et al* (2009) reported that Henderson had later refined the original model to reduce the mass estimate to 5.072 tonne.

[1] Previous studies indicate that the mass of these specimens of *Tyrannosaurus rex* would be approximately 6.1 tonne. See Hurrell (2019) for additional discussion.

Bates *et al* (2009) estimated a "best estimate" mass of 6.177 tonne using a 3D digital model based on the *Acrocanthosaurus atokensis* "Fran" NCSM 14345 skeleton. They selected this specimen because it was the "most complete specimen (54% complete)". The maximum body mass range was estimated at between 5.75 to 7.25 tonne for their model. The average tissue density was computed to be 0.91163 tonne cu.m. They considered the latest Henderson estimate of 5.072 tonne was unreasonable because it disagreed with their most gracile model of 5.75 tonne. Interestingly, the Bates *et al* (2009) team also estimated a best mass of 6.07182 tonne for the "Wankel rex" MOR 555 *Tyrannosaurus rex*, implying that a similar length *Acrocanthosaurus atokensis* would be heavier than a *Tyrannosaurus rex*, seemingly conflicting with the observation of their relative widths.

Paul (2010, 2016a) estimated a mass of 4.4 tonne for *Acrocanthosaurus atokensis*. Paul (2016b) confirms this estimate is for the "Fran" NCSM 14345 in his Dinosaur Mass Tables. Since Paul is well known for producing "shrink-wrapped" reconstructions this is probably amongst the lowest possible mass estimates.

Carpenter (2016, p86) estimated the mass of *Acrocanthosaurus atokensis* to be 4.5 tonne, rounding up from Paul's estimate of the "Fran" specimen (personal communication, 2019).

Snively *et al* (2019) calculated the mass of the "Fran" NCSM 14345 specimen as 5.47 tonne during their project to calculate the rotational inertia of a number of theropod dinosaurs. This estimate was produced by first digitising body segments to calculate the body volume, then multiplying this by the tissue density to calculate the mass. Various densities were chosen for different parts of the body: the head was 0.99 tonne cu.m, the neck 0.93 tonne cu.m, the trunk 0.74 tonne cu.m and post-thoracic and leg regions 1.06 tonne cu.m.

The scaled mass of a commercially available model was calculated. The model chosen was a 1/40 scale model from "The Carnegie" collection. The volume mass estimate apparatus described by Alexander (1989, p19-20) indicated the measured scaled mass was 4.347 tonne.

Certain assumptions need to be made to produce a "best guess" optimal mass estimate. The initial scientific description of Currie & Carpenter (2000) estimated the mass as lighter than a similar length *Tyrannosaurus* and this would indicate a mass around 3 to 4 tonne. The Henderson & Snively (2004) estimate of 5.67 tonne was later reduced to 5.07 by Henderson (2008). The Bates *et al* (2009) estimate of

6.18 tonne is larger than their estimate for a similar length *Tyrannosaurus rex*. The Paul (2016a, 2016b) "shrink-rapped" estimate of 4.4 is likely to be amongst the lowest possible. The Carpenter (2016) mass of 4.5 tonne is a rounded up estimate. The Snively *et al* (2019) is high at 5.47 tonne, and the "Carnegie collection" 4.35 tonne model is the lowest of all the estimates. Trying to remove all sources of possible error indicates a reasonable average mass estimate would be about 4.5 tonne, assuming the specimen was an optimal size and density.

4. Weight from bone dimensions

The weight of the *Acrocanthosaurus atokensis* "Fran" NCSM 14345 specimen can be directly calculated from the strength of its leg bones. The standard metric unit for weight is newton but the incorrect unit of kg or tonne has been widely used in most previous studies. I have highlighted it is really a force by denoting weight as either kg(f) or tonne(f). A kg(f) force would be multiplied by 9.81 to convert it to the standard metric unit of newton.

Anderson *et al* (1985) studied the bones of a range of mammals to see if there were any rules that would allow them to estimate the weight of an animal from just its leg bones. This would be very useful for extinct animals such as dinosaurs.

The Anderson team chose to study the major leg bones which are often well preserved in otherwise incomplete fossils. A good indication of the weight of present-day animals is the circumference of the upper leg bones – the humerus and the femur. The bones were measured where they were the thinnest, and so the weakest, usually about half way along the length of the bones. These two circumferences were then added together to give the total circumference. Bipedal animals only need the femur circumference.

The Anderson team used statistical analysis to define the equation for a bipedal animal:

$$W = 0.00016.c^{2.73}$$

where: W = body weight in kg(f), and c = femur circumference in mm.

This equation can be used to estimate the body weight of a bipedal animal from just the femur bones.

One use of these equations would be to calculate the weight of extinct animals and the Anderson team applied their equations to a number of dinosaurs. Most dinosaurs should have been close to the best fit line, and certainly within ± 30%, but the calculated results indicated dinosaurs that were much lighter than anyone had ever thought possible.

Since the bone results were first published in 1985 the mass of dinosaurs based on volume methods has been reduced to try to agree with these super-lightweight estimates for dinosaurs. Since the two methods give very different results some palaeontologists, as noted previously for Hutchinson *et al* (2007), advised abandoning the use of the formula based on leg bones entirely, since they cannot get dinosaurs' mass small enough to agree with the bone weight calculations. These types of criticisms encouraged Campione *et al* (2012) to slightly modify the original Anderson *et al* (1985) formula to produce increased weight estimates for larger dinosaurs more in line with the volume mass estimates.

The original Anderson *et al* (1985) formula was chosen to calculate the weight estimates in this study.

Currie & Carpenter (2000) calculated the weight of *Acrocanthosaurus atokensis* "Fran" NCSM 14345 to be 2.4 tonne based on the Anderson *et al* (1985) formula and the measured mid-shaft circumference of 425 mm. As might be expected, these results agreed with the calculated value of weight produced directly from bone dimensions.

5. Palaeogravity

Palaeogravity was calculated using the standard formula previously described:

$$g_{113} = w_{113} / m$$

For the *Acrocanthosaurus atokensis* "Fran" NCSM 14345 specimen palaeogravity was estimated as 0.54g at approximately 113 million years ago.

6. Accuracy

The specimen considered in this paper was 54% complete and the identification of four other partial specimens enables an accurate restoration. It has been placed within a ± 20% accuracy band for palaeogravity estimates.

7. Suggested Citing Format

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