Palaeogravity calculations based on weight and mass estimates of two *Coelophysis bauri* specimens

Stephen W. Hurrell
email: papers@dinox.org

First Published: 21 June 2019

Cite: Hurrell, S.W. (2019). Palaeogravity calculations based on weight and mass estimates of two *Coelophysis bauri* specimens. http://dinox.org/hurrell2019c

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 *Coelophysis bauri* specimens AMNH 7223 and AMNH 2704. The results indicate palaeogravities of 0.44g ± 20% for the AMNH 7223 specimen and 0.42g ± 40% for the AMNH 2704 specimen are reliable estimates for 210 Ma.

Key words: Palaeogravity, *Coelophysis bauri*

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 specimens chosen for this study of palaeogravity were two *Coelophysis bauri* specimens, AMNH 7223 and AMNH 2704.

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

2. *Coelophysis bauri*

Coelophysis bauri is one of the earliest known dinosaurs, living during the latter part of the Triassic Period. It was a small and slender bipedal carnivore, growing up to 3 metre long.

Specimens of *Coelophysis bauri* were found as early as the 1880s but the remains were too poorly preserved to allow a complete description of the species. In 1947 hundreds of *Coelophysis bauri* specimens were discovered in a substantial 'graveyard' at the Whitaker Ghost Ranch Quarry in New Mexico. The vertebrate fossil assemblage at the Ghost Ranch Quarry is considered to have formed in the Apachean (late Norian-Rhaetian) in the Triassic Period, placing its age at approximately 210 Ma.

Colbert (1989) conducted a comprehensive study of all the fossils. The new fossils were so numerous that this primitive theropod became one of the best known dinosaurs. One of the nearly complete specimens (AMNH FR 7224) was chosen as the type specimen for the entire genus, replacing the original poorly preserved specimen.

Rinehart et al (2009) described how the finely serrated teeth of *Coelophysis bauri* indicated a carnivorous lifestyle. This was further confirmed by the skeleton of NMMNH P-44801 which had a small amount of very small, sparse, unidentifiable bone fragments within its stomach.

Colbert (1989) considered *Coelophysis bauri* was adapted for running. Carrano (1999) and Rinehart *et al* (2009) agreed that the evidence indicated it was cursorial. The hind limb of *Coelophysis bauri* had a short femur, long tibia and pes, a reduced number of functional toes, and a strong simple ankle that clearly sacrificed flexibility for strength. It all indicated that this animal must have been a runner.

Rinehart *et al* (2009) considered that the large group of *Coelophysis bauri*, and other animals, were probably killed when they were buried by a flood. The quarry site was a generally small, probably ephemeral pond or oxbow lake lying on the floodplain of a river. These indicators, taken together with the fact that the dinosaur skeletons are contained in an overbank flood deposit, give a fairly strong impression that the animals were overcome, drowned and buried by a flood event, and that they may have been alive and struggling to remain upright during the process.

Coelophysis bauri shows variations in the skull and neck lengths of various specimens and this is generally considered to be due to sexual dimorphism. The long skull and long neck morph is “gracile,” and a short skull and short neck morph is “robust.” Rinehart *et al* (2009) applied the empirical formula of Christiansen & Fariña (2004) to calculate the mass of the 70 specimens for which they had femur length data. The typical mass of the largest gracile form was estimated at approximately 15 kg while the robust form was 20 kg.

Griffin & Nesbitt (2016) challenged the concept of specific gracile and robust forms of *Coelophysis bauri*. After studying 174 specimens they found that this population contained a wide range of mature animals of different body sizes. They concluded that the variation in body size was a product of a variation in

Figure 1.

A commercial model of *Coelophysis* produced by Wild Safari.

developmental patterns between individuals instead of sexual dimorphism.

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 many 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.

- 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 body mass 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 to 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.

One useful check of mass is to measure a commercially available model and compute the mass for that reconstruction using the volume mass estimate apparatus described by Alexander (1989, p19-20). The model chosen was a *Coelophysis* produced by Wild Safari (see figure 1). Measurements of the model enabled the correct scale to be determined for both specimens considered.

3.1 Specimen AMNH 7223

Paul (1988) estimated the mass of the AMNH 7223 specimen to be 15.3 kg after drawing up the skeleton contained in one fossil block. He considered this specimen to be a gracile form. Paul (2010, 2016a) gives a mass estimate of 25 kg at 3 metre long which is presumably a generic mass estimate for the largest specimen. Reducing this mass estimate to the scale of the AMNH 7223 specimen would give 25 x $(2.52/3)^3$ = 14.8 kg. Paul (2016b) gives a mass estimate of 13.5 to 15.3 kg for the AMNH 7223 specimen in his Dinosaur Mass Tables and the average of these two values would be 14.4 kg.

Rinehart *et al* (2009) applied the empirical formula of Christiansen & Fariña (2004) to calculate mass based on the femur length of the specimens. Applying this formula to the AMNH 7223 specimen estimates the mass at 15.39 kg.

Henderson (2018) constructed a three-dimensional digital model of *Spinosaurus* to test the suggestion that it would have been able to float. Five other theropods were chosen for comparison and this resulted in the reconstruction of a digital model of *Coelophysis*. The source of the illustrations used to create the model was Paul (1988) and Currie (1997). The specimen is not identified but the overall length of the model is 2.52 metre with a mass of 10.3 kg assuming an average density of 0.828 tonne cu.m with a volume of 0.0124 cu.m. Paul (1988) estimates the overall length of the AMNH 7223 specimen as 2.68 metre and this would indicate that a digital model scaled-up to the size of the AMNH 7223 specimen would be 10.3 x $(2.68/2.52)^3$ = 12.39 kg, with a scaled-up volume of 0.0124 x $(2.68/2.52)^3$ = 0.0149 cu. m.

The commercial model was used as a standard reference and indicated a mass of 14.7 kg, with a calculated scale of 1/9.7.

These estimates are all within a close range. In practice the largest variation is the assumption of different values of tissue density. Taking all these factors together an optimal "best" mass estimate would be 15 kg.

3.2 Specimen AMNH 2704

Rinehart *et al* (2009) applied the empirical formula of Christiansen & Fariña (2004) to calculate mass based on the femur length of the specimens. Applying this formula to the AMNH 2704 specimen estimates the mass at 17.38 kg.

The commercial model was used as a standard reference and indicated a mass of 16.7 kg, with a calculated scale of 1/9.3.

Mass and weight estimates in kg for *Coelophysis bauri* AMNH 7223				
Mass from models kg				
Reference	Mass	Notes	Density tonne/cu.m	Volume cu.m
Paul (1988)	15.30	Specimen identified: 2.68 m long	0.85	0.0180
Rinehart *et al* (2009)	15.39	Using fermur length formula	?	
Paul (2010, 2016a)	25.00	3 m long: specimen unclear	0.85	0.0294
Paul (2016b)	14.40	Specimen identified: between 13.5/15.3	0.85	0.0169
Henderson (2018)	10.30	Specimen unidentified: 2.52 m long	0.83	0.0124
Model	14.70	Scaled to AMNH 7223: See text	0.95	0.0155
Best estimate	**15.00**		0.95	0.0158
Weight from leg stress kg(f)				
Reference	Weight	Notes		
Bone dimensions	6.58	Bipedal calculation		
Best estimate	**6.58**			

Within ±	20%	Gracile
Best gravity estimate	**0.44**	
Average Age	210	

Table 1.

Mass and weight estimates in kg for the *Coelophysis bauri* AMNH 7223 specimen.

Mass and weight estimates in kg for *Coelophysis bauri* AMNH 2704				
Mass from models kg				
Reference	Mass	Notes	Density tonne/cu.m	Volume cu.m
Rinehart *et al* (2009)	17.38	See text	?	
Model	16.70	Scaled to AMNH 2704: See text	0.95	0.0176
Best estimate	**17.00**		0.95	0.0179
Weight from leg stress kg(f)				
Reference	Weight	Notes		
Bone dimensions	7.15	Bipedal calculation		
Best estimate	**7.15**			
Within ±	40%	Gracile		
Best gravity estimate	**0.42**			
Average Age	210			

Table 2.

Mass and weight estimates in kg for the *Coelophysis bauri* AMNH 2704 specimen.

There is not as much data available for the AMNH 2704 specimen but an optimal "best" mass estimate would be 17 kg.

4. Weight from bone dimensions

The weight of the two *Coelophysis bauri* specimens can be directly calculated from the strength of their 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 published in 1985 the mass of dinosaurs based on volume methods have 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.

The weight of the AMNH 7223 and the AMNH 2704 specimen was calculated as 6.58 kg(f) and 7.15 kg(f).

5. Palaeogravity

Palaeogravity was calculated using the standard formula previously described:

$$g_{210} = w_{210} / m$$

Palaeogravity for the *Coelophysis bauri* AMNH 7223 specimen was estimated as 0.44g, while the AMNH 2704 specimen was 0.42g, both at approximately 210 million years ago.

6. Accuracy

The AMNH 7223 specimen was confidently placed within a ± 20% accuracy band for palaeogravity estimates, while the AMNH 2704 specimen was placed in a tentative ± 40% accuracy band.

7. Suggested Citing Format

Hurrell, S.W. (2019). Palaeogravity calculations based on weight and mass estimates of two *Coelophysis bauri* specimens . http://dinox.org/hurrell2019c

8. Publication History

First published at dinox.org: 21 June 2019.

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