Palaeogravity calculations based on weight and mass estimates of four *Tyrannosaurus rex* specimens

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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 four specimens of *Tyrannosaurus rex*, representing some of the most complete theropod dinosaur skeletons known. For the *Tyrannosaurus rex* specimens "Carnegie" CMNH 9380, "Wankel rex" MOR 555, "Stan" BHI 3033 and "Sue" FMNH PR 2081, the results indicate that palaeogravities of 0.67g, 0.66g, 0.61g, and 0.64g ± 20% respectively are reliable estimates for 67 Ma.

Key words: Palaeogravity, *Tyrannosaurus rex*

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 methods 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 bone 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 *Tyrannosaurus rex* since this is one of the best known carnivore theropod dinosaurs.

[1] See for example: Harlé (1911), Kort (1949), Pennycuick (1992, 2008, 2016), Hurrell (1994, 2011, 2012, 2014a, 2014b, 2018), Carey (2000), Mardfar (2000, 2012, 2016), Erickson (2001), Sato *et al* (2009), Scalera (2003a, 2003b), and Strutinski (2012, 2016a, 2016b)

2. Tyrannosaurus rex

The large carnivorous dinosaur *Tyrannosaurus rex* has a special place in the general public's heart. Many people are fascinated by one of the largest most ferocious two legged animals to ever walk our planet. It is easily recognisable by its giant size with long hind limbs, large head, small forelimbs and long tail. For the professional palaeontologist it provides a set of near-complete skeletons capable of providing years of study.

Tyrannosaurus rex was amazingly large by present-day standards. The average adult specimens found to date had a body mass around 6 to 8 tonne with the largest specimens reaching nearly 10 tonne. That is more massive than most present-day African bull elephants.

The name *Tyrannosaurus rex* was first published by Henry Osborn in 1905 to describe a large theropod dinosaur discovered by Barnum Brown within the Hell Creek Formation of Montana.[1] This first specimen went on display at the Carnegie Museum of Natural History and became known as the "Carnegie" CMNH 9380 specimen. "Carnegie" is an informal nickname while CMNH 9380 is the official reference allocated by all museums. A more complete specimen AMNH 5027 was later discovered in 1908 and this specimen was often used to fill in some of the details missing in the "Carnegie" skeleton.

In 1987 Stan Sacrison discovered a nearly complete skeleton of *Tyrannosaurus rex* near Buffalo in the Hell Creek formation and this became known as the "Stan" BHI 3033 specimen. In 1988 Cathy Wankel was hiking in Hell Creek when she discovered the "Wankel rex" MOR 555 specimen. The discovery of another *Tyrannosaurus rex* specimen occurred in 1990 when Susan Hendrickson discovered the "Sue" FMNH PR2081 specimen. The publicity surrounding its disputed ownership in the early 2000s re-ignited even more interest in fossils of this gigantic creature.

The discovery of these near-complete specimens combined with numerous other finds has enabled palaeontologists to reconstruct *Tyrannosaurus rex* in impressive detail, making it one of the best known dinosaurs.

Johnson (2008) noted that the exact age of a Tyrannosaurus rex specimen is still surprisingly difficult to ascertain. The geological formations where they are found have been radiometrically dated at between 65 ± 0.3 Ma to 70.6 ± 0.6 Ma. More accurate values within the formation are prone to errors. Fortunately an average of 67 Ma is sufficient for the palaeogravity estimates in this paper.

[1] See Larson (2008a) for a complete account of one hundred years of *Tyrannosaurus rex.*

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 these palaeogravity calculations we need to specify an optimal mass estimate, or a "best guess", for each 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.

Early mass estimates up to the late 1980s covered a wider range than those of today. Paul (1988) for example estimated the mass of the biggest specimen indicated a mass up to 12 tonne based on a tooth-bearing upper jaw. Within less than a decade it was clear this was unlikely, allowing Paul (1997, p135) to revise his thoughts and declare mass estimates as high as 12 tonne as excessive.

With the new discoveries it was possible for palaeontologists to estimate the mass of different-sized individuals. The amount of skeleton recovered for each specimen varies. According to Hutchinson *et al* (2011) the "Carnegie" specimen was only 11% complete even though it is the type specimen[1], "Wankel rex" was 49% complete, "Stan" 63% and "Sue" 73%. Sometimes various parts of a skeleton can be mirrored to fill in missing elements, thereby further increasing the totality of the skeleton. Palaeontologist can now even provide mass estimates for specific specimens of *Tyrannosaurus rex* split between "robust morph" and "gracile morph" skeletal reconstructions to try to account for sexual dimorphism.

Hutchinson *et al* (2011) used three-dimensionally scanned computer models of four large, well-preserved fossil specimens as well as a putative juvenile individual to estimate body mass. The computer models produced were for the aforementioned "Carnegie" CM 9380, "Sue" FMNH PR 2081, "Stan" BHI 3033, "Wankel rex" MOR 555 plus "Jane" BMR P2002.4.1. The team characterised possible inaccuracies in their reconstructions, including not only subjectivity but also incomplete preservation and inconsistent articulations of museum skeletons. They also found that some of their reconstructions had a larger external outline and smaller internal chambers than others, hence lowering the size of the zero-density respiratory structures. This led to different density estimates for the different specimens: i.e., the density of the "Wankel rex" reconstruction was 0.985 tonne cu.m, 0.870 tonne cu.m for "Stan", 0.85 tonne cu.m for "Jane" and 0.807 tonne cu.m for the "Sue" and "Carnegie" specimens. Although these results caused ambiguity, they concluded that an average adult *Tyrannosaurus rex* had a body mass around 6 to 8 tonne, although the largest specimen, Sue, was more in the region of 9.5 tonne.

Perhaps the most interesting aspect of the Hutchinson *et al* (2011) study is their minimum mass estimates since the team considered it unlikely that the mass of the particular specimens studied could be much less than that calculated. Since the mass reconstructions of some other palaeontologists are based on skinny reconstructions these minimum mass estimates are a useful comparison. More details of their estimates are given later for each specimen quantified.

Many reconstructions assume the average tissue density of *Tyrannosaurus rex* 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 % for a range of life from small to large. It would seem unlikely that *Tyrannosaurus rex* 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 mean that living animals can float in water because they are slightly less dense but 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

[1] A "type" specimen (or a group of specimens) is the example that is formally attached to the published scientific name and defines the characteristics of the species.

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 *Tyrannosaurus rex* produced by Bullyland, specified as a 1/30 scale model. Measurements of the model indicated that its size was based on the "Carnegie" CMNH 9380 specimen. We know that the four specimens examined in this paper were all slightly different sizes: e.g. the femur bone lengths of the "Carnegie" CMNH 9380, “Wankel rex” MOR 555, "Stan" BHI 3033 and "Sue" FMNH PR 2081 specimens are 1200, 1275, 1310 and 1340 respectively. If we assume that femur bone length is a true indication of body scale then the respective scale of this model would be 1/30, 1/31.875, 1/32.75 and 1/33.5 with a calculated body mass of 6.328, 7.590, 8.232 and 8.811 tonne. However, this obviously assumes that the body shapes were all identical and we know this is not true since all animals have a range of body shapes from thin to fat. Various specimens of *Tyrannosaurus rex* have also been identified as “robust” and “gracile” and this difference in body shape is widely thought to be due to a difference between the sexes of the specimens.

3.1 Specimen "Carnegie" CMNH 9380 (& AMNH 5027)

Although this is the original type specimen it is only 11% complete. To overcome the incompleteness of the type specimen many mass estimates have incorporated partial skeletal material from other similar sized individuals such as AMNH 5027. Colbert (1962) reconstructed *Tyrannosaurus rex* as a robust animal with a mass of 7.7 tonne. Alexander (1985) used a model from the Natural History Museum of London to calculate a mass of 7.4 tonne. These early reconstructions were slightly incorrect since it was noted in the 1970s that the partial tail had been restored with too many vertebrae. The total length of the “Carnegie” *Tyrannosaurus rex* should be about 10 metres long, not the 13 metres once claimed.

Paul (1988) estimated a mass of 5.7 tonne for a composite of the first two known skeletons: specimen "Carnegie" CMNH 9380 and AMNH 5027. Although Paul’s reconstructions are nominally based on the mounted skeleton it would seem that he also modified his reconstructs thanks to his additional ability to produce a “shrink-wrapped” version. This would imply that the possible sources of error producing higher estimates, as noted by Hutchinson *et al* (2011), may have been removed to produce a lower estimate. One interesting observation by Paul (1988, p344) is that the previous mass estimates of Colbert (1962)

Table 1.

Mass and weight estimates in tonne for *Tyrannosaurus rex* “Carnegie” CMNH 9380 specimen.

Mass and weight estimates in tonne for *Tyrannosaurus rex* "Carnegie" CMNH 9380				
Mass from models tonne				
Reference	Mass	Notes	Density tonne/cu.m	Volume cu.m
Colbert (1962)	7.70		?	
Alexander (1985)	7.40		1.000	7.400
Paul (1988)	5.70	"Up to 7 tonne with fat"	0.850	6.706
Christiansen (1998)	6.30		0.950	6.632
Christiansen & Fariña (2004)	6.30	1273 mm long femur	0.950	6.632
Paul (2008)	5.70	Robust morph	0.850	6.706
Hutchinson *et al* (2011)	7.39	Possible range 7.394-14.6, prefer lower	0.807	9.162
Paul (2016b)	5.67	Dinosaur Mass Tables	0.850	6.671
Snively *et al* (2019)	6.99	Multiple body densities	?	
Model	6.33	Scaled to "Carnegie": see text	0.950	6.661
Best estimate	**7.00**		0.950	7.368
Weight from leg stress tonne(f)				
Reference	Weight	Notes		
Larson (2008b)	4.73			
Bone calculation	4.70	Bipedal calculation		
Best estimate	**4.70**			

Within ±	20%	Skeleton found = 11%, Robust
Palaeogravity	**0.67**	
Average Age	67	

and Alexander (1985) "massed close to 7 tonne are reasonable if they are presumed to include fat reserves". A decade later, Paul (2008) still estimated a mass of 5.7 tonne but now indicated this was a "robust morph" because Paul (2010, 2016a) had by then begun providing "robust morph" and "gracile morph" skeletal reconstructions. Paul (2016b) gives a more exact estimate of 5.67 tonne for the "Carnegie" CMNH 9380 specimen in his Dinosaur Mass Tables.

Christiansen (1998) calculated the body masses of a number of species, including *Tyrannosaurus rex*, by measuring the volume of scale models constructed from measurements taken directly from the mounted skeletons. Using the relative volume of muscles and the abdominal width estimate by Paul (1987, 1988), he obtained a mass of 6.3 tonne based on detailed measurements of the AMNH 5027 specimen, which is often combined with the "Carnegie" CMNH 9380 specimen to form a composite skeleton. The density was set at 0.95. The calculated mass for *Tyrannosaurus rex* was later repeated in Christiansen and Fariña (2004).

Hutchinson *et al* (2011) used a three-dimensionally scanned computer model of the "Carnegie" CM 9380 specimen to estimate a minimum possible mass of 7.39 tonne. This minimum mass estimate seems a useful comparison for the minimum possible mass estimates produced by other palaeontologists. In their discussion about possible sources of error they noted the "Carnegie" specimen was mounted with a proportionately longer, wider and taller torso than other more recent specimens, which would have increased their estimates for the Carnegie specimen.

Snively *et al* (2019) calculated the mass of a composite of the "Carnegie" CMNH 9380 and AMNH 5027 specimen as 6.9866 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 the post-thoracic and leg regions 1.06 tonne cu.m.

The commercial model was used as a standard reference and indicated a mass of 6.33 tonne. The fact that it indicates a low mass seems to confirm the Hutchinson *et al* (2011) observation that the "Carnegie" specimen is proportionally bulkier than other more recent specimens.

Certain assumptions need to be made to produce a "best guess" optimal mass: the reconstructions of Colbert (1962) and Alexander (1985) must have slightly overestimated the mass because the tail was too long and they used a high density estimate, the low estimates of Paul are too low due to the "shrink-wrapped" reconstructions combined with the reduced chest area and low density estimate, the Christian (1998) estimate is still low because it followed Paul but obtained a higher estimate with increased density, the higher estimates of Hutchinson *et al* (2011) are too high because of the reconstruction differences in the skeleton noted by the team, the Snively *et al* (2019) estimate is very nearly the same as the final "best guess" and the reference model is too low because of reconstruction differences in the skeleton. Trying to remove all sources of possible error indicates a reasonable average mass estimate would be about 7 tonne, assuming the "Carnegie" specimen was an optimal size.

3.2 Specimen "Wankel rex" MOR 555

This specimen is 49% complete. The 'Wankel rex' was discovered in 1988 and was exhibited at the Museum of the Rockies in Bozeman, Montana. Casts of this specimen are also on display at the National Museum of Scotland, the Australian Fossil and Mineral Museum, and the California Museum of Paleontology.

Farlow *et al* (1995) sculpted a 1/20 scale life restoration as a "gracile morph" based on the MOR 555 specimen. The volume of the model was then measured and the team made two estimates of the live mass: 6.325 tonne assuming a density of 1 tonne cu.m, and 5.376 tonne assuming a density of 0.85 tonne cu.m. They estimated the live mass of the full-sized dinosaur as approximately 6 tonne.

Paul (1997, p133) reconstructed MOR 555 with a volume of 6.3 cu.m. This has the typical "shrink-wrapped" reconstruction so it is probably the smallest volume possible. Combined with a low density estimate of 0.85 tonne cu.m this produces a mass of 5.4 tonne.

During a study to estimate the turning and running performance of *Tyrannosaurus rex* Hutchinson *et al* (2007) digitised a cast of the "Wankel rex' MOR 555 skeleton and constructed 30 different 3D models. Their body mass estimates ranged from 5.074 to 8.405 tonne, with various body volumes and densities. The team estimated that mean body densities probably fell within a range of 0.787 to 0.894 tonne cu. m. They found it was difficult to produce models that fell below 6 tonne but considered that their larger models greater than 8 tonne had an unrealis-

Mass and weight estimates in tonne for *Tyrannosaurus rex* "Wankel rex" MOR 555				
Mass from models tonne				
Reference	Mass	Notes	Density tonne/cu.m	Volume cu.m
Farlow *et al* (1995)	6.33	Gracile morph "approximately 6,000 kg"	1.000	6.325
Farlow *et al* (1995)	5.38	Gracile morph "approximately 6,000 kg"	0.850	6.325
Paul (1997)	5.40	Physical model volume	0.850	6.300
Hutchinson *et al* (2007)	6.58	5.074 to 8.405 tonne, best guess 6.583	0.827	7.960
Bates *et al* (2009)	6.07	Computer model	0.926	6.554
Hutchinson *et al* (2011)	5.93	Range 5.777-10.8: authors 'prefer lower'	0.985	6.024
Model	7.59	Scaled to "Wankel rex": see text	0.950	7.989
Best estimate	**6.10**		0.950	6.421
Weight from leg stress tonne(f)				
Reference	Weight	Notes		
Anderson at al (1985)	4.50			
Campbell, Marcus (1993)	3.50			
Larson (2008b)	4.03			
Bone calculation	4.00	Bipedal calculation		
Best estimate	**4.00**			

Within ±	20%	Skeleton found = 49%, Gracile
Palaeogravity	**0.66**	
Average Age	67	

Table 2.

Mass and weight estimates in tonne for *Tyrannosaurus rex* "Wankel rex" MOR 555 specimen.

tic amount of external flesh. There 'best guess' model had a mass of 6.583 tonne with a density set at 0.827 tonne cu.m.

Bates *et al* (2009) used laser scanning and computer modelling methods to create a range of 3D models, one of which was based on the "Wankel rex' MOR 555 skeleton. The computer models incorporated hollow structures within the body to represent respiratory structures such as lungs and air sacs. The calculated mass was 6.07182 tonne with an average density of 0.92643 tonne cu.m.

Hutchinson *et al* (2011) reconsidered the mass problem by estimating the effect of more "fleshy" reconstructions. This produced a range of estimates of between 5.8 to 10.8 tonne although the authors still preferred the lower of these estimates. They estimated the best minimal mass at approximately 5.934 tonne, with a density of 0.985 tonne cu.m.

The reference model indicates a higher mass of 7.59 tonne. Most other reconstructions are "gracile" so they would be expected to be lower.

Certain assumptions need to be made to produce a "best guess" optimal mass: the Farlow *et al* (1995) reconstructions provide an approximate mass of 6 tonne for what is a gracile reconstruction, the Paul (1997) estimate of 5.4 tonne provides a useful "shrink-wrapped" estimate that is virtually identical to the lowest estimate of Farlow *et al* (1995), the Hutchinson *et al* (2007) and Hutchinson *et al* (2011) estimate of 6.58 tonne is heavier than other studies but they seem to have preferred a more robust reconstruction, the Bates *et al* (2009) reconstruction of 6.07 tonne falls within the general mass range, and the reference model is higher because it is not "gracile". The 'Wankel rex' MOR 555 mass estimates only vary between about 5.38 to 6.58 tonne when studied by three different research teams with much of the variation resulting from differing density estimates. The best guess estimate of 6.1 metric tonne seems a reasonable estimate for the mass of this specimen.

3.3 Specimen "Stan" BHI 3033

This specimen is 63% complete. It was discovered in 1987 and the original fossil skeleton is now housed at Black Hills Institute of Geological Research, Inc. About 30 casts of the original fossil are now on display worldwide, including the Manchester Museum in the UK, The Children's Museum of Indianapolis, the New Mexico Museum of Natural History and Science, the Houston Museum of Natural Science, the National Museum of Natural History in the US, the Rocky Mountain Dinosaur Resource Center, the Oxford University Museum of Natural History, the Natural History Museum in Oslo, the Cerritos Public Library in Cerritos, the Wyoming Dinosaur Center and the Dinópolis in Spain.

Paul (2008) estimated a mass of 5.6 tonne assuming a gracile morph. The average tissue density was set at 0.85 tonne cu.m. Paul (2016b) gives a more exact

Mass and weight estimates in tonne for *Tyrannosaurus rex* "Stan" BHI 3033				
Mass from models tonne				
Reference	Mass	Notes	Density tonne/cu.m	Volume cu.m
Paul (2008)	5.60	Gracile morph (Male)	0.850	6.588
Stevens *et al* (2008)	4.40	"a lithe reconstruction"	?	
Bates *et al* (2009)	7.65	Computer model	0.905	8.462
Hutchinson *et al* (2011)	5.93	Range 5.934-10.8: authors prefer lower	0.870	6.821
Paul (2016b)	5.62	Dinosaur Mass Tables	0.850	6.612
Sellers *et al* (2017)	7.21	minimum hull method "within ± 0.24866"		
Model	8.23	Scaled to "Stan": see text	0.950	8.665
Best estimate	**6.10**		0.950	6.421
Weight from leg stress tonne(f)				
Reference	Weight	Notes		
Larson (2008b)	3.74			
Bone calculation	3.74	Bipedal calculation		
Best estimate	**3.74**			
Within ±	20%	Skeleton found = 63%, Gracile		
Palaeogravity	**0.61**			
Average Age	67			

Table 3.

Mass and weight estimates in tonne for *Tyrannosaurus rex* “Stan” BHI 3033 specimen.

estimate of 5.62 tonne for the "Stan" BHI 3033 specimen in his Dinosaur Mass Tables.

Stevens *et al* (2008) produced the low mass estimate of approximately 4.4 tonne based on a computerised reconstruction of the "Stan" BHI 3033 specimen, assigning densities of 0.8 to 1.0 tonne cu.m to various regions of a digital model. The average density wasn’t specified. This model was produced as part of a study to show how *Tyrannosaurus rex* could have raised itself off the ground. It was described as a “lithe reconstruction”.

Bates *et al* (2009) used laser scanning and computer modelling methods to create a range of 3D models, one of which was based on the "Stan" BHI 3033 skeleton. The computer models incorporated respiratory structures representing lungs and air sacs. The calculated mass was 7.65471 tonne with a density of 0.9046 tonne cu.m.

Figure 1.

The cast of the *Tyrannosaurus rex* "Stan" BHI 3033 specimen displayed in a running pose at the Manchester Museum in the UK. Note how this specimen does not include the rib-like bones called gastralia visible on the “Sue” specimen.

Hutchinson *et al* (2011) used a three-dimensionally scanned computer model of the "Stan" specimen to estimate a minimum possible mass of 5.934 tonne. The average tissue density was 0.870 tonne cu.m.

Sellers *et al* (2017) used the minimum hull technique to estimate a mass of 7.206 tonne as part of their study into the running ability of *Tyrannosaurus rex*. This technique shrink-wraps a skeleton and adds 21% for extra tissue. Since the calculation is based on results from extant animals it does not use any density estimates.

The commercial reference model produces a high mass of 8.23 tonne but once again other estimates are for “gracile” reconstructions.

Certain assumptions need to be made to produce a “best guess” optimal mass estimate: the low estimates of Paul are based on his “shrink-wrapped” reconstructions (but this estimate is only slightly lower than our final “best guess”), the “shrink-wrapped” reconstruction is taken to the extreme by Stevens *et al* (2008), the computer model of Bates *et al* (2009) was a bulkier reconstruction and provides a useful maximum mass estimate, Hutchinson *et al* (2011) produced a range of models from thin to fat but preferred a mass of about 5.93 tonne while discussing possible inaccuracies, Sellers *et al* (2017) produced an estimate of 7.21 tonne that was nearly as large as the Bates *et al* (2009) estimate, and the reference model is too high because it is not a “gracile” reconstruction. Trying to remove all sources of possible error indicates a reasonable average mass estimate would be about 6.1 tonne, assuming the “Stan” specimen was an optimal size and density.

3.4 Specimen "Sue" FMNH PR 2081

Specimen “Sue” FMNH PR 2081 is widely reported as the largest, most extensive and best preserved *Tyrannosaurus rex* specimen ever found, being reconstructed at more than 12 metres long. After it was discovered in 1990, various ownership disputes developed until it finally found a permanent home at the Field Museum of Natural History in Chicago, Illinois.

Henderson and Snively (2004) estimated a mass of 10.2 metric tonne. As the two researchers explained, this estimate was much greater than those for other specimens of *Tyrannosaurus rex* because mass is proportional to the cube of length and the greater length of the Field Museum of Natural History specimen FMNH PR 2081, measured by the researchers at 12.01 metres, results in a substantially larger body mass. Coordinates defining the limb and body shape were digitised from published illustrations of Paul (1988) and Currie (1997), 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 in the anterodorsal thoracic regions and set to a volume equal to 10% of the axial body. They conservatively set craniocervical

Figure 2.

Tyrannosaurus rex specimen “Sue” FMNH PR 2081 on display at the Field Museum of Natural History, Chicago, Illinois. “Sue” is widely reported as the largest, most extensive and best preserved *Tyrannosaurus rex* specimen ever found, being reconstructed at more than 12 metres long. It was remounted in 2018 with rib-like bones called gastralia and a shifted posture. Picture © Zissoudisctrucker (2018).

Table 4.

Mass and weight estimates in tonne for *Tyrannosaurus rex* “Sue” FMNH PR 2081 specimen.

Mass and weight estimates in tonne for *Tyrannosaurus rex* "Sue" FMNH PR 2081				
Mass from models tonne				
Reference	Mass	Notes	Density tonne/cu.m	Volume cu.m
Henderson & Snively (2004)	10.20		0.900	11.333
Paul (2010, 2016a)	6.00	Specimen undefined but 12 m long	0.850	7.059
Hutchinson *et al* (2011)	9.50	"perhaps approx. 9500 kg"	0.807	11.774
Hartman (2013)	8.40	Double intergration	0.913	9.200
Paul (2016b)	6.14	Dinosaur Mass Tables	0.850	7.224
Garilken (2017)	8.83	Double intergration	0.912	9.681
Henderson (2018)	9.75	12 m lg	0.851	11.457
Field Museum (2018)	9.00	"About 9 metric tonnes"	?	
Snively *et al* (2019)	9.13	Multiple body densities	?	
Model	8.81	Scaled to "Sue": see text	0.950	9.275
Best estimate	**8.80**		0.950	9.263
Weight from leg stress tonne(f)				
Reference	Weight	Notes		
Larson (2008b)	5.60			
Bone calculation	5.60	Note dimensions differ from different sources		
Best estimate	**5.60**			

Within ±	20%	Skeleton found = 73%, Robust
Palaeogravity	**0.64**	
Average Age	67	

densities at 0.9 tonne cu.m. An average tissue density wasn’t given by the authors but the detail given suggests it would be 0.9 tonne cu.m.

Paul (2010, 2016a) gave a surprisingly low estimate of 6 tonne with an average tissue density of 0.85 tonne cu.m for one *Tyrannosaurus rex* reconstruction. Although he didn’t specify which specimen this was based on the overall length was given as 12 m: this matches the “Sue” specimen the closest. Paul (2016b) gives a more exact estimate of 6.14 tonne for the "Sue" FMNH PR 2081 specimen in his Dinosaur Mass Tables.

The Hutchinson *et al* (2011) team produced three-dimensionally scanned computer models of five well-preserved fossil specimens of *Tyrannosaurus rex* including “Sue”. They noted that “Sue” is the largest *Tyrannosaurus rex* found so far, estimating mass at approximately 9.502 tonne, with a density of 0.807 tonne cu.m.

Hartman (2013) produced his own skeletal restoration and used double integration analysis to produce a mass estimate of 8.4 tonne with a density of 0.91 tonne cu.m.

Garilken (2017) also produced his own skeletal restoration, producing a mass estimation of 8.83 tonne with a density of 0.91 tonne cu.m. This estimate used a high fidelity MATLAB program to perform a double integration analysis of two views of the same section of the body and then construct a three-dimensional model of it. The skeletal reconstruction corrected some of the distortion of the transverse processes in the vertebrae in order to avoid the artificial expansion of some of the ribs and the angle of the ribs was modified. Garilken (2017) considers that “…it is not surprising that the results of this estimation are moderately lower than those of Hutchinson *et al* 2011” due to these modifications.

Henderson (2018) produced a model of *Tyrannosaurus rex*, based on the published illustrations of Paul (1988) and Currie (1997), during a study of the floating abilities of a number of theropod dinosaurs. The mass estimate for *Tyrannosaurus rex* was estimated as 9.75 tonne. This is lower than the Henderson and Snively (2004) estimate of 10.2 metric tonne but this was mainly because the average tissue density was taken as 0.85 tonne cu.m with a body volume of 11.46 cu.m. The length was given as 12 metres which is the size of “Sue”.

The Field Museum of Natural History (2018) issued a blog report about a new reconstruction of the “Sue” specimen in November 2018: *A Fresh Science Makeover for SUE: The same dinosaur you know and love—now bigger and more scientifically accurate than ever*. The new SUE has added rib-like bones called gastralia and a rearranged posture. They gave a revised estimate of “about 9 tonne” for its mass.

Snively *et al* (2019) calculated the mass of the "Sue" FMNH PR 2081 specimen as 9.13087 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 density 0.74 tonne cu.m and the post-thoracic and leg regions as 1.06 tonne cu.m.

The commercial reference model indicates a mass of 8.81 tonne. This time the reference model conforms to the general observation that this specimen is a "robust" reconstruction and the estimated mass is close to the "best estimate".

Certain assumptions need to be made to produce a "best guess" optimal mass estimate: the initial reconstruction of Henderson & Snively (2004) was the largest at over 10 tonne with a high density estimate, the lower estimate of 6 tonne by Paul (2010, 2016a, 2016b) is due to the "shrink-wrapped" reconstruction and low density estimate, the Hutchinson *et al* (2011) was about 9.5 tonne, both Hartman (2013) and Garilken (2017) produced their own skeletal restorations and used double integration to estimate masses of 8.4 tonne and 8.83 tonne respectively, the Field Museum (2018) published a revised estimate of "about 9 tonne", the Snively *et al* (2019) mass estimate is 9.13087 tonne and the reference model gave a value of 8.81 tonne. Trying to remove all sources of possible error indicates a reasonable average mass estimate would be about 8.8 tonne, assuming the "Sue" specimen was an optimal size and density.

3.5 Remaining specimens

A range of other more incomplete specimens was also examined but these were outside the accuracy required for these palaeogravity calculations.

4. Weight from bone dimensions

The weight of *Tyrannosaurus rex* 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 need to 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.

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 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 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* (2010) 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.

Larson (2008b, p122) estimated the weight from the bone dimensions of a number of *Tyrannosaurus rex* specimens as part of his sexual dimorphism study. As might be expected, these results agreed with the calculated values of weight produced directly from bone dimensions.

5. Palaeogravity

Palaeogravity was calculated for all four specimens of *Tyrannosaurus rex* using the standard formula previously described:

$$g_{67} = w_{67} / m$$

For the *Tyrannosaurus rex* specimens: "Carnegie" CM-NH 9380, “Wankel rex” MOR 555, "Stan" BHI 3033 and "Sue" FMNH PR 2081 respectively, the palaeogravity estimates were: 0.67g, 0.66g, 0.61g, and 0.64g.

6. Accuracy

The general interest in *Tyrannosaurus rex*, by the public and scientists alike, has produced some of the best weight and mass estimates available for any animal.

Despite the unfeasibility of constructing statistically valid 95% confidence intervals it is obvious that some weight and mass estimates are more accurate than others. The specimens considered in this paper are some of the most detailed three dimensional fossils so I have tentatively placed these specimens within a ± 20% accuracy band for palaeogravity estimates. Some other specimens of *Tyrannosaurus rex* considered were incomplete or distorted so they fall outside this limit.

Larson (2008a, p51) gives an estimate of the completeness of a number of skeleton specimens and this level of completeness was found to have a great bearing on the ability to calculate accurate mass and weight estimates. Generally specimens with a skeletal completeness of better than 40% have mass and weight estimates within the assumed ± 20% accuracy range if they also have the femur preserved. The original type specimen was also included within this ± 20% accuracy range since there are many estimates of its mass with reference to other fossil material.

Possible sexual dimorphism may have introduced a mass variation between the sexes that is hindering more accurate mass estimates but this may begin to be resolved in the future.

7. Suggested Citing Format

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9. References

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