Supersonic Sauropods: The Physical Model

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Abstract

Previous work [1] used computer modeling to show that the "whiplash" tails of the diplodocid sauropods (and several other sauropod groups) could have functioned like a bullwhip to make a loud cracking noise by having its tip exceed the speed of sound.

We report on the construction of a ¼-scale physical model of the tail of *Apatosaurus* (modeled after specimen CM 3018) to confirm the plausibility of the computer-based finding with a physical experiment. The model has 82 vertebrae constructed using CNC machine tools and 3-D printing. Each vertebra has accurate size and joint-angle constraints based on the osteology of CM 3018. Neoprene bumpers play the role of intervertebral discs.

Each vertebra is weighted to model the mass of the flesh during life. The total model mass is 20 kg, corresponding to a mass during life of 1306 kg. The model is mounted on a tripod with a bearing and equipped with a handle so that a person can supply the motive power to emulate the hindquarters of an *Apatosaurus*.

The model produces a cracking sonic boom; a live demonstration of the tail model will be performed. Analysis of high-speed video measured supersonic speeds up to 370 m/s. This experiment confirms the plausibility of supersonic tail cracking consistent with prior work. The model could also serve as the basis for a dynamic museum exhibit.

Bullwhip Mechanics and Wear Patterns

Initiating transverse motion in a whip introduces angular momentum, given by $m\,v\,r$, where m is the mass, v is the velocity, and r is the radius of each cross-sectional segment of the whip. Abruptly changing the direction of motion causes a wave to propagate along the whip. Under certain conditions, a traveling loop can form (fig. 1).

As the wave moves along a tapered whip away from the operator, both the mass and the radius of the segments involved in the wave decrease rapidly. Conservation of momentum dictates that the speed of the wave must therefore rapidly increase in order to conserve momentum. High-speed photography of bullwhips [2] shows that only a few millimeters of the distal end of the bullwhip are responsible for creating the shock wave that we perceive as the crack of the whip.

Bullwhips are typically prone to wear in the region intermediate to the thick, weighted handle and the thin, whiplash region.

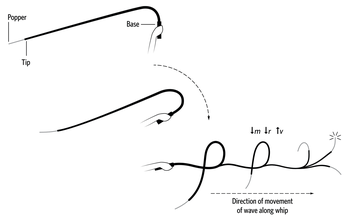


Figure 1. A modern bullwhip is used with a quick flick of the arm and wrist that introduces an impulse of energy, which propagates as a wave along the length of the whip. Typically a loop forms and gains velocity as the mass and radius of tapered whip decreases. The tip of the thin popper reaches supersonic velocity and creates an acoustic shock wave when the loop unfolds. *Illustration by Tami Tolpa*

Whip-like Features of Diplodocids

Like a bullwhip, the long tails of large diplodocid dinosaurs such as *Apatosaurus* tapered dramatically from base to tip. In *Apatosaurus* specimen CM 3018, the cross-sectional tail area shrinks faster toward the tip than a modern bullwhip does (fig. 2).

About half of diplodocid specimens show wear similar to that seen in whips, in the form of coossification of one or more pairs of vertebrae, typically in the region of mid-caudal vertebrae 18–25 (fig. 3 and shaded vertebrae in fig. 2).

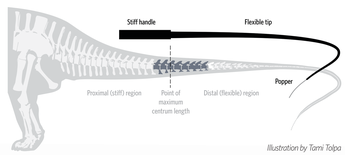


Illustration by Tami Tolpa

Figure 2. Like a modern bullwhip, the tail of *Apatosaurus* included a stiff region, proximal to the hind legs, as well as a more flexible distal region that tapered in diameter down to a very thin end: the "popper." Diplodocid tails tapered to an even greater extent than bullwhips typically do.

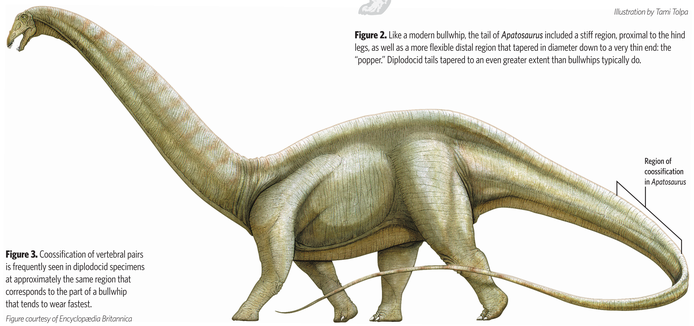
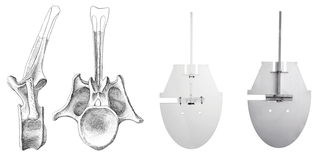


Figure 3. Coossification of vertebral pairs is frequently seen in diplodocid specimens at approximately the same region that corresponds to the part of a bullwhip that tends to wear fastest.

Figure courtesy of Encyclopædia Britannica

Drawings of *Apatosaurus louisae* specimen CM 3018 by Gilmore (fig. 4) revealed that coossification is found only in the centrum, which suggests that these animals held their tails parallel to the ground. That interpretation is supported by the lack of damage to neural spines in the region, as would be expected from vertical overextension. Likewise, CM 3018 shows no evidence of damage to chevrons caused by the animal rearing on its hind legs.



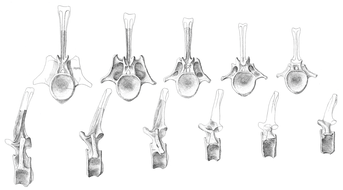


Figure 4. Mid-caudal vertebrae of the *A. louisae* holotype CM 3018, as recorded by Gilmore [3] (above), show no evidence of the kind of damage that would be expected if the animal raised its tail high or used it for support as it reared on two legs. We used dimensions reconstructed from this and other work to construct ¼-scale physical models of the vertebrae in plastic and aluminum (*left*).

We built on Gilmore's work to reconstruct the dimensions of the centrums and chevrons in each of the vertebrae of *A. louisae* holotype CM 3018 (fig. 5). Although the chevrons were poorly preserved in CM 3018, we were able to reconstruct the probable chevron size by using published data on *Mamenchisaurus* [4], which shows similar geometric scaling to *Apatosaurus*. Vertebrae 65–82 were also damaged in CM 3018; we used measurements from *A. louisae* specimen CM 3378 to estimate those dimensions. We then used the dimensional data to create schematic representations of each vertebra (fig. 6) that capture the mechanical interactions essential for high-speed tail movement.

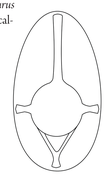


Figure 6. Schematic representations of caudal vertebrae 11 and 66, drawn from a set of measurements of *A. louisae* CM 3018 vertebrae as well as from dimensions estimated by using geometric scaling on published data for CM 3378 and *Mamenchisaurus*.

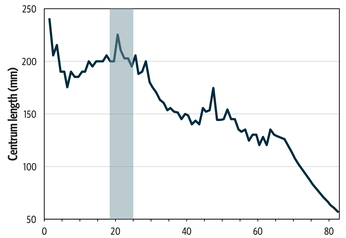


Figure 5. Centrum length of *A. louisae* for caudal vertebrae 1–85, as reconstructed using actual or scaled measurements from CM 3018, CM 3378, and *Mamenchisaurus*. Coossification was apparent for vertebrae 18–25 (shaded region).

Computer Simulation

We used the data reconstructed for CM 3018 to create a computer simulation of the tail of a living *Apatosaurus*. Estimations of flexibility at each vertebral junction were made based on measurements of *Apatosaurus* specimens found at Howe Quarry with the whiplash portion of their tails curved.

Results from simulation of all 82 vertebrae indicate that this sauropod could achieve supersonic speeds at the tip of its tail by applying 5×10^4 N-m of torque to the base of the tail, followed by a counter-application of 6×10^4 N-m of torque (figs. 7 and 8). The rocking at the base would have created a propagating wave that resulted in a whipping motion and likely a very loud crack.

Based on the estimated weight of *A. louisae* and the estimated speed of the animal (as derived from trackway patterns), the application of force required to achieve supersonic speed at the end of the tail is less than that required to take one step.

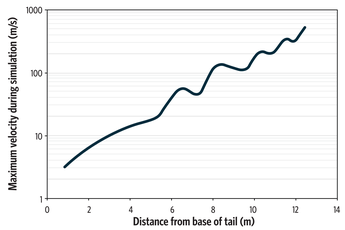


Figure 7. The maximum velocity achieved during the simulated tail-whipping motion increased in a roughly exponential fashion from 3 m/s at the base to nearly 600 m/s at the tip.

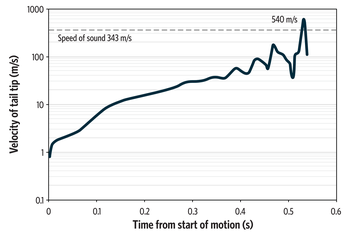
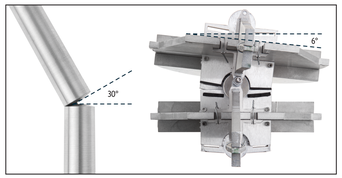


Figure 8. The velocity of the tail tip exceeded the supersonic barrier of 343 m/s for about 10 ms near the end of the motion. This is comparable to the duration of cracks made by bullwhips. Given the much greater size of the sauropod tail, however, it seems probable that if diplodocids did produce tail cracks, they were much louder than any crack ever made by a bullwhip.

Construction of the ¼-Scale Physical Model

A ¼-scale model of the CM 3018 tail was constructed by using CNC machining, water-jet cutting, and 3-D printing. Vertebral bone structures were simulated from aluminum and stainless steel parts. Neoprene foam, rubber, and hinged, stopped joints were used to simulate intervertebral discs. Vertebrae were scaled in size to match the reconstructed measurements for CM 3018. We used nylon-coated, stainless steel cables to support and tension the assembly.



Velocity Measurements

Tests of the tail confirmed that when a human operator applies a specific cadence of force and counterforce, the tail produces an audible crack, similar to the supersonic crack of a bullwhip. We used high-speed videography (Phantom v12 camera, Vision Research Inc.) at 6270 frames per second to estimate the peak velocity of the end of the popper (fig. 9). The position of the popper relative to a 122 cm background grid was marked at each frame, and velocity was calculated from the distance covered in the 152 µs interval between marks. The maximum measured speed was 361 m/s, well into the supersonic regime.

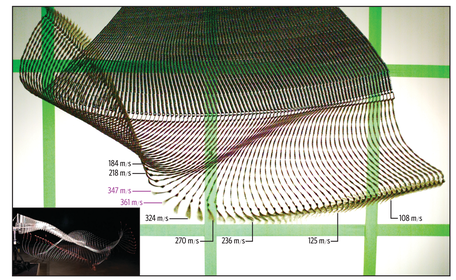


Figure 9. Images composited from high-speed videos illustrate the high speed of the popper as the looped tip of the model tail uncurls. In the larger composite at right, the motion of the popper at the tip of the tail attained measured velocities that exceeded the sound barrier (*magenta labels*).

Discussion and Conclusions

Mathematical and computer analyses based on a subset of vertebrae had previously suggested that some diplodocids could move their tails at supersonic speeds [1]. Our new computational simulations and physical model confirm the plausibility of this behavior for *Apatosaurus louisae*.

Several factors suggest that this species did not use its tail as a weapon. The smallest caudal vertebrae were the size of a human finger. Any predator likely to threaten *Apatosaurus* would hardly be deterred by strikes from such a small bone. Indeed, a hit of sufficient force to cause serious damage to such a hypothetical predator would likely cause more damage to the tail than to the assailant. Furthermore, no adaptations (such as the fused vertebrae of *Shunosaurus lii*) have been found that indicate a club-like structure at the end of the tail.

Comparisons with other diplodocid tails suggest that the whiplash feature was conserved in diplodocids, but was not present in other sauropods. Trackway patterns suggest that *Apatosaurus* was a herd animal, perhaps living within social hierarchies. This suggests the possibility that the tail was a noisemaker used to enforce order or social dominance—not altogether different from the way humans use bullwhips.

The exact amount of energy generated by an *Apatosaurus* tail crack is difficult to calculate. But if one assumes that it scales linearly as a function of mass, a crack would have generated 2000 times more energy than a bullwhip. Such a shock wave could have served as a deterrent to competitors or predators.

The presence of damage to caudal vertebrae 18–25 in approximately half of the discovered *Apatosaurus* specimens invites speculation that tail whipping was a sexually dimorphic behavior, perhaps used to attract potential mates.

References and Acknowledgments

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[4] C. C. Young, M. N. Bien, T. H. Mi. 1972. *Mamenchisaurus* from Ho Chuan. *Academia Sinica, Institute of Vertebrate Paleontology and Paleoanthropology Monographs A*, 8:1–30.

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