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MUSCLE-BOUND T. REX

A 13,000-pound chicken wouldn't run too well either, according to Stanford University's John Hutchinson. As a University of California, Berkeley, graduate student in biomechanics, he attempted to settle the question of tyrannosaur's fleetness.

With help from UC-Berkeley postdoctorate researcher Mariano Garcia (now working on engine simulations for BorgWarner Morse TEC of Ithaca, N.Y.), Hutchinson determined *T. rex* couldn't have been any too quick because muscle mass and muscle force scale at different rates. For the dinosaur to have run quickly, each of the extinct biped's leg muscles would have had to make up nearly half its body mass.

Hutchinson combined techniques from previous studies to predict what kinds of forces muscles can exert based on their volumes and other parameters.

One way of calculating muscle volume is by multiplying muscle fascicle length by physiological cross-sectional area (PCSA), and dividing that product by the cosine of something called the pennation angle, Garcia explained.

"Think of muscles as two offset tendons with a bunch of angled force-generating elements in parallel acting between them, kind of like a four-bar linkage," he said.

Mathematically, PCSA equals muscle force divided by stress. And muscle force is the necessary joint torque divided by a muscle's moment arm.

The resulting equation for muscle mass,

$$\frac{\text{torque} \times \text{fascicle length} \times \text{density}}{\text{muscle stress} \times \text{moment arm} \times \cos(\text{pennation angle})}$$

gives a lower bound estimate on how much mass is needed to produce a given torque about a joint. The equation assumes all of the muscle mass is actively producing force, which is usually not the case, Garcia said.

The researchers had surprisingly good estimates of moment arm data for dinosaurs, in part because of earlier studies of birds and other animals to which the extinct animals were related. The

fossil record itself in many cases clearly shows the tendon insertion points.

What wasn't as well known was *Tyrannosaurus's* running posture. For that reason, the researchers employed a method of sensitivity analysis to see how different leg angles would affect the outcome. Even in a fairly upright stance, where leg muscles need not produce as much force, *T. rex's* ability to run turned out unlikely, Garcia said.



Both contestants would have walked this race.

Working with Matlab software from Mathworks Inc. of Natick, Mass., Hutchinson and Garcia produced a series of free-body diagrams that summarized the internal and external forces acting on the joints. For standing, the sum of all the forces equaled zero.

Using a quasistatic analysis (zero velocity, non-zero acceleration), the engineers then estimated the muscle force necessary to support the dinosaur's body on one leg at the midstride running position. Across a wide range of animals, the ground reaction force at this position is more or less vertical, consistently equaling about 2½ times body weight when quantified with force plate measurements, Garcia said.

Running can be defined in several ways, he said, all of which work out the same for most cases. It can be thought of as legged movement that has an aerial portion or as motion in which the body's kinetic and potential energies are in phase. Running is

also defined as the Froude number being greater than one. Hutchinson and Garcia used this last definition in their analysis.

The Froude number, a nondimensional velocity, essentially "levels the playing field among different-size animals," Garcia said. It is a measure of centripetal force over weight. If a walking body resembles an inverted pendulum rotating over the foot, then, at Fr equals 1, the centripetal force is equal to body weight. "That's the theoretical point at which you should switch to a run, because your feet wouldn't stay on the ground," Garcia said.

For an ostrich running at 12 meters per second, Fr equals 16 and the maximum ground reaction force is about 2.7 times the bird's body weight. A comparable Froude number for *Tyrannosaurus* pegs its dynamically similar running speed near 45 mph—about where some people had previously thought it to be, Garcia said.

But to make that speed, the equation told the engineers that *T. rex* would need 43 percent of its total body mass as supportive muscle in each leg—just about an impossible distribution from what is known about the dinosaur's anatomy.

For comparison, Hutchinson and Garcia ran the numbers for chickens and alligators, the dinosaurs' distant relatives. Each leg's muscles make up about 8.8 percent of a chicken's total mass—almost twice what's needed to send a hen skittering across the barnyard. Alligators, none too fast on hind legs alone, muster only about 3.6 percent of their body mass in each group of leg muscles. Calculations said they need at least twice that to get up and going on two feet.

The bigger things get, the worse they become: A *Tyrannosaurus*-size chicken would need 99 percent of its body mass in each leg in order to run. Such a bird, if it could run, would look a lot like a chicken running around without a head. PAUL SHARKE