SCALING OF THE EFFECT OF INERTIA ON RESPONSE TIME IN TERRESTRIAL MAMMALS

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INTRODUCTION
Inertia acts to oppose acceleration, thereby impeding changes to an animal’s motion and slowing their response time. Assuming geometric similarity, moment of inertia scales with $M^{5/3}$, while muscle torque scales with $M^{1}$ (Muscle force with $M^{2/3}$ and moment arm with $M^{1/3}$), implying that larger animals could be disproportionately burdened by inertia. However, we need to use computational modeling to solve the equations of motion and simulate the movement in order to actually quantify the relationship between inertia and the delay in response time (inertial delays). In addition to inertial delays, the response time of an animal also includes delays within the nervous system, which we had previously quantified as the sensorimotor delays in an animal’s fastest reflex response [3]. Here we seek to quantify the scaling of inertial delays and compare it to sensorimotor delays in its contribution to response time, using simple biomechanical models that represent common tasks in animal movement.

METHODS
The swing task, which represents repositioning the swing limb, was modeled using a distributed mass pendulum. We defined inertial delay as the time required to move from rest at a specified angle of flexion (varied from 0° to 30°), to rest at the same angle in extension. (Fig. 1A). The posture task (Fig. 1B), which represents a quadruped correcting its upright posture after a perturbation, was modeled using an inverted pendulum with point mass properties. The system, initially at rest at vertical, was subjected to a destabilizing forward push, modeled as an initial dimensionless velocity (varied from 0 to 0.44 $v/\sqrt{g \cdot l}$). We quantified inertial delay as the time required to return to rest at a vertical posture.

We obtained scaling values for limb inertial properties from Kilbourne et. al. [2], and scaling values for muscle force and moment arm from Alexander et. al. [1]. We applied the control torque in a bang-bang profile and minimized movement duration by optimizing the time at which the commanded torque was reversed. This control method is the fastest strategy for achieving the task goal, ensuring that the delay reflects inertial effects and not control inefficiency.

RESULTS AND DISCUSSION
Morphological and physiological parameters of animals that are influenced by animal size—including inertial and sensorimotor delays, can often be expressed as a power function of animal mass known as the allometric equation, expressed as $y=a\cdot M^b$.

Figure 2: Variation in the coefficient “a” (top left) and exponent “b” (top right) of the power law with change in magnitude of the initial angle (swing task in blue) and dimensionless velocity perturbation (posture task in red). The bottom graph is a log-log plot of the scaling relationship between inertial delay and mass, for an initial angle of 20.72° for the swing task and a dimensionless velocity of 0.245 for the posture task, the movements for which inertial delays equal sensorimotor delays for a 1 kg animal.

While sensorimotor delays scaled with $33\cdot M^{0.2}$ milliseconds [3], the scaling of inertial delays depended both on the task and the size of the movement (Fig. 2). Inertial delays scaled less steeply (swing task: $M^{0.30}$; postural task: $M^{0.37}$) than predicted by geometric similarity (swing task: $M^{0.33}$, postural task: $M^{0.50}$), partly due to positive allometry in the scaling of muscle force and moment arms.

For inertial delay to exceed sensorimotor delay in its contribution to response time, a simulated five gram shrew would have to swing its limb through 57°, while a five ton elephant needs to move its limb through only 4°. The results show that sensorimotor delays dominate response time in smaller mammals while inertial delays dominate in larger animals during common movement tasks.

REFERENCES