Analyzing the Scale-dependent Force Contributions of Rat Hindlimb Muscles During the Swing Phase of Locomotion

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BIOLOGICALLY INSPIRED ROBOTICS LABORATORY

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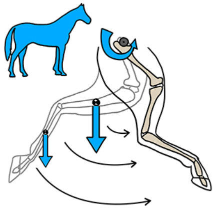
Abstract

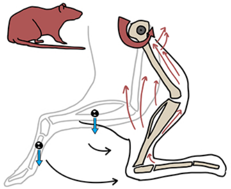
We have developed a process to analyze the relationship between the **size-scale of an animal and the resulting activation profiles of individual hindlimb muscles**. Large animals, which have heavy limbs, are able to leverage the **inertial properties of their body to aid in the natural development of motion**. In contrast, smaller animals must rely on the **elastic properties of their muscles to generate motion due to their lightweight limbs**. Across size scales, the relationship between passive elastic and inertial properties changes dramatically. We are interested in the ramifications of scale-dependent relationships on the activation profiles of muscles because we hypothesize that they are the **primary constraints for the types of control schemes that animals use for locomotion**.

Motion and Control



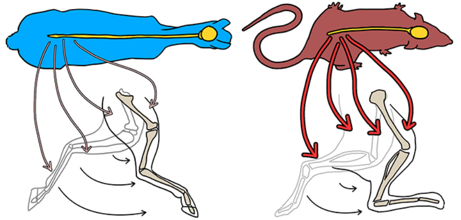
Large animals are able to leverage the weight of their limbs to generate **inertial torques for the swing phase** of motion.

Gravitational forces (blue) propel limbs forward, transferring most of the energy of motion into kinetic energy.



Small animals are unable to rely on inertia to move their limbs forward and must **compensate through muscular action.**

Muscle forces (red) generate energy through a **combination of viscous and elastic forces.**

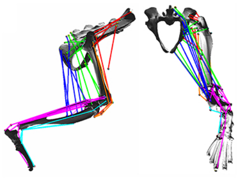


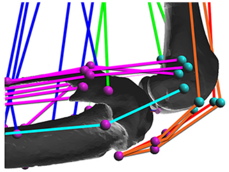
How do the **descending motor control commands influence the motion** during the swing phase of motion? Larger animals, like horses, need **lower muscle activity during shorter time periods**. Smaller animals, like rats, need **more motor activity during a longer duration** in order to prepare the limb for touch down.

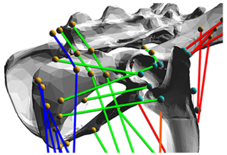
Neuromechanical Modeling in Animatlab

Recently, Animatlab has been used to develop **a many-muscle model of a rat hindlimb**[1] (right).

Animatlab is a neuromechanical simulator that couples a 3D physics environment with a neural control system[2].







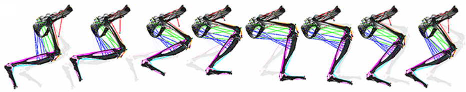
Details of **attachments spanning the hip and knee** are shown (left).

Colored lines represent muscle lines of action between attachment and via points (spheres).

Muscle coloring is non-functional and used to **visually distinguish muscle groups.**

The development of neural control in Animatlab has been used to model **dogs[3] and praying mantises[4].**

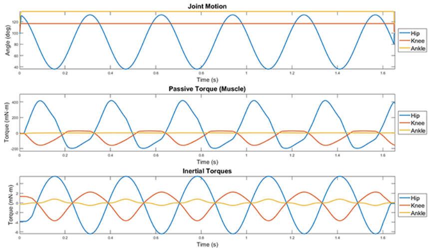
Kinematics



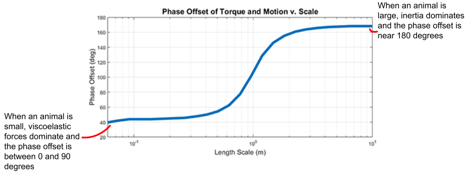
A walking pattern is injected into the model to determine **muscle force profiles necessary to recreate motion**. At every simulation timestep, an **optimization routine is performed to distribute muscle forces** such that necessary joint torques are produced.

Scale-dependent Viscoelasticity

The phase angle between motion and torque can be used to determine the **relative contributions of viscoelastic and inertial forces** on a joint. Inertial forces, which are proportional to acceleration, **are offset by 90 degrees** from motion. Viscoelastic torques, which stem from a combination of elastic and viscous forces, are **offset between 0 and 90 degrees**.

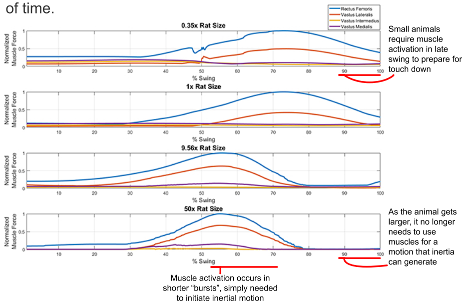


By changing the length-scale of the model, we are able to **change the relationship between viscoelastic and inertial torques.**



Muscle Forces

Below, **knee extensor muscle activation profiles** are shown for four length scales (.35x, 1x, 9.56x, 50x). When inertia dominates, as in large animals, muscles do not need to be active for extended periods of time.



Conclusions

The size of an animal determines the proportion of inertial and viscoelastic torques that it will experience during periodic motion

Larger animals are able to "turn off" their muscles and allow inertia to carry their limb forward during swing phase

Smaller animals require extended muscle activity in order to supplement inertial torque

The interplay between inertial and viscoelastic forces is important for understanding the neural activation patterns for locomotion

References

[1] **F. Young**, A. J. Hunt, and R. D. Quinn, "A **Neuromechanical Rat Model with a Complete Set of Hind Limb Muscles**," in Biomimetic and Biohybrid Systems, Paris, France, Jul. 2018, pp. 527–537.
[2] **D. Cofer**, G. Cymbalyuk, J. Reid, Y. Zhu, W. J. Heitler, and D. H. Edwards, "**AnimatLab: A 3D graphics environment for neuromechanical simulations**," J. of Neuroscience Methods, 2010.
[4] **N. S. Szczecinski**, J. P. Martin, R. E. Ritzmann, and R. D. Quinn, "**Neuromechanical Mantis Model Replicates Animal Postures via Biological Neural Models**," in Biomimetic and Biohybrid Systems, 2014.
[3] **A. Hunt**, N. Szczecinski, and R. D. Quinn, "**Development and Training of a Neural Controller for Hind Leg Walking in a Dog Robot**," Front. Neurorobot., vol. 11, 2017, doi: 10.3389/fnbot.2017.00018.
[5] **F. Young**, C. Rode, A. Hunt, and R. Quinn, "**Analyzing Moment Arm Profiles in a Full-Muscle Rat Hindlimb Model**," Biomimetics, vol. 4, no. 1, p. 10, Mar. 2019, doi: 10.3390/biomimetics4010010.

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