Understanding the functional role of muscles during movement: The kangaroo rat as an ideal model system

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Introduction

Understanding individual muscle function (i.e., the functional role of muscles during movement) is necessary to probe theories of motor control and characterize adaptations to injury. Static-based, isolated, single-joint perspectives fail to capture how a muscle, operating within a coordinated network of muscles, causes motion of a multi-joint system. To understand muscle contributions to motion it is advantageous to study a biological system with derived structure-function relationships specialized for high performance tasks with explicit performance objectives.

Desert kangaroo rats are small (~100g) bipedal rodents that escape predators using explosive vertical jumps, reaching up to 10 times their standing hip height by generating large ground reaction forces (9.4x body weight) over a short time (<100ms) to accelerate the body center-of-mass. Ankle power dominates joint contributions to jumping by kangaroo rats, yet ankle extensor muscles and elastic energy in tendon cannot account for the total power observed [1]. Furthermore, there are discrepancies in estimated mechanical work done by proximal muscles between inverse dynamics and *in vivo* muscle measurements [1,2]. Forward dynamics simulations can resolve such discrepancies and elucidate causal relationships between muscle activity and motion. We hypothesized that proximal uniarticular muscles would generate power that is transferred via biarticular muscles and delivered at the ankle joint during jumping by kangaroo rats.

Methods

A detailed musculoskeletal model of the kangaroo rat hindlimb has been developed and implemented in OpenSim for the purposes of performing forward dynamics simulations. Foot-ground contact was modelled using 4 contact spheres spanning the midfoot and toes. The model was driven by 20 musculotendon units representing the major muscles of the hindlimb (Figure 1).

Muscle-driven simulations of jumping were generated within an optimal control framework with the objective function to minimize differences between simulated and experimentally measured kinematics and ground reaction forces (100g kangaroo rat, 0.27m jump height, 0.095s ground contact time, 7N peak vGRF). Simulation results of interest in the current study include musculotendon unit (MTU) power throughout the hindlimb and how they compare to estimates of net joint moment (NJM) power using an inverse dynamics approach.

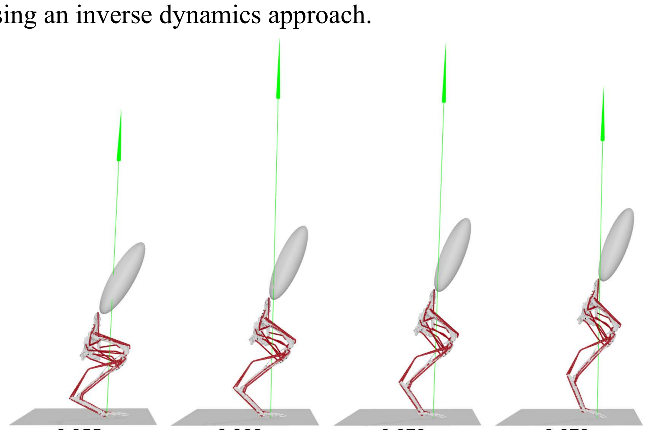

Figure 1: Visualization of the model simulation at times of peak power.

Results and Discussion

MTU power profiles indicate a proximo-distal sequence in power generation across the hindlimb (Figure 2). As expected, the ankle plantarflexor MTUs generate the greatest power output during jumping but cannot account for the total NJM power, suggesting that power generated proximally has been transferred distally to the ankle joint. Uniarticular hip extensors drive the MTU power generated at the hip in the first half of the jump. The subsequent power absorption is due to activity of biarticular hip extensors with large knee flexor moment arms slowing the knee joint angular velocity to prolong propulsion such that hindlimb joint extension can be coordinated near take-off – phenomena unable to be captured by the NJM power. MTU power of the knee extensors exceeds the NJM power and is consistent with *in vivo* muscle measurements that found high knee extensor muscle activity and shortening during jumping.

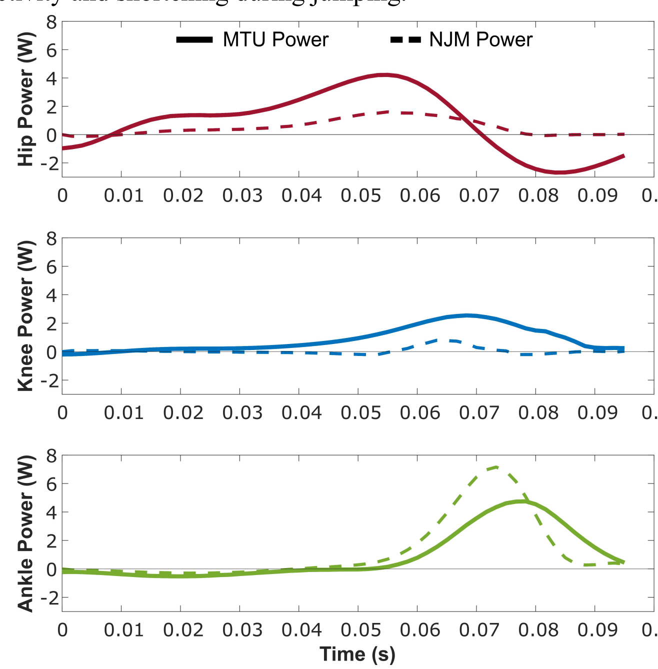

Figure 2: Summed musculotendon unit power from forward dynamics simulation versus the net joint moment power from inverse dynamics.

Significance

Muscle-driven simulations can overcome inherent limitations in interpreting muscle function from inverse dynamics and *in vivo* approaches. The MTU power profiles suggest a proximo-distal transfer of energy, but only provide insight at the MTU level. These preliminary simulations laid the foundation for ongoing work quantifying individual muscle contributions to GRFs, acceleration of body center-of-mass, and energy transfer between segments during successively higher jumps. Investigating muscle function in a specialized biological system with explicit performance objectives allows for general principles and mechanisms to be established that may be extended to understand more complex systems, such as human movements.

References

[1, 2] Schwaner, Lin, & McGowan, *J. Exp. Biol.*, [2018, 2021]