A Data Driven Neuromuscular Model of the Leg During Walking

Jared Markowitz, Hugh Herr
Massachusetts Institute of Technology
jaredm@mit.edu, hherr@media.mit.edu

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Motivation

Biological neuromuscular systems typically employ redundancy in joint actuation, using several muscle tendon units to rotate a joint and produce motion. Resolution of this redundancy is of fundamental importance for the fields of biomechanics and neuroscience, as well as for developing control schemes for robotic prosthetic limbs. Determination of the roles of individual muscles in a given task requires knowledge of both the neural control of the acting muscles and the morphology of the muscle-tendon unit. Krishnaswamy et al [1] recently proposed a framework for resolving the roles of individual muscles in the actuation of the human ankle while walking at self-selected speed. Here we extend that method to evaluate the ankle, knee, and hip joints during walking, elucidating the workings of the major muscle groups of the leg as well as the interaction among its joints during locomotion.

State of the Art

Human locomotion may be understood as an interplay between neural coordination and legged biomechanics. However this interplay has not been thoroughly investigated in recent inverse modeling efforts. Complex dynamic optimization schemes such as those in [2] and [3] use motion capture data and detailed musculoskeletal models to produce estimates of optimal time-varying neural commands to the muscles of the leg. They are limited, however, in that they typically use values found in the literature to set the parameters governing the force-generating properties of muscle-tendon units, ignoring subject-to-subject variation. Further they rely on complicated objective functions to determine neural control without systematically accounting for the possibility that different activation patterns of multiple muscles can produce the same gross joint behavior. Other inverse analyses use simpler mechanical models to successfully reproduce the main features of gait. One such analysis uses clutch-spring systems to represent muscles [4], and has demonstrated significant predictive power. However models of this type also cannot be used to capture the interplay between neural control and legged mechanics as they do not attempt to reproduce muscle-tendon morphology.

The inverse model put forth in [1] does address the concerns described above. However it only evaluates the action of the ankle joint during walking, and therefore cannot be used to evaluate the overall function of the leg during walking. By extending this method to the full leg, we can evaluate muscles spanning the knee and hip joints, investigate the role of biarticular muscles in linking joints, and estimate the metabolic cost of transport.

Own Approach

Here we extend the work of [1] to evaluate actuation of the hip, knee, and ankle joints during human walking at the speed where the metabolic cost of transport (MCOT) is minimal. Using kinematic, kinetic, and electromyographic data we apply similar techniques to resolve the redundancy at each joint, performing an extensive sensitivity analysis to determine the effects of using different activation estimation methods, different muscle models, different metabolic cost estimation methods, different muscle sets, and different muscle-tendon parameter sets. We are able to determine the roles of each major muscle group of the leg in walking at the speed where the metabolic cost of transport (MCOT) is minimal, evaluate the interaction of the different joints of the leg (as mediated by biarticular muscles), and compare the metabolic cost of transport to its empirically measured value.

Current Results

Using the approach described above we are able to simultaneously match the moments produced by the ankle, knee, and hip joints while matching the measured metabolic cost of walking for each participant at the speed where MCOT is minimal. We find that the muscle fascicle trajectories at the ankle qualitatively match those found in [1].

Best Possible Outcome

We are currently testing the ability of the optimized parameter sets to match the required joint moments and empirically measured MCOT at different walking speeds. For each subject, we hope that one closely packed region of parameter space is able to match the kinetic and metabolic data across speed. The next step will be to apply the optimized morphological parameter sets in a forward dynamic simulation of walking. The forward dynamic simulation will use a reflex-based control scheme similar to that developed in [5], seeking to produce biomimetic behavior across speed.

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Keywords

Biomechanics, Neural control, Neuromuscular model

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