Active Control of Unsteady Legged Locomotion

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1. Introduction

Motivation. *How do humans adapt locomotion to maneuver and remain stable?* Surprisingly, we do not have good answers to this question. Research has primarily focused on steady-state, constant-average-velocity (CAV) walking and running. However, locomotion in the environment is seldom steady-state, and must constantly adapt to a variety of environmental and internal conditions. Animals and humans must *maneuver* to change direction and negotiate obstacles. Movement can also be *perturbed* away from steady-state by both internal (reflecting physiological variability) and external (reflecting environmental variability) factors. There is a major gap in our understanding of the mechanics and control of this *unsteady* locomotion.

Performance of unsteady locomotion can determine predation risk for animals and the risk of injuries for athletes, the elderly or impaired individuals. We are performing a series of experimental and analytical investigations to broaden our understanding of the biomechanics, neurophysiology, and evolution of motor control during complex dynamic behaviors. We seek to provide a foundation for studies of the neuromechanical control of locomotion in three-dimensions, and trace the co-evolution of neural and muscle physiological systems enabling high performance movement.

State of the Art

Locomotion is a complex task. The passive dynamics of segmented systems can show unpredictable or chaotic behavior. Joints are actuated by many redundant muscles, and forces from uniarticular muscles alone can cause movements of many segments. Muscles, and the many neurons that innervate them, are heterogeneous and have non-linear, time-dependent behavior. Despite this complexity, research on terrestrial legged locomotion has revealed general mechanical principles that apply to a diversity of animals. Terrestrial animals show remarkable similarities in locomotion mechanics after controlling for factors like body size and speed. Bipedal humans and birds, quadrupedal vertebrates, and even arthropods use two basic mechanical mechanisms for walking and running. Walking is mechanically similar to an inverted pendulum, where the body vaults over a stiff leg exchanging kinetic and potential energy. At faster speeds, leg compliance becomes more important and the body and stance leg resemble a pogo-stick or "spring-mass" system. Both the pendular and spring-like aspects of legs serve to reduce mechanical and metabolic energy flux during locomotion. Although walking and running are usually considered to be distinct, there is evidence that both gaits can be described by making quantitative changes to parameters of a single Spring-Loaded Inverted Pendulum (SLIP) model (consequently, we will use the term "SLIP" to refer to both gaits). Because approaches such as SLIP models seek to represent locomotion with the fewest parameters possible, we will term them "task-level" approaches.

Task-level models are useful for describing locomotion dynamics. Experimental studies have revealed many consistent relationships among SLIP parameters chosen by humans and animals. For example, the transition from walking to running occurs at a consistent speed depending on leg length, as described by the value of the dimensionless Froude number (based on an inverted-pendulum model of walking) of approximately 0.5. When running, faster speeds are associated with increased stance leg angle, but not by changes in leg or joint stiffness.

Parameterizing locomotion with simplified models can help to interpret motor output at the many lower-level degrees of freedom (DOFs) coordinated during movement. Kinematics, muscle activities, forces and moments can be understood in the context of their effects on achieving overall task objectives. For example, when changes in leg stiffness are required, they are achieved both by changes in ankle joint stiffness and in knee angle at touchdown. Consequently, simplified models can describe the mechanics of CAV locomotion in a diversity of animals, and identify possible constraints that explain the behavior of the redundant, complex neuromuscular system. Once task-level behavior has been described, detailed studies of musculoskeletal and neural function can reveal how physiological systems are integrated to achieve behavioral goals. This presents the question: can unsteady locomotion (stability and maneuverability) be described with task-level models?

2. Approach

We are conducting experiments to determine the behavioral strategies used to control unsteady locomotion: to generate maneuvers and to maintain stability. Movement parameters that are actively modulated during unsteady walking and running are investigated within the framework of simplified mathematical models. We are performing experiments to determine whether humans use common strategies for maneuvers and stability, the extent to which behavioral control can be separated from the inverted-pendulum and spring-mass dynamics of walking and running, and whether functional differences among joints are used to organize motor control.

Maneuverability: Studies our laboratory currently seek to understand how the nervous system works within the mechanical constraints and capabilities of the musculoskeletal system to achieve stable maneuvers. We are conducting experiments to assess the behavioral consequences of perturbations to two morphological parameters of the maneuvering model: mass (M) and rotational inertia (I). We are studying humans during walking and moderate-speed running. We constructed a rigid backpack frame with poles attached at the waist, extending fore and aft. The apparatus weighs 5.7 kg. The pack is tightly fitting and adjustable to each participant. By adding mass to different locations fore and aft of the center of mass (COM), *M* and *I* can be independently changed. Changes in M of approximately 15% can increase *I* about the vertical axis by 1-3 times. We collected kinematics using a VICON® 3-D motion tracking system, and ground-reaction forces using two force platforms (Bertec) covered by rubber mats to obscure their location. Subjects ran at 3 m/s and executed sidestep cuts with their right leg. Our results suggest that although increasing *I* did not alter ground-reaction forces, i.e. braking forces, to the extent predicted by a simple model of maneuvering mechanics that can successfully describe forces during unperturbed turns in humans and ostriches. However, increased inertia did appear to provide more flexibility for the control of body orientation, allowing for similar GRFs to be maintained by relatively minor changes to stance period and lateral foot placement. However, braking forces continued to be associated with controlling body rotation during turning maneuvers.

Figure 1. Device to increase moment of inertia (*I*) consisting of a backpack frame with two 1.4 m galvanized steel poles attached to the hip. Weights added to different locations on the increase *M* and *I*. The device weighs 5.7 kg.

Stability: We do not have a full understanding of the control policies used to actively stabilize walking and running. Importantly, how different, coupled COM DOFs are simultaneously stabilized remains an important question. However, in the 1980s, Raibert and colleagues designed and built dynamically-stable robots inspired by running animals. The controller for these robots could maintain stable running by independently controlling hopping height, body attitude, and forward running speed without requiring complex, global models of locomotion dynamics. These parameters could, in turn, be controlled by adjustments to initial foot placement, leg stiffness, and by generating torques about the hip. Despite its simplicity, Raibert's controller could be used to control multiple legs in two- and three-dimensional movements. Raibert's robots demonstrated that relatively simple control strategies are capable of stabilizing SLIP systems. Humans have the capacity for substantially more sophisticated motor control of locomotion than used by Raibert's robots. However, the active, task-level control policies used by humans to stabilize legged locomotion are not well understood.

We conducted experiments to test whether humans use control strategies analogous to those used by Raibert's robots to stabilize running. Specifically, we tested the hypotheses that: 1) humans control running height by modulating leg force (not stance duration), 2) humans control running speed by changing stance leg placement relative to a "neutral point", and 3) humans control body attitude using hip torques. We studied movements and forces of humans performing five running tasks that changed body height, speed, and orientation. The strategies used to perform these tasks were most often consistent with robotic control principles. Leg force was linearly related to running height. Running speed was changed by adjusting fore-aft foot placement. Body orientation could be modeled as a first order proportional-derivative feedback system with a time lag (75 ms) consistent with those associated with rapid, programmed reactions. These results suggest that the interaction of independent feedback control strategies could be employed by humans to maintain stable running.

Current research focuses on understanding the relative contributions of musculoskeletal, reflex, and higher-order neural systems to stabilizing locomotion using biomechanical, neurophysiological, and direct perturbation studies. To this end, we have built a custom split-belt, force-sensor-mounted treadmill and a device to perturb the COM during walking and running based on the design used by Hof et al. We are conducting experiments using horizontal-plane (lateral and fore-aft) and rotational perturbations to compare the *reactive* strategies used for stability to the *proactive* strategies used for maneuvers.

Figure 2. Device to directly perturb walking and running.

3. Key Questions

Are the* reactive *compensations used to maintain stability consistent with the* proactive *strategies used for maneuvers?

Preliminary studies in our laboratory suggest that humans perform sagittal-plane maneuvers using strategies consistent with the feedback control rules used by bouncing robots. Simplified mathematical models can describe horizontal-plane maneuvers. We will directly perturb walking and running to test the hypothesis that reactive compensations to mechanical perturbations are consistent with the relationships among parameters observed during maneuvers in the sagittal and horizontal planes.

Are the compensations used for unsteady locomotion superimposed on underlying gait dynamics?

Previous studies in our laboratory suggested that active control of maneuvers during running may be superimposed on spring-mass mechanics. This presents the possibility that control of unsteady locomotion could be superimposed on lower-level mechanics that differ for walking and running. We will test the hypothesis that unsteady walking and running involve common strategies, consistent with the functional separation of compensatory control from underlying leg mechanics during locomotion.

Do joints make different functional contributions to unsteady locomotion?

Individual joints can influence overall leg properties in different ways, depending on factors such as morphology and posture. Joints differ in their functional contributions to movement in several contexts. We are testing the hypothesis that motor behavior is organized to allow leg joints to make distinct functional contributions to unsteady locomotion.

References

Hof, A. L., Vermerris, S. M. & Gjaltema, W. A. Balance responses to lateral perturbations in human treadmill walking. J. Exp. Biol. 213, 2655-2664, (2010).