Think With Your Feet, Not With Your Head: A Biologically Inspired Design Approach for Augmenting Unsteady Locomotion

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1 Introduction

1.1 Animals can navigate unsteady environments

Animals are highly stable and agile when moving through complex and unexpected environments. Despite the leaps and bounds of success that legged robots have had, they still cannot match the performance of legged animals in these maneuvers. Interestingly, animals achieve this despite having extremely long sensorimotor delays [1], noisy sensors and compliant actuators. These problems would render today's state-of-the-art robot closed loop feedback controllers infeasible. So how do animals achieve these awe-inspiring behaviors with theoretically less capable sensors and actuators?

1.2 Embedding intelligence in mechanics

One method could be to embed intelligent behavior into the mechanics of their movement. There are a lot of examples of animals doing this. The most extreme example is that dead fish can swim upstream by tuning the mechanical properties of their bodies to turbulent flow. In legged locomotion, guinea fowl retract their swing legs in a purely feedforward manner while running and this behavior provides automatic self-stability against changes in terrain [2]. Cockroaches can run over varying terrain without changing their neural input [3]. These examples indicate that these animals may rely on the adaptive context-dependent behavior of their bodies and actuators (i.e. muscle-tendon units) rather than closed-loop control to navigate these environments.

However, there hasn't been a careful study of (1) What mechanisms allow muscle-tendon units to display context-dependent adaptive behavior in unsteady conditions and (2) Can external devices improve this adaptive behavior in human locomotion? To answer these questions, we present a series of in-silico and in-vitro studies where we choose to study the simplest possible unsteady locomotion task : hopping on a surface that can change its height arbitrarily.

2 Muscles as Smart Actuators

2.1 Phase-dependent muscle-tendon mechanics drive self-stability

In our first study, we developed a model of human hopping on a surface that can change it's height arbitrarily. This consists of a mass in gravity actuated by a Hill-type muscle-tendon unit - a classical model of muscle that is widely used in simulation paradigms such as OpenSim. The muscle is cyclically stimulated by a purely feedforward signal to generate stable hopping (Fig 1B1). When the height of the ground is suddenly dropped, we observe that the system dissipates the energy injected into the system by the drop over several hops and gets back to steady hopping.

This dissipation is enabled by the phase-dependent behavior of muscle-tendon units. When the height of the ground is suddenly dropped, the mass has to travel through the air for a longer period of time to reach the ground. Thus, the timing of ground contact is delayed with respect to when the muscle is stimulated. This advance in the phase of stimulation has been shown to produce negative work in cyclical tasks [4]. Thus, the phase-dependent mechanics of muscle-tendon units enable automatic self-stability in uneven terrain.

2.2 Transient muscle properties enhance robustness against a broad range of perturbations

The previous study models the muscle as a Hill-type contractile element. These models are developed by measurements of muscles in steady state conditions, and do not display transient muscle mechanics which may be important for rejecting perturbations. Thus, for our next study, we perform a biology-in-the-loop experiment where a real muscle-tendon unit is cyclically stimulated and interacts with a simulated mass in gravity through a biorobotic interface to generate hopping [5]. Similar to the modeling studies, we drop the height of the ground once the hopping has settled.

Unlike Hill-type muscle tendon unit based hopping which required increasing number of hops to settle as we increased the height of the drop, we see that real muscle-tendon units dissipate the energy injected into the system within two hops across a broad range of heights (Fig 1B2). Thus, the transient properties of muscle-tendon units and their phase-dependent mechanics are likely key to robust locomotion in uneven terrain. Inclusion of transient properties such as short range stiffness, force enhancement and force depression in Hill-type models or using cross-bridge models that have these properties may improve accuracy of muscle-tendon simulations in unsteady conditions.

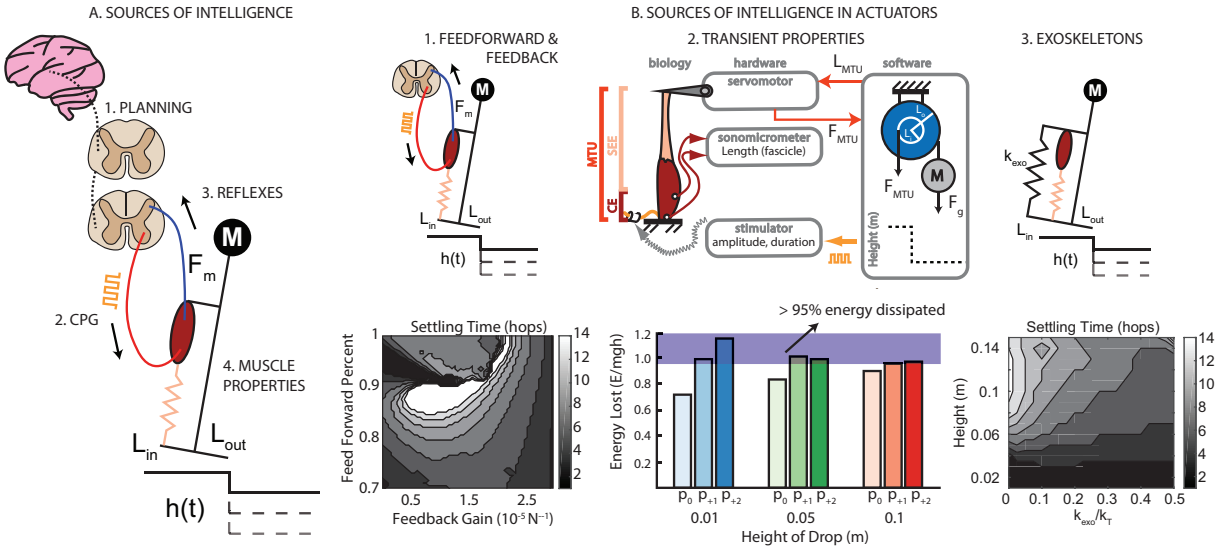

Figure 1: A. Sources of intelligent control include (1) planning (2) central pattern generators (3) reflexes and (4) muscle properties. B. We are focused on how reflexes, transient muscle properties and exoskeletons embed intelligence in mechanics.

3 How To Make Muscles Smarter?

3.1 Positive force feedback does not improve stability but reduces safety and economy of unsteady locomotion

One mechanism that could augment stability in unsteady locomotion is positive force feedback. Thus, we modified the hopping model to add positive force feedback and simulated the model for varying levels of feedback gains and feedforward stimulation amplitudes. When we drop the height of the ground, we see that the amount of time taken to get back to steady hopping after the perturbation does not improve with feedback (Fig 1B1). However, the metabolic energy required to hop during steady hopping as well as the muscle strain during the perturbed step increase with positive force feedback. Thus feedforward dominated strategies are equally robust against changes in the height of the ground as feedback based strategies, while being safer and more economical. These results are contrary to previous studies that don't include tendons [6]. They also assume that stimulation is a function of state (i.e. it starts at apex height) and hence requires the animal to have state estimation, whereas our stimulation is purely a function of time.

3.2 Springy exoskeletons improve self-stability, safety and economy of unsteady locomotion

For our fourth study, we ask the question, can purely passive exoskeletons, that cannot dissipate perturbations by themselves, make the underlying morphology better able to dissipate perturbations? To answer this question, we modified the hopping model of our first study by adding a purely passive springy exoskeleton in parallel with the muscle-tendon unit. We followed the same protocol as above, across different drop heights and exoskeleton stiffnesses. We observed that purely passive exoskeletons allow for faster (Fig 1B3) and safer recovery from perturbations while also making steady locomotion more economical. They do this despite not being able to dissipate any energy, but make the muscle-tendon unit dissipate more appropriate amounts of energy (i.e. make muscles smarter) and hence may compensate for limitations in Hill-type muscles in such conditions.

4 Conclusions

Through this body of work, we show that an alternative strategy to intelligent control is embedding intelligent and adaptive behavior in the mechanics of actuators (i.e. think with your feet, not with your head). This allows animals to navigate unsteady conditions despite having large sensorimotor delays. The prime factors that allow for this behavior are having series-elastic actuators that have phase-dependent mechanics that enable automatic self-stability in uneven terrain. We can make these smart actuators even smarter by developing passive exoskeletons, that lack active control (i.e. brains), but enable the underlying morphology to better dissipate environmental perturbations.

References

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