# Towards Dynamic Walking in Musculoskeletal Simulation

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## 1 Motivation

Musculo-skeletal simulation is an increasingly important research tool, and has provided useful insight and prediction regarding human gait and rehabilitation. Further applications include human animation and simulation of humanoid robotic systems and humans interacting with prosthetics, orthotics and other devices in their environment.

An important *next step* is to increase the capabilities of musculo-skeletal simulations to accurately predict robust stability of whole-body dynamic locomotion. Accomplishing this step is expected to positively enable biomechanical simulation, prosthetics, rehabilitation, and robotics research. Greater stability and robustness of musculo-skeletal simulations enables vertical advancement of the field. The longterm outcomes of this work will enable improved understanding and rehabilitation of gait dysfunction and enhanced tools to analyze stability and robustness of gait.

## 2 State of the Art

Currently, musculo-skeletal simulations are good predictors of anatomically-relevant component-level states, forces, and functions, but not of whole system stability of locomotion. For example, OpenSim and related multi-body biomechanical simulations have opened new possibilities for discovery and prediction of muscle lengths and internal forces during locomotion [5, 4]. However, robustly stable dynamic locomotion has yet to be achieved in such simulation environments.

On the other hand, some existing whole-body spring-mass models of locomotion can predict basic features of the qualitative dynamic stability of locomotion, but cannot make concrete predictions regarding anatomical components of real systems. The spring-loaded inverted pendulum (SLIP) or SLIP-like models [1, 16, 3, 7, 17, 20, 13, 11] were among the first theoretical models used to investigate the dynamic stability of legged locomotion. The SLIP model has been proposed as the organizing principle or 'template' for coordination because it appears ubiquitous in legged animals, it can be self stabilizing [11], and because humans alter properties of it under certain conditions. (e.g. Humans adjust landing angle versus speed [7] and leg stiffness versus ground stiffness [6, 8]). Analytical models of whole-body locomotion, like those first proposed by Blickhan [2] and McGeer [14, 15] have been useful in the development of basic theory for the field of dynamic walking and running.

More recently, it has become increasingly important to use analytical models to predict the stability of motion in cases of large environmental disturbances or internal parameter variations, in order to better understand and predict the robust stability of animals and robots. For this purpose, new classes of SLIP-based models have been proposed and analyzed for their greater robustness such as CT-SLIP [19]. Further, extensions of basic SLIP results in the sagittal plane have been made to three-dimensional motion [18] and trunk dynamics. Further, extensions of whole-body dynamic approaches have been made to increasingly realistic models of locomotion in the sagittal plane including muscle and controller models [12]. However, while such models of intermediate complexity are a very necessary component to understanding dynamic walking, they do not currently integrate with general, standard platforms such as OpenSim. It is this author's opinion that the field of dynamic walking (and running) could benefit from greater integration of basic tools such as simulation packages. OpenSim is one candidate platform to build on. Other simulation programs exist, such as those developed at MIT's leglab and later Boston Dynamics, as well as many physics engines for animation programs. In this talk, the author will provide a more extensive review and comparison of they many current offerings in the world of multi-body and musculoskeletal simulation.

## 3 Approach

The objective of the author is to increase the center-of-mass stability of human walking and running in musculo-skeletal simulation by integrating whole-body lumped models with component-based musculo-skeletal models. The *central hypothesis* is that existing biomechanical simulations of human locomotion can be modified to approximate the whole-body dynamics of Spring-Loaded Inverted Pendulum (SLIP)-type models. This hypothesis was formed from current investigations by the author in which anatomical "anchor" models of locomotion are made to have approximately equivalent whole-body dynamics a reduced "template" models (See [9] for a discussion of Templates and Anchors terminology). In particular, the author is currently investigating relationships between canonical SLIP models and multi-segmented human models, hexapedal cockroach models, and rigid-body models of the Robotic Hexapod (RHex).

The proposed *approach* is to approximate the whole-body dynamics of low-order Spring-Loaded Inverted Pendulum based models of locomotion in the OpenSim environment using existing OpenSim tools. This is part of a broader approach to use template-based models for parameterizing and controlling musculo-skeletal simulation. To increase stability further beyond energy-conserving models, the author proposes to create an OpenSim simulation based upon the Clock-Torqued Spring-Loaded-Inverted-Pendulum (CT-SLIP) model of locomotion (that can achieve full asymptotic stability of motion and requires minimal state feedback [19]). We extend such models to three-dimensions by including a hip adduction control and a leg retraction control for the swing phase.

This approach provides foundations for greater integration between lumped whole-body models with anatomically-representative multi-physics models, for an integrated multiscale biomechanical simulation environment

## 4 Discussion

The author intends to encourage discussion centered on the following questions:

Does our field require greater integration of simulation platforms and tools?

What might an integrated approach to modeling look like?

What are the basic requirements that a simulation package should offer both senior and beginning practitioners in this field?

Can such packages be used in the engineering design cycle?

Is it possible to achieve both the benefits of lumped whole-body models of locomotion and component-based musculoskeletal simulation?

What are the important next steps for improving modeling and simulation of dynamic walking?

What are milestones we can agree on?

## 5 Preferred Format

(first) talk, (second) poster.

## References


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