Simulation of Aperiodic Sprinting with a Spring-Loaded Inverted Pendulum Model

[1]Huseyin Celik, [1,2,3]Stephen J. Piazza
[1]Department of Mechanical and Nuclear Engineering, [2]Kinesiology, and [3]Orthopaedics and Rehabilitation,
The Pennsylvania State University, University Park, PA 16802, USA
email: *piazza@psu.edu*

1 Motivation

A characteristic common to many simulations of bipedal gait of gait simulations is the constraint that the gait is periodic. Inclusion of a periodicity constraint is a reasonable choice when the movement of interest is steady-state walking or running, but not for others such as sprinting from rest. Performance during sprint races is critically dependent on effective rapid acceleration using aperiodic strides just after the start. Previous modeling investigations of sprinting have focused on periodic steady-state running that occurs in the latter portion of the race. The aim of the present study is to simulate aperiodic sprinting from rest for 20 m using a relatively simple torque- and force-driven spring-loaded inverted pendulum biped model.

2 State of the Art

Bipedal sprinting has been simulated using several mathematical models of varying complexity and numerical optimization schemes. For instance, Lee and Piazza (2009) [1] simulated the push-off phase of a sprinting stride using a three-link muscle-driven model and parameter optimization to determine the muscle excitation controls. Van den Bogert and Ackermann (2009) [2] simulated periodic maximal sprinting with a seven-segment nine-DOF muscle-driven model using the direct collocation method to determine the controls. Schultz and Mombaur (2010) [3] simulated periodic sprinting using a 25-DOF three-dimensional torque-driven model with controls determined using a "multiple shooting" approach. None of the these, however, were simulations of multiple discrete steps during aperiodic sprinting.

3 Own Approach

Most optimization algorithms need a good initial guess to converge on an optimal solution for complex high dimensional nonlinear problems. There are two main ways to determine this initial guess for simulations of gait: (i) collecting experimental gait data, then solving for kinematics, kinetics, controls, etc. using inverse approaches; and (ii) implementing a controller that produces the desired gait using a forward simulation approach. For this study, in which several aperiodic steps were to be simulated, limitations on the length of instrumented walkway and on the motion capture volume make the first approach problematic. We employed the second approach using a three-phase scheme in which proportional-derivative control of trunk orientation, foot placement, and leg rotation was used to simulate an alternating gait with successive steps from rest. A similar approach was previously described by Raibert (1986) [4].

Generalized coordinates and controls from the initial guess simulation were then used as the input in an optimization in which time at the 20 m mark was minimized. The nonlinear programming problem was solved using SNOPT as the optimizer and a direct multiple shooting method, in which continuity between simulation segments was enforced by constraint.

4 Current Results

An optimal solution was found that represented considerable improvement over the initial guess. The model traversed 20 m in 2.79 s following optimization but required 6.64 s in the initial guess simulation. Improvements were also noted in the time needed to reach steady-state volocity (1.2 s versus 4.3 s) and top speed (8.5 ms^{-1} versus 4.3 ms^{-1}) (Figure 1). The optimized sprint simulation demonstrated many features of human sprinting such as forward trunk lean at the start, straightening of the trunk during acceleration, and a dive at the finish (Figure 2); none of these were explicitly constrained to occur in the problem formulation.

5 Best Possible Outcome

Using numerical approaches similar to those of the present study with additional muscle actuators and joints, this work will be extended to study relationships between muscle and joint structure and optimal sprinting performance.

References

[1] Lee et al (2009) J Exp Biol
[2] Van den Bogert et al (2009) XII Congress of ISB
[3] Schultz et al (2010) IEEE/ASME Trans Mechatronics
[4] Raibert (1986) "Legged Robots that Balance"

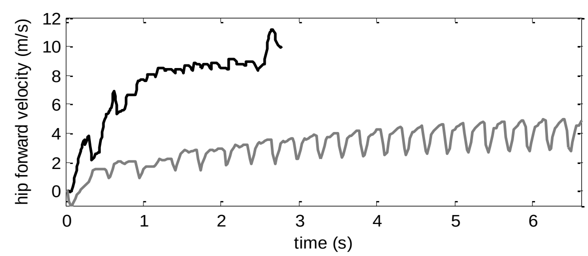

Figure 1. Forward velocity in the initial guess (*gray*) and optimized (*black*) simulations.

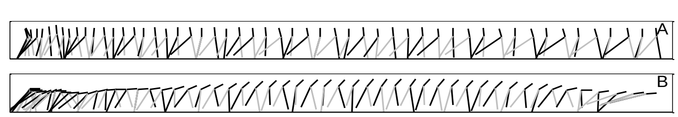

Figure 2. Motion trajectories in the (A) initial guess and (B) optimized simulations.