Optimal Control Workshop

B.J. Fregly, Ph.D. and Anil Rao, Ph.D.
Department of Mechanical & Aerospace Engineering,
University of Florida, Gainesville, FL

Motivation

Why are we here?

We want to simulate and predict how the human body moves, and we want to find better ways to do it.

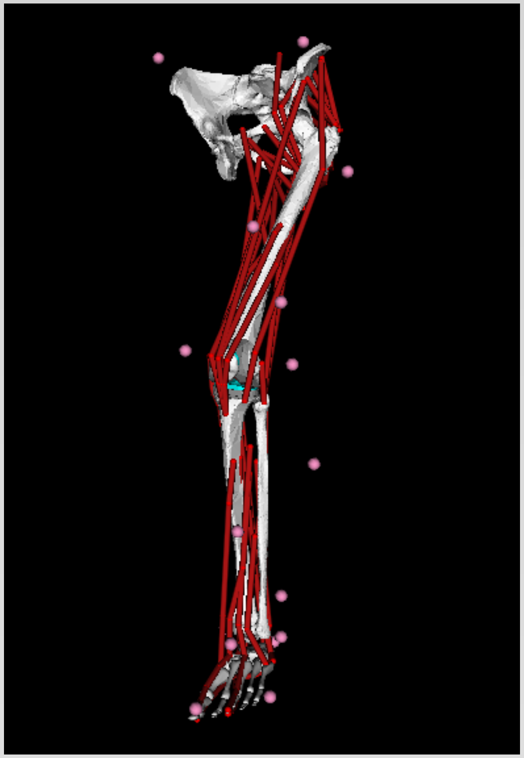
How do we simulate movement?

Movement simulation typically requires two elements – dynamics (ODEs) and controls.

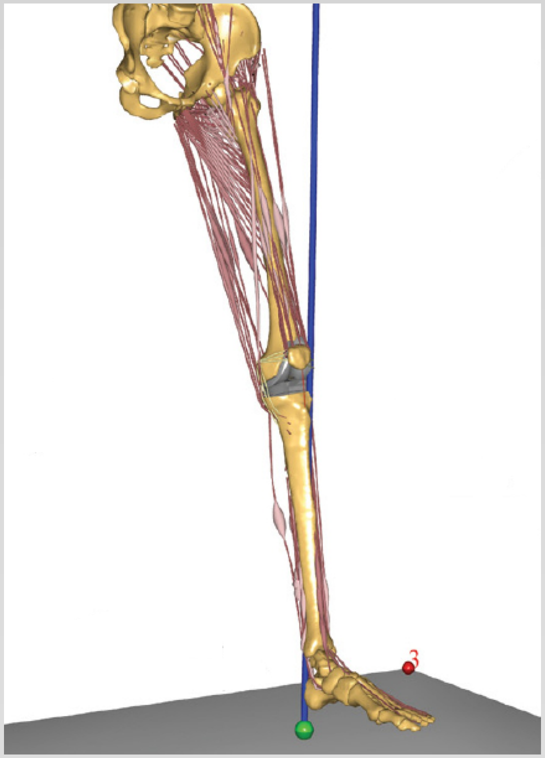
What constitutes “better”?

“Better” means easier, faster, and more robust.

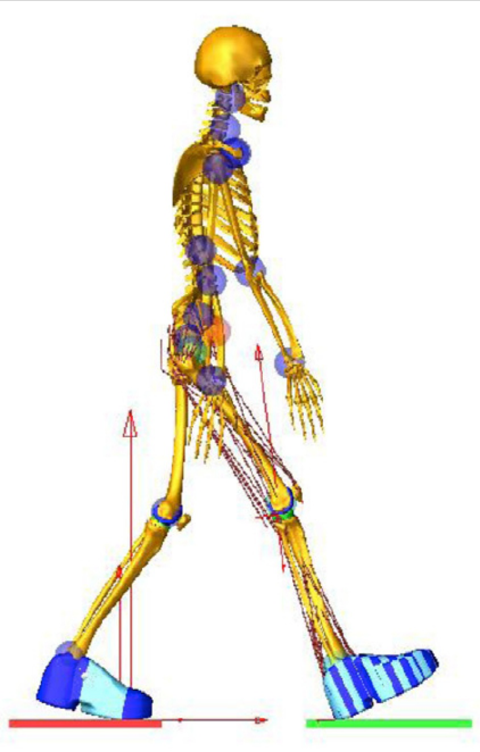
Available Software



OpenSim
(Walter *et al.*, 2014)



AnyBody
(Marra *et al.*, 2015)



Adams
(Kia *et al.*, 2014)

Typical Problems

Computational Biomechanics Laboratory

What are some human movement simulation or prediction problems that we typically try to solve?

- Inverse kinematic analyses
- Residual elimination simulations
- Muscle force simulations/predictions
- Skeletal motion simulations/predictions
- Combined muscle force and skeletal motion simulations/predictions
- Joint contact force simulations/predictions

Dynamics (ODEs) and controls are inherent in all of these human movement problems.

Typical Solution Methods

What are some ways that we typically try to solve these human movement problems?

- Inverse kinematic analyses - multi-joint (global) optimization (positions only) or Kalman smoothing
- Residual elimination simulations – residual elimination algorithm (repeated forward dynamic simulations with feedback control within an optimization)
- Muscle force simulations/predictions – static optimization, dynamic optimization
- Skeletal motion simulations/predictions – forward dynamic optimization, inverse dynamic optimization

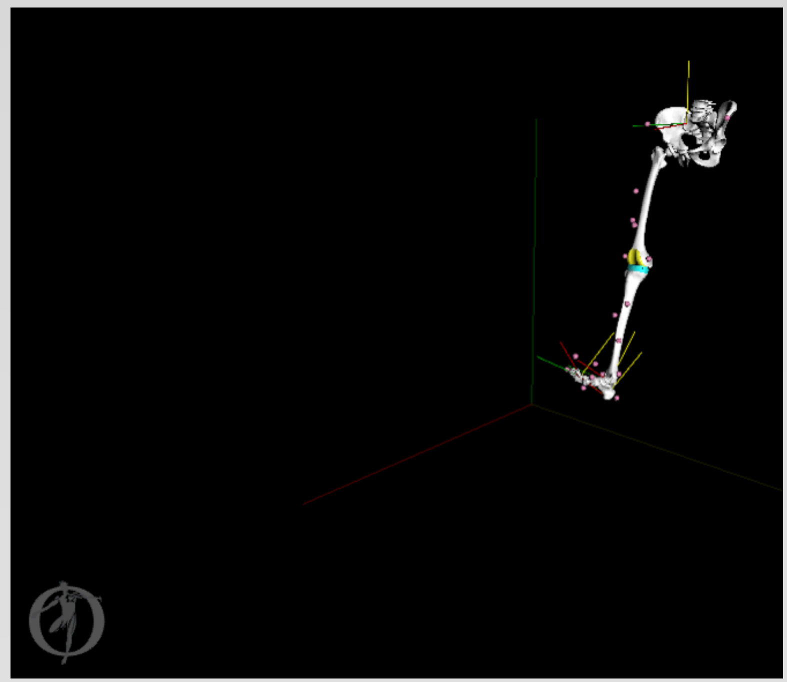
Typical Solution Methods

Observations:

1. Lots of different optimization-based solution methods exist for lots of different problems.
2. Wouldn't it be nice if we could find one optimization-based solution method that could handle most of these typical problems!
3. Function evaluations for optimizations often involve performing forward dynamic simulations using numerical integration time stepping (i.e., shooting methods).

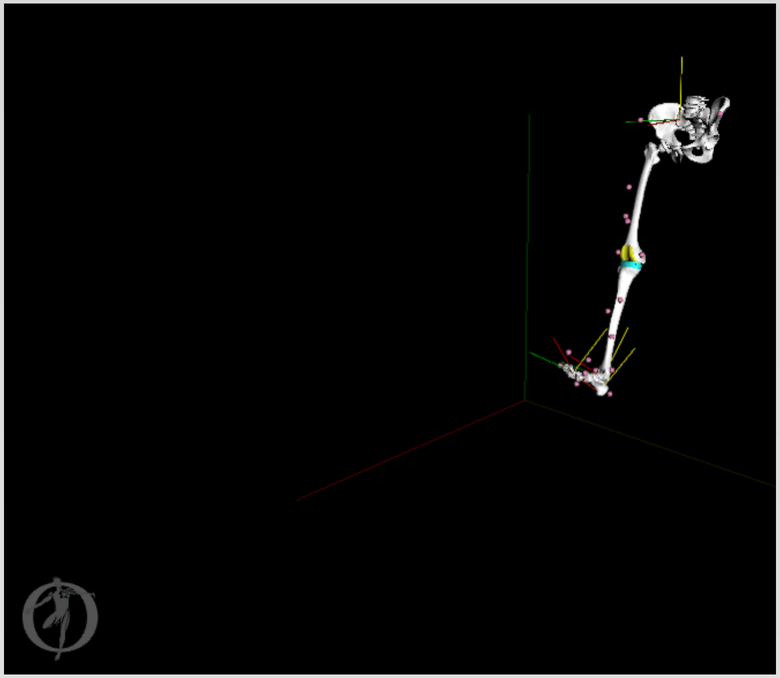
Shooting Methods

- Method: Guess controls, **numerically integrate** dynamics equations to find **motion** for each time frame **sequentially**, iterate controls guess
- Strength: Dynamically consistent (no residual loads on pelvis)
- Weaknesses: Numerical integration (integration drift, integration cost), stability (feedback control required)

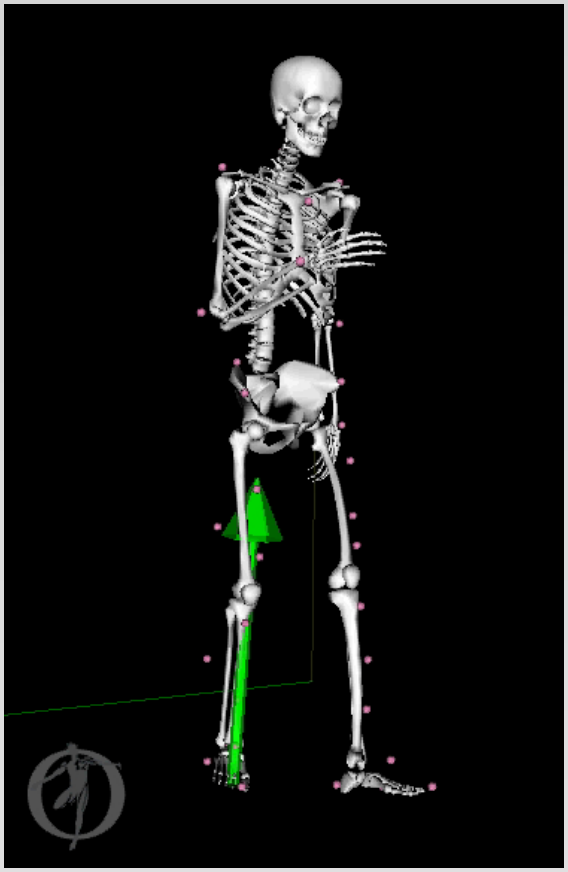


Direct Collocation Methods

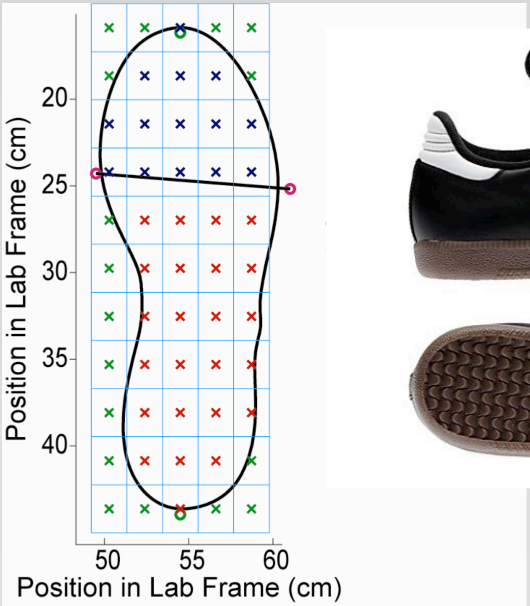
- Method: Guess controls/**motion**, **discretize** dynamics equations, iterate controls/motion guess to find motion and controls over all time frames **simultaneously**
- Strengths: Dynamically consistent (no residual loads), **no numerical integration** (performed as part of optimization), **no stability problems** (no feedback control required)
- Weaknesses: Larger number of design variables, higher optimization cost



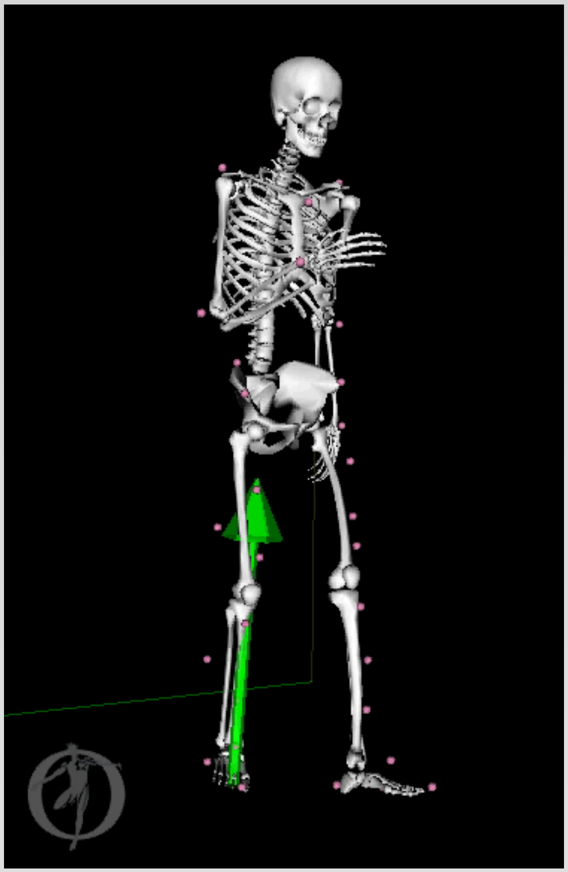
Direct Collocation Example – Stroke Walking



- 29 DOF OpenSim walking model
- Calibrated two-segment foot-ground contact model (both feet)



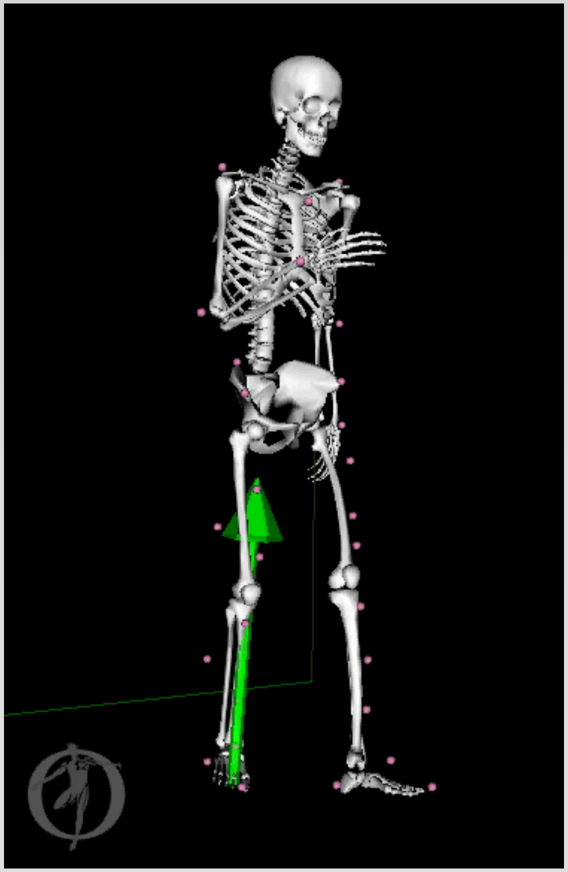
Direct Collocation Example – Stroke Walking



- 29 DOF OpenSim walking model
- Calibrated two-segment foot-ground contact model (both feet)
- Calibrated EMG-to-moment model (35 muscles controlling each leg)

Processed EMG →
Joint kinematics →
EMG-to-Moment Model
→ Muscle moments

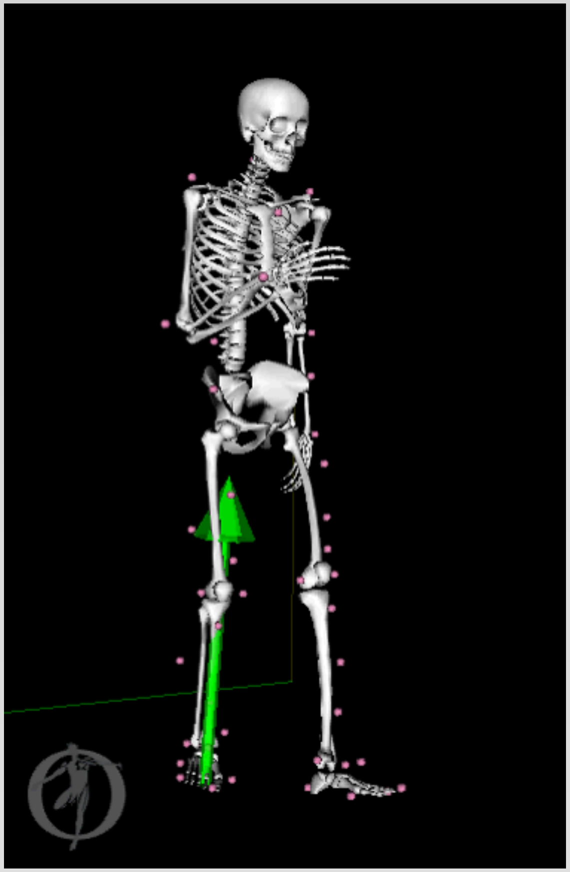
Direct Collocation Example – Stroke Walking



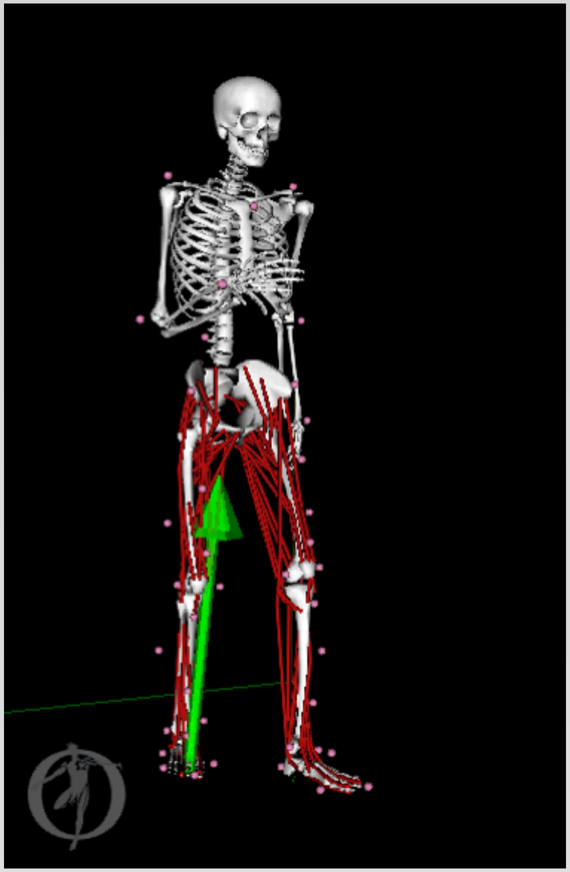
- 29 DOF OpenSim walking model
- Calibrated two-segment foot-ground contact model (both feet)
- Calibrated EMG-to-moment model (35 muscles controlling each leg)
- Torque actuators controlling arms, back, and toes joints
- Minimized changes in activation and torque controls to produce a periodic walking motion
- Problem solved in Matlab using GPOPS-II optimal control software

Patterson and Rao (2013) *ACM TOMS*

Direct Collocation Example – Stroke Walking



Experimental Animation
(visualization only)



Activation-driven Optimization
(35 muscles in each leg)

Workshop Outline

Session 1:

Theoretical Background for Optimal Control (Rao)

Session 2:

Overview of Numerical Solution Methods (Rao)

Specific Numerical Solution Methods (Rao)

Session 3:

Introduction to GPOPS-II Optimal Control Software (Rao)

Human Movement Example Problems (Fregly)