

Constraint-Based Contact Modeling for Predictive Simulation of Gait

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Introduction

The generation of realistic human gait through predictive simulation remains a cornerstone of biomechanical research. Unlike inverse dynamics, that is a clinical standard for analysing recorded motions, predictive simulation generates motion from scratch by solving Optimal Control Problems (OCP) that minimize physiological costs, such as metabolic cost [1]. This approach is essential for exploring "what-if" scenarios, allowing researchers to predict how changes in mechanical properties or physiological constraints influence gait strategies without relying on exhaustive experimental trials.

A critical challenge in these predictive simulations lies in the mathematical modelling of foot-ground interactions, which approximates non-penetration and sticking contact constraints. Conventional approaches typically employ penalty-based contact models or compliant contact models, thereby avoiding non-smooth contact behaviours. While effective, these models require careful tuning of local stiffness parameters, which can introduce convergence difficulties [7]. To address this, this work utilizes the Odin software framework developed at ULiège [2]. Unlike traditional recursive codes, Odin is built on a finite-element-like architecture that utilizes geometric methods for spatial discretization. By representing kinematics as elements of the Lie group $SE(3)$, the framework supports the modular definition of complex topologies, e.g., with closed kinematic loops. Additionally, Odin employs specialized numerical integrators designed to resolve constrained-based contact models and non-smooth dynamics efficiently. By integrating Hill-type muscle models, adapted from De Groote and Fregly [4], into this robust framework, while using OpenSim solely for pre- and post-processing, as shown in Fig. 1, we establish a streamlined workflow to test the efficacy of constraint-based contact formulations in prosthetic gait generation.

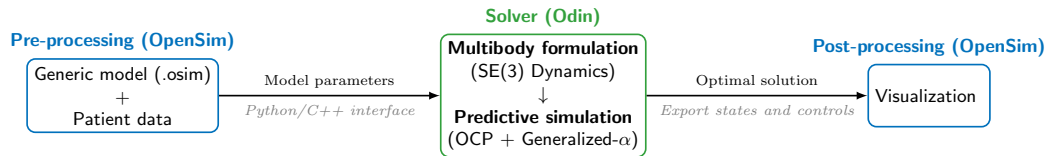


Figure 1: Workflow between OpenSim and Odin.

Methodology

We formulate the predictive simulation as a trajectory optimization problem. To resolve the intrinsic muscle redundancy of the musculoskeletal system, we solve for the muscle excitation patterns and system states that minimize metabolic cost subject to the equations of motion [1, 6].

We model the foot-ground interface using hard constraints leading to constrained equations of motion. The smooth phases of motion (swing and stance) are governed by Differential Algebraic Equations (DAE), while the foot-ground collisions are treated as instantaneous events governed by a Newton impact law. This hybrid mechanics formulation is then formulated in a reunified manner in terms of differential measures and solved using the non-smooth generalized- α time-stepping scheme [3] to enforce strict non-penetration and impact consistency at the velocity and position level.

For the optimal control transcription, we utilize a single-shooting formulation. Although rigid contact interactions introduce discontinuities at the moment of impact, the core of this work is to investigate the behaviour of gradient-based optimization solvers for this class of problems when exploiting the gradients

obtained by propagation of the sensitivities using the non-smooth time integrator, based on the tangent operator readily available for the Newton semi-smooth iterations of the time-step solver. This computational framework is applied to a musculoskeletal model adapted from the existing Gait2354 OpenSim model [5].

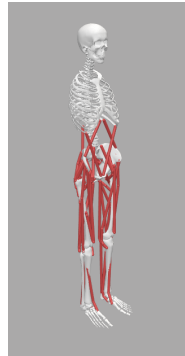


Figure 2: Musculoskeletal model of gait model in OpenSim [5].

Conclusion

The primary focus of this study is to investigate the feasibility of a single-shooting optimal control formulation for the predictive simulation of non-smooth gait. By employing a rigorous formulation and numerical treatment of the contact constraints and a semi-smooth evaluation of the gradient, we aim to evaluate the behaviour of gradient-based optimal control solvers for gait analysis.

Acknowledgments

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