Turning a corner in predictive musculoskeletal simulations of gait using implicit dynamics

Marlies Nitschke[1], Eva Dorschky[1], Heiko Schlarb[2], Bjoern M. Eskofier[1], Antonie J. van den Bogert[3], Anne D. Koelewijn[4]
[1]Machine Learning and Data Analytics Lab, University of Erlangen-Nürnberg (FAU), Germany
[2]FUTURE Sport Science, adidas AG, Germany
[3]Department of Mechanical Engineering, Cleveland State University, Cleveland, OH, USA
[4]Biorobotics Laboratory, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland
Email: marlies.nitschke@fau.de

Summary

Recently, 3D gait simulations were generated by solving optimal control problems using musculoskeletal models. However, these simulations lack predictive power and require long computation time. We formulated implicit dynamics for a full-body 3D musculoskeletal model to solve optimal control problems in a computationally efficient way. We show that with the implicit formulation a full-body predictive simulation of curved running can be generated from a random initial guess in about two hours.

Introduction

Predictive simulations of human motion could potentially aid prosthesis design (e.g. [1]), and reinforcement learning of human movements. 3D motion simulation is challenging due to its high-dimensional solution space and requires quick and efficient algorithms. Direct collocation has been applied successfully to solve predictive simulations in two dimensions [1]. Recently, it was also applied to 3D simulations by Lin and Pandy [2]. However, computed muscle control [3] was required to generate an initial guess, and the predictive simulation deviated little from the initial guess [2], meaning that this approach lacks predictive power. Furthermore, model dynamics were provided by OpenSim [3], and formulated explicitly, leading to long computation time [2]. An implicit formulation could overcome the numerical stiffness and high non-linearity associated with musculoskeletal dynamics and could thus decrease computation time [4].

In this abstract, we show the efficacy of predictive simulation of a full-body 3D musculoskeletal model using implicit dynamics by creating a tracking simulation of straight running from a standing initial guess, and a predictive simulation of curved running from the straight running simulation.

Methods

Predictive simulations were solved for a musculoskeletal model that was derived from [5]. It has 33 degrees of freedom and 92 Hill-type muscles in the legs and the trunk. Arms were operated using 10 torque units. It was scaled to match a male subject (92 kg, 195 cm). Model dynamics were formulated implicitly as $f(x, \dot{x}, u) = 0$ for states x and controls u [1].

First, standing was found from a random initial guess. The objective was to minimize effort (cubed neural excitation in the muscles and squared torque in the arms), while constraining the control input and state derivatives to be zero. Secondly, a tracking simulation was solved of straight periodic running at 4.0 m/s. Here, the objective was to minimize effort, while global orientation, joint angles, and 3D ground reaction forces (GRFs) were tracked. Third, a predictive simulation of curved running at 2.7 m/s was solved. Here, the objective was to minimize effort, while joint angles and vertical GRFs of straight running were tracked. Curved running was achieved by constraining the translation and rotation of the body and its velocities for a turn radius of 3.7 m. The optimization problems were solved in IPOPT [6] using direct collocation with 50 nodes and a backward Euler formulation.

Results and Discussion

Standing required less than 1 min CPU time, straight running required 1 h 14 min, and curved running 56 min. As expected, the tracking simulation of straight running matched the experimental kinematics and GRFs well. In the simulation of curved running, the predicted pelvis rotation was similar to the experimental data, even though straight running data at a larger speed was tracked. Fig. 1 shows the trajectory of curved running using stick figures.

The joint angles in the curved running simulation showed greater similarity to the (tracked) data of straight running than the data of curved running. The radius of the curve was larger and a slight turn was required to compensate. A higher weighting of the effort objective would allow further deviation from tracking data. Furthermore, the periodicity constraint for curved running could be extended to avoid turning between gait cycles.

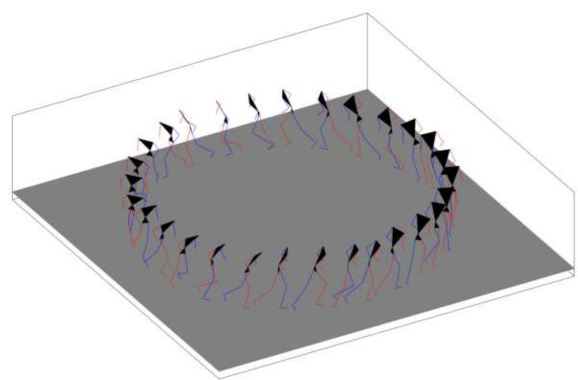

Figure 1: Simulated curved running.

In conclusion, predictive simulation using implicit dynamics can track and predict movements for detailed full-body 3D musculoskeletal models with low computational cost.

Acknowledgments

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