Task-Based Trajectory Optimization in Musculoskeletal Systems

[1]Antonie J. (Ton) van den Bogert, [2]Patrick Kugler, [3]Heiko Schlarb

[1]Cleveland State University, US; e-mail: a.vandenbogert@csuohio.edu
[2]Friedrich-Alexander University Erlangen-Nuremberg, Germany
[3]adidas AG, Herzogenaurach, Germany

1 Motivation

When designing sports equipment or rehabilitative devices, the goal is to alter or improve the movement of a human user who is mechanically coupled to the system. We are interested in developing computational models that can guide the design process by predicting these effects. Such models will need to represent musculoskeletal dynamics as well as behavioral principles for control.

2 State of the Art

To solve the human movement prediction problem, trajectory optimization is typically performed with an objective function that represents the task (e.g. distance travelled) as well as a behavioral principle such as minimal energy or minimal force [1]. The trajectory optimization problem is then solved by shooting methods, in which the system is simulated repeatedly until muscle excitation patterns (controls) are found that minimize the cost function. In recent years, efficient collocation methods have been developed [2], which lead to a large scale nonlinear program (NLP). This made it possible to include task constraints and produce solutions that are, for instance, perfectly periodic and walk at a prescribed speed. However, it remains difficult to obtain true *de novo* solutions because a good initial guess is required for convergence. We believe that the strong nonlinearity of musculoskeletal dynamics, including the foot-ground contact model, was partially responsible.

3 Own Approach

Nonlinearities and poor numerical conditioning were addressed by an implicit formulation of musculoskeletal dynamics [3]. The multibody dynamics consists of Kane's equations for the force balance between inertial effects and applied loads. Muscle dynamics was described by an equation for the force balance between series elasticity and the contractile component. More recently, we extended this approach with an implicit representation of foot-ground contact, which includes foot and footwear deformation in all directions, rather than normal to the contact surface as was assumed in the past [2]. An array of massless contact points is defined, each coupled to the rigid body system by a 2D spring-damper element and interacting with the ground through hard contact and dry friction (Figure 1). Four state variables are introduced for each contact point: position (x,y) and force (F_x,F_y). Two equations are added to the system dynamics to represent the load-deformation properties and two Fischer-Burmeister equations for contact and friction [4].

This contact model increases the number of unknowns and equations, but extreme nonlinearities are avoided and convergence of the NLP solution process may be improved.

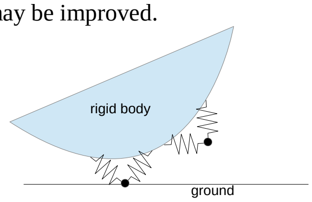

Figure 1: Schematic representation of the contact model.

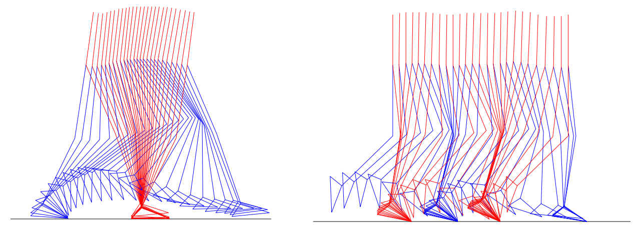

Figure 2: Two solutions of the trajectory optimization for walking at 1.1 m/s, with cost of 0.071 (left) and 0.158 (right). Half of the symmetric gait cycle is shown.

4 Current Results

Trajectory optimizations were performed on a planar musculoskeletal model. The minization objective was the mean squared muscle excitation, sometimes augmented by a second term to track an observed human performance. With a fully random initial guess for states and controls, convergence was usually achieved. This reduces the need for an initial guess, and eliminates potential concerns that the solutions could be biased by the initial guess. However, without a tracking term in the objective, a wide range of solutions was found. All solutions were biomechanically feasible and locally optimal, but most had high cost and were outside of normal human behavior (Figure 2). Many attempts were required to find a realistic solution with low cost. Fortunately, this lowest cost solution could also be obtained very quickly by either using a tracking solution as initial guess, or by a continuation scheme which started with a fully predictive optimization of standing, followed by gradual increase in walking speed.

Certain novel movements cannot be reached by continuation but can sometimes still be discovered from a random initial guess. For instance, when the task was specified as walking at 1.1 m/s with a full somersault in each step, a realistic (but probably not globally optimal) solution was found after several attempts.

5 Best Possible Outcome

The current methods allow predictive simulations for walking and running for footwear design and prosthetics/orthotics development. The results suggest that a globally optimal trajectory can be found by continuation. It would, however, be desirable if the problem could be reformulated such that novel movements and unbiased predictions can be generated quickly from a random initial guess. We are also working on extending the methodology towards three-dimensional musculoskeletal models of walking, running, and sports maneuvers.

5 References

1. Miller RH, et al. (2013) *J Biomech Eng* **135**: 011007.
2. Ackermann M., van den Bogert AJ (2010) *J Biomech* **43**: 1055-1060.
3. van den Bogert AJ, *et al.* (2011) *Procedia IUTAM* **2**: 297-316.
4. Todorov E (2010) *IEEE Int Conf Robotics Autom.*