New Computational Models for Musculoskeletal Simulation in Three Dimensions

Dinesh K. Pai, Ye Fan, David I. W. Levin, D. Li, J. Litven, S. Sueda, Q. Wei

Sensorimotor Systems Laboratory, University of British Columbia

Introduction

Models of musculoskeletal systems are constrained not only by experimental data but also by the technology available to make predictions with these models. The technology includes not only the computer hardware used to simulate these models but also the mathematical formulation of the models in the form of software. Limitations of modeling technology can have a subtle but inexorable influence on how we view complex biomechanical phenomena. Two broad types of models currently in use are: (1) models of large scale musculoskeletal dynamics, involving multiple joints and muscles (e.g., models developed using OpenSim [Delp et al. 2007]); (2) models of muscle deformation in contact with other muscles (e.g., using finite element models). Both types of models have been well studied, and mature software is available.

In this thematic presentation, we will describe new computational approaches that may address some of the current limitations of these types of models.

Musculoskeletal dynamics

Most current models of musculoskeletal biomechanics extend the multibody dynamics models developed in robotics by adding abstract muscles, so that muscle activations can be used as a more natural input. This is now the standard approach in biomechanics. The muscle is abstract because it has no mass and only serves to compute the joint torques via the muscle’s “moment arm”. While these serve a useful purpose, the underlying architecture imposes two significant limitations for simulating dynamics. First, as pointed out in [Pai 2010], since muscles are massless in these models, with their mass lumped with a body segment, the computed joint inertias (and potentially all aspects of dynamics) are inaccurate. For example, to move the most distal joint of your finger, you must move not only the mass of the tiny distal phalanx, but also the mass of larger muscles in the forearm which are connected to it. This is not accounted for in the standard approach. Second, the moment arm is a useful concept when a muscle has a simple action, but this is not true for many muscles, e.g., the lumbricals and others that insert in the tendon network of the finger. Even though an instantaneous but time-varying moment arm could be defined in these cases, it no longer provides a parsimonious description of the muscle action.

To address these and other challenges we have introduced a new technique for representing the fiber-like structure of biological tissues using thin elastic solids called “strands” that can curve and make contact in 3D, but can be efficiently simulated [Sueda et al. 2008]. Using strands we have modeled the dynamics of the hand with 54 musculotendons and 17 bones. We have also constructed a 3D model of the dynamics of the ocular motor system, including muscles and connective tissue pulleys [Wei et al. 2010]. Recently we addressed the challenge of discretizing highly constrained strands (e.g., tendon in a sheath) by introducing new reduced-coordinate and Eulerian nodes [Sueda et al. 2011].

Muscle Deformation in Contact

Models of muscle deformation are usually discretized using Lagrangian finite elements (FEM) (e.g., [Blemker and Delp 2005]). FEM models are very general in principle, but can have significant computational cost and modeling complexity, especially if dynamics, contact, and large deformations are required. In addition to the difficulties in detecting close contact, such as that between adjacent muscles, methods relying on Lagrangian discretizations must handle degenerate cases by explicitly remeshing the deformed object. Fully dynamic FEM simulations have therefore been limited to small numbers of muscles and joints.

We recently introduced a new Eulerian discretization to address these limitations [Levin et al. 2011]. Eulerian methods, which discretize space itself, provide an interesting alternative due to the fixed nature of the discretization. Our method features a contact detection and resolution scheme which does not require explicit surface-tracking to achieve accurate contact response. Time-stepping with contact is performed by the efficient solution of large sparse quadratic programs; this avoids constraint sticking and other difficulties. Simulation and collision processing can share the same uniform grid, making the algorithm easy to parallelize. We have demonstrated an implementation of all the steps of the algorithm on GPUs (commodity many core parallel computers). The method is effective for simulation of complicated contact scenarios involving multiple highly deformable objects, and can directly simulate volumetric models obtained from medical imaging techniques such as CT and MRI. Work on modeling muscle with this new framework is in progress.

Conclusion

We have introduced two new modeling technologies motivated by the needs of 3D musculoskeletal modeling. Even though both these technologies are in their infancy, they may enable fresh insights into the biomechanics of the musculoskeletal system.

References