A Full-Body Musculoskeletal Model for Predictive Simulation of Human Motion

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Summary

We present a full-body musculoskeletal model for predictive simulation of human motion. To demonstrate its capabilities, we used direct shooting to optimize neuromuscular control policies for various high-level tasks and validated the results against experimental data. Our complete model (Figure 1) has 58 degrees-of-freedoms (DOFs) with a freely moving scapula, and 234 musculotendon units (MTUs) with elastic tendons and variable pennation angles. Despite its complexity, performance is sufficient for predictive and interactive simulations. We also provide simplified and partial variants with less DOFs and MTUs for additional performance.

Introduction

Predictive musculoskeletal simulations have been holding a longstanding promise to transform biomechanics research. Unlike inverse or tracking simulations, in which actuator inputs are derived from recorded motion data, predictive simulations generate motions *de novo*, by optimizing the actuator inputs required to perform specific high-level tasks. These actuator inputs typically consist of either feedforward trajectories (optimized using direct collocation), or the outputs of a feedback control policy (optimized using direct shooting or reinforcement learning). Control policy methods can model the underlying neurological control system, enabling them to simulate perturbation responses, facilitate clinical decision-making for neuromuscular disorders, and aid in the design of assistive devices through human-in-the-loop simulations.

The limited availability of suitable musculoskeletal models is a bottleneck in the progress of predictive simulation research. While several suitable lower extremity models exist, activities like assisted gait, reaching, raising from a char, or breaking a fall require accurate full-body models. Unlike models for inverse or tracking simulations, predictive models require a) contact geometry to detect contacts and avoid inter-limb collisions; b) joint limits to prevent movement beyond physical ranges; c) high simulation performance to minimize policy optimization time; and d) accurate and robust behavior across all conditions, since invalid states that occur during policy training can derail or halt the optimization process.

Methods

Our model was constructed by combining and adapting existing datasets (e.g. [1]). For the shoulder, we developed a scapulothoracic constraint based on contact forces, similar to [2] but with customizable contact stiffness and damping parameters. Furthermore, we: a) added mass properties and compounded segments where needed; b) modified muscle paths to use via points and wrapping lines for increased performance, while maintaining moment arms reported in literature; c) added contact geometries; d) defined joint limit torques; and e) we extensively tested and tuned the model for robustness, performance and accuracy.

Our complete model (Figure 1) contains 58 DOFs, 234 Hill-type MTUs with elastic tendons and variable pennation angles [3], and uses Hunt-Crossley contact forces with static, dynamic and viscous friction. All model parameters can be personalized. For validation we used direct shooting with SCONE [4] and the Hyfydy simulation engine (hyfydy.com) to optimize neuromuscular control policies for arm elevation [5], target reaching (Figure 1), full-body gait and tripping.

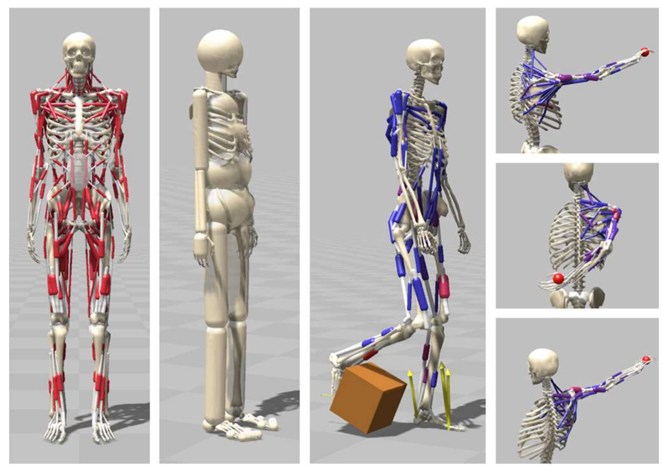

Figure 1: Full model, contact geometry, tripping, target reaching.

Results and Discussion

On modern hardware, the single-core simulation performance of our full-body model is ~5X real-time (with an error-controlled integration step size of ~0.1ms) – adequate for use in predictive and interactive simulations. Our partial shoulder-arm variant runs at ~50X real-time. While our simulation results agree with experimental kinematics and forces, further validation is required before clinical usage is warranted.

Conclusions

Our model provides a solid foundation for predictive neuro-musculoskeletal simulation studies in various novel areas. All model variants will be published in the open and customizable Hyfydy file format (see hyfydy.com/documentation).

References

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