Dynamic Simulation of Musculoskeletal Biomechanisms in 3D

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INTRODUCTION

Our approach to biomechanical modeling is motivated by the long term goal of developing a precise and constructive understanding of how the central nervous system (CNS) controls movement. The dynamics of the biomechanical plant could potentially account for many features of movement and coordination that should not be attributed to neural control. I discuss what is needed for this task, and describe our solution, using biomechanical strands.

REQUIREMENTS

It is helpful to first discuss the constraints imposed on biomechanical models used for motor control.

Complexity. Even simple natural movements, such as reaching for an object, involve large numbers of muscles in the body. A long standing challenge of neural control is to understand how the CNS coordinates these large numbers of muscles, perhaps organizing them in a flexible way into a small number of synergies. To test hypotheses of motor control it is essential to model large scale biomechanical systems, with a large numbers of muscles. Robust algorithms are required to simulate these large scale systems efficiently, preferably at interactive rates.

Biomechanisms. Frequently, muscles do not simply insert on a bone but terminate in a complex network of tendons and connective tissues. It is well known that the tendons of many muscles span multiple joints resulting in complicated mechanical coupling between joints, and that fascia could couple the action of different muscles. Particularly striking is the insertion of the extensor muscles of the hand, which terminate in a complex mechanism. Perhaps most suprising is the relatively recent discovery that even the apparently simple extraocular muscles (EOMs) of the eye are held in the orbit by pulley-like structures made of connective tissue and smooth muscle. We will call such biomechanical networks of tendon, connective tissues, and muscle ``biomechanisms," to suggest a role similar to that played by mechanisms in engineering. Even though it is generally believed that biomechanisms are functionally important, their precise functions are not very well understood. For instance, it has been proposed that orbital pulleys may help implement Listing's law and make rotations of the eye appear commutative, but this has not been shown with dynamic simulations with realistic anatomy.

Realistic dynamics. A series of remarkable papers from the laboratories of McMahon, McGeer, Ruina and others have shown that many features of walking, in both humans and robots, could be generated by ballistic movements. This suggests that it is important to simulate the dynamics of biomechanical systems, and not just statics or kinematics. But this is complicated for two reasons: (1) Biomechanisms significantly modify the dynamics of a plant, since they could couple the mass of a muscle in one body segment to distant body segment. (2) Constitutive models of active muscles that can accurately predict the action of muscles in normal use are not yet known.

Proprioception. Neural control and learning of movement requires proprioceptive information from muscle spindles and golgi tendon organs. To model these mechanoreceptive sense organs, it is important to not only simulate the gross behavior of muscle but also the strains, strain rates, and stresses within muscle.

METHODS

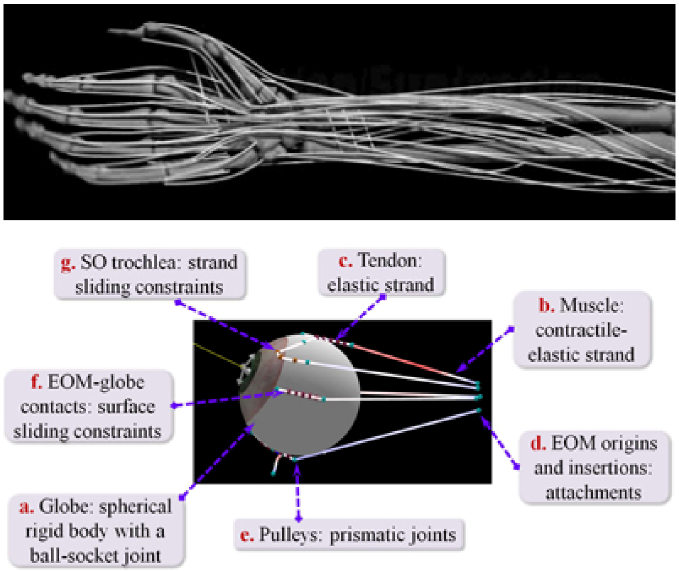
In my laboratory we have developed a new approach to biomechanical simulation that addresses these requirements and combines the advantages of solid mechanics models with the efficiency and scalability of line-of-force models.

Unlike standard FEM models of solid mechanics that discretize muscles into tetrahedral elements, we discretize into thin rod-like elastic elements called **strand** elements, that can curve in three dimensions [1]. A strand has distributed mass, physiological cross sectional area (PCSA), and elastic properties that can vary along its length. Each strand receives a single neural activation signal that affects its constitutive properties; thus a strand is a unit of motor action. A strand could represent either an entire musclulotendon, a compartment within a muscle, or a single motor unit - this is a choice a user can make based on the level of detail required for a specific investigation.

RESULTS AND DISCUSSION

Hand [1]. We developed a model of the hand and forearm with 54 musculotendon strands and 17 bones (see Figure). Musculotendon paths were constructed based on standard textbook models in the literature. The simulation currently runs at interactive rates on ordinary PCs. To test the utility of the model for motor control, we developed an inverse activation algorithm that estimates motor commands from a given target hand movement.

Oculomotor System [2]. We developed a model of the human orbit with realistic anatomy, including the EOMs, connective tissue pulleys, ligaments, and constraints due to contact between tendons and the globe. The resulting model generates realistic gaze positions and saccade trajectories given EOM innervations, and can simulate pathologies such as acute superior oblique palsy.



Above: strand model of the hand and arm [1]. **Below**: model of the human orbit [2].

CONCLUSIONS

The key advantage of our approach is that a strand represents in detail the mechanical actions of muscles that are most useful for motor control, while ignoring other effects in the transverse directions. Thus a strand is not a general purpose model of muscle (for instance, it would be unsuitable for simulating palpation or surgical incision of muscle). It was specifically designed for motor control. A second advantage is that we can model constraints such as tendon sheaths in a dynamically consistent way, with constraint forces computed using Lagrange multipliers. This is makes it possible to simulate complex biomechanisms.

REFERENCES

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