Simulation of 3D neuro-musculo-skeletal systems with contact

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Understanding the neural control of movement requires realistic computational models of the underlying musculo-skeletal system. Even though detailed models exist for the biomechanical properties of muscle tissue, current models of entire systems do not fully account for the distributed, three dimensional nature of muscle action. The importance of detailed biomechanical models for neuroscience have been described by (Loeb, Brown, Lan, & Davoodi, 2001), and even earlier by (Lombard & Abbot, 1907) who said: "before we can arrive at reliable conclusions as to the method of action of the central nervous mechanisms concerned in reflex actions, we must obtain a clear picture of the mechanics of the limb itself." Current models either represent muscle by lines of force with via points (e.g., (Delp & Loan, 1995), or require expensive finite element methods (e.g., (Hirota, Fisher, State, Lee, & Fuchs, 2001; Teran, Blemker, Hing, & Fedkiw, 2003)).

We are developing a new computational model for neuro-musculo-skeletal simulation which addresses these problems. The model is based on a computational primitive called a "muscle strand." The passive elastic behavior of the strand is based on the theory of Cosserat rods (Rubin, 2000; Pai, 2002). These one-dimensional primitives are well suited for incorporation of muscle activation models along the principal axis of the strand (e.g., (Zajac, 1989; Cheng, Brown, & Loeb, 2000)).

The muscle strand primitive could be used to represent muscles and tendons at different levels of detail, ranging from a single muscle fiber in a pennate muscle to an entire muscle. We model each tendon as a single passive strand without activation, with material properties different from that of muscle. Bones are modeled as degenerate passive strands without deformation. Because the underlying physical model computes stresses, strains, and strain rates in muscles and tendons, the model supports simulation of the afferent output from muscle spindles and Golgi tendon organs.

Figure 1 shows muscles of the forearm which have been discretized as muscle strands, with one strand per major muscle. The stresses and strains in the muscle are evaluated at a discrete set of nodes, which can be viewed as coordinate frames embedded in the material (see (Pai, 2002)). The figure shows the locations of the frames. Constitutive properties of the muscle are written in terms of these variables; hyperelastic materials such as muscle can be modeled within this framework.

A key aspect of our model is that the geometry of individual muscles and bones, and contact between them, is taken into account to determine the action of the forces generated in muscle. Figure 2 shows the detail of two extensor muscles in the forearm. We observe that the muscles curve significantly and make close contact with other muscles and bones. The shape of a muscle is modeled as a generalized cylinder whose spine is the axis of the Cosserat rod. The cross-sectional area is scaled with volume preservation as a constraint. This allows muscles to wrap over each other realistically, and takes into account the lateral forces due to contact and fascia between muscles.

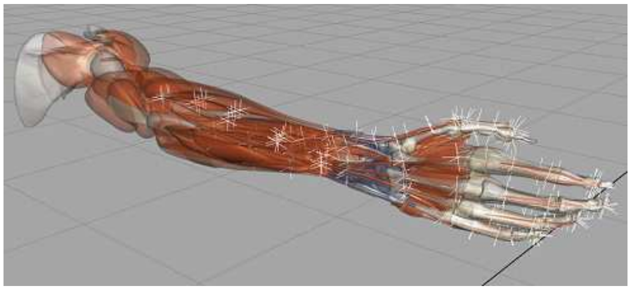
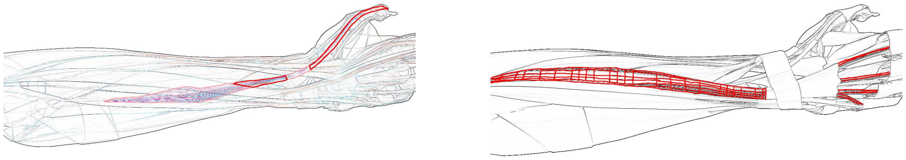


Figure 1: Model of forearm muscles using our approach. The nodes at which stresses and strains are computed are shown.



Detail of *extensor pollicis longus* Detail of *extensor digitorum communis*

Figure 2: Details of two extensor muscle of the forearm.

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