3D MUSCLE MODELING WITH APPLICATION TO MUSCLE STRAIN INJURY

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INTRODUCTION

Advances in computational mechanics have inspired a new class of three-dimensional (3D) muscle models that allow us to explore complex structure-function relationships in skeletal muscle and tendon [e.g., 2,8]. These models have expanded the applications of muscle modeling, motivated the need for new types of experimental validation, generated new hypotheses, and provided a bridge between whole muscle mechanics and muscle fiber mechanics.

This presentation will describe the integration of 3D muscle models of the hamstrings muscles with novel medical imaging techniques to understanding how internal muscle morphology influences muscle injury susceptibility. Future directions of 3D muscle models will also be discussed.

3D MODELING FRAMEWORK

We have created three-dimensional models from magnetic resonance image (MRI) data of individual subjects. Muscles, external tendons, aponeuroses, and bones are all manually segmented (Fig. 1A), and three-dimensional volumetric hexahedral meshes are generated from the segmentations (Fig. 1B). Representations of the muscle fiber geometry (Fig. 1C) are created by morphing template fiber geometries to each 3D model [2]. In the simulations, a transversely isotropic, incompressible, hyperelastic constitutive model is used to describe the active and passive stress-strain relationship in the muscle and tendon tissue [1]. Additionally muscle-muscle and muscle-bone contact can be resolved using a penalty formulation. These models allow us to analyze muscle tissue strains, whole fiber strains, and whole muscle strains during a given set of joint movements and activation patterns. As an example, simulations of active lengthening contractions performed with 3D models of the biceps femoris long head muscle (Fig. 1D) demonstrate that peak strains are localized near the proximal myotendinous junction of the muscle.

In addition to creating models directly from MRI data, we have also created simplified models that allow us to perform systematic sensitivity studies and explore how specific features of a given muscle's internal muscle-tendon morphology affect the muscle behavior.

IMAGING AS VALIDATION

In order to test predictions from 3D models, we have employed dynamic MRI techniques to measure strains within muscles during passive and loaded joint motion conditions. For example, we are using cine Displacement ENcoding with Stimulated Echoes (DENSE) to determine the displacements and strains [7,9] of tissues in the biceps femoris long head (BFLH) muscle during both passive and eccentric contractions. We compared the strain distributions determined using cine DENSE with those determined by a 3D model of the BFLH (Fig. 1D-E). Strains predicted by the model were similar to the dynamic imaging data. The region of largest strain was concentrated near the medial border of the muscle, which corresponds to the proximal muscle-tendon junction.

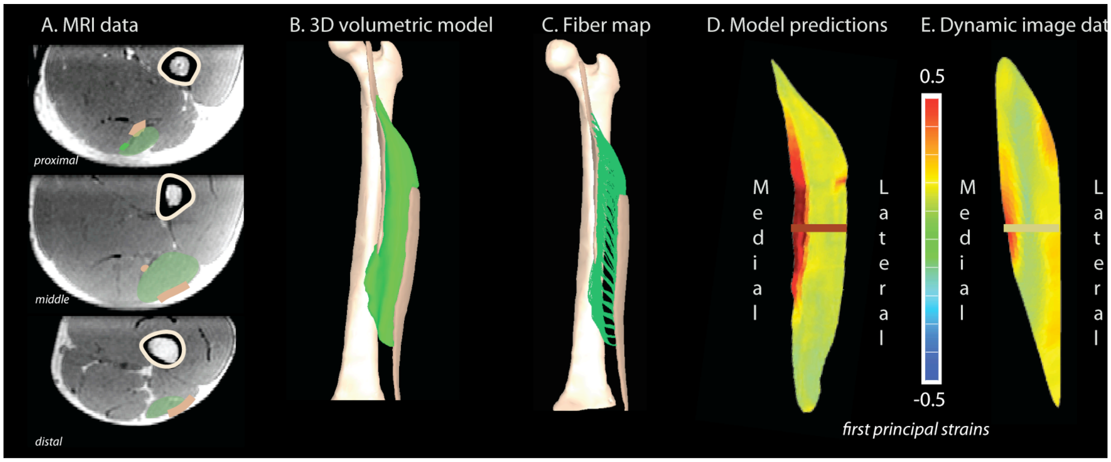

Figure 1. 3D models and experimental strain data. Static MRI data (A) is used to created 3D volumetric meshes (B) of muscles, aponeuroses, and tendons (B) and a corresponding fiber map (C). Strains predicted by the model in a given plane (D) are compared to strains determined from dynamic MRI data (E).

APPLICATION TO MUSCLE INJURY

Hamstring strain injury is a significant problem for many athletes. Of the hamstrings muscles, the biceps femoris longhead (BFLH) is the most commonly injured and reinjured, with the injury most frequently localized along the proximal muscle-tendon junction [3], which corresponds precisely with the region of peak localized strains which we measured with cine DENSE imaging as well as that we predicted by the 3D model.

A sensitivity study performed with the 3D model showed that the relative widths of the proximal and distal aponeuroses greatly affect the magnitude and location of the peak strain in the BFLH muscle [6]. Decreasing the width of the muscle's proximal aponeurosis increased the magnitude of the strains localized near the proximal myotendinous junction. MR images of 14 healthy volunteers demonstrated a significant variation in the dimensions of the proximal aponeurosis [5]. Dynamic MR images of these same volunteers [4] showed that muscles with narrow proximal aponeuroses had higher peak strains as compared to muscles with narrow proximal aponeuroses. These results support the predictions made by the 3D models and suggest that variations in internal muscle-tendon morphology may be a factor that influences muscle injury susceptibility.

FUTURE DIRECTIONS

There are several fruitful areas of modeling extensions that we are currently exploring. Areas that will be discussed during this presentation include: micromechanical models to appropriately model the myotendinous junction; incorporation of passive and active velocity-dependent effects in the constitutive formulation, and simulating muscle tissue behavior during complex loading situations such as running.

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