

# A Micromechanical Model of Skeletal Muscle to Explore the Effects of Fiber and Fascicle Geometry

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## INTRODUCTION:

Most finite element models of muscle lump the properties of fibers and intramuscular connective tissue (IMCT) into one transversely isotropic material<sup>1</sup>. These models do not take into account how the complex microstructure of a muscle affects its macroscopic properties. The tensile properties are dependent only on the material properties of fibers and connective tissue and the fiber volume fraction. The shear behavior, however, is also dependent on microstructure geometry. The along-fiber shear modulus is thought to play an important role in the transfer of force between neighboring fibers and the overall ability to produce force<sup>3,5</sup>. In this study we created a finite element micromechanical model to investigate the effects of fiber and fascicle geometry on the macroscopic shear modulus of muscle tissue.

## METHODS:

We obtained histological cross-sections from two different rabbit muscles: the rectus femoris (RF) and the soleus (SOL). These muscles have different macroscopic architectures. The RF is bipennate and has a larger cross-section area and pennation angle, as compared to the SOL<sup>4</sup>. A comparison of the microstructure of the two muscles revealed that the fiber shapes are similar (Fig. 1.A-B), while the fascicle shapes are different (Fig. 1.C-D). We used Ansys 11 to create finite element meshes representing fiber and fascicle geometries for each muscle (Fig. 1 A-D). We used a transversely isotropic, hyper-elastic constitutive model to represent both fibers and the IMCT<sup>1</sup>. Finite element simulations were performed using NIKE3D, a nonlinear implicit code<sup>6</sup>. The concept of a repeating unit cell and periodic boundary conditions<sup>2</sup> were employed to derive the macroscopic along-fiber shear modulus,  $G_{macro}$ , from the

simulations. Since measurements are not available for fiber shear modulus,  $G_f$ , and IMCT shear modulus,  $G_{ct}$ , we ran a number of simulations over a range of shear moduli. In presenting our results, we normalized the macroscopic and fiber or fascicle shear moduli by the shear modulus of the IMCT and have plotted  $G_{macro}/G_{ct}$  against  $G_f/G_{ct}$ . This normalization allowed us to focus on the effect of geometry.

## RESULTS:

We found that the macroscopic shear moduli of the two fascicle geometries show a greater difference (SOL is 62% less than RF) than that between the two fiber geometries (SOL is 11 % less than RF) (Fig. 1 E-F).

## DISCUSSION:

Our results have shown that different fascicle geometries can result in different macroscopic shear moduli. We hypothesize that the variation of fascicle geometry among muscles can be due to each muscle's need to accommodate greater or lesser shear during joint motion. These models provide a new paradigm for structure-function assessment at the microscopic level that can be used to assess healthy muscle behavior as well as investigate the effect of pathological change in muscle microstructure on overall muscle properties.

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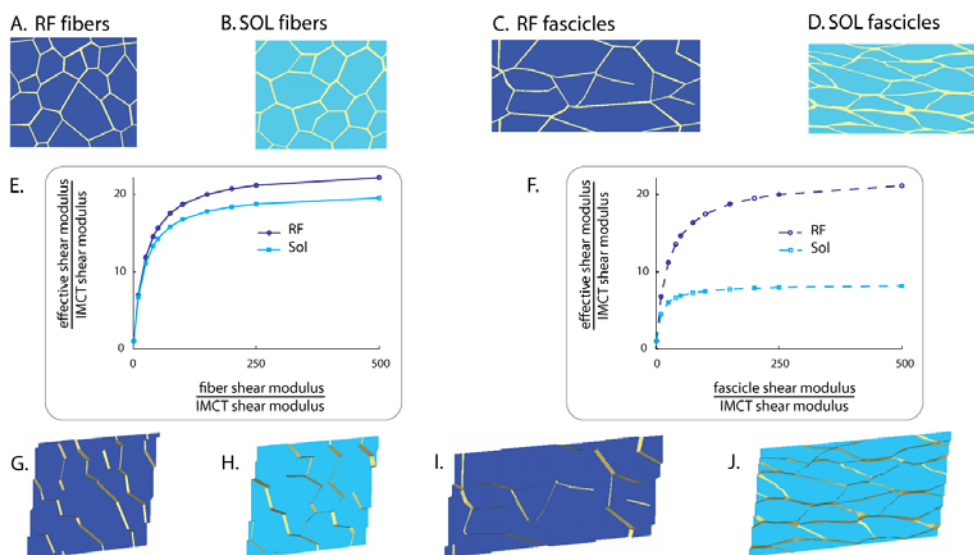


Fig. 1. We created unit cell geometries for rectus femoris fibers (A), soleus fibers (B), rectus femoris fascicles (C), and soleus fascicles (D). These model geometries were used along with a range of values for the shear moduli of fibers, fascicles, and the IMCT to create the plots shown in E and F. The deformed shapes (shown here for a fiber or fascicle modulus to IMCT modulus ratio of 500) highlight the different behaviors of the models.