The Influence of Fascicles and Extracellular Matrix Volume Fraction on Macroscopic Performance of Skeletal Muscle

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Skeletal muscle, the body's most abundant muscle tissue, has a hierarchical structure spanning sarcomeres to whole muscles. Computational modeling enables non-invasive analysis of its complex mechanical behavior. This study develops a 3D microscale finite element model with continuum constitutive laws to investigate how fascicle-level structural variations—particularly fascicle morphology and extracellular matrix (ECM) volume fraction—affect macroscopic muscle performance.

INTRODUCTION: Skeletal muscle consists of fibers grouped into fascicles, each surrounded by connective tissue layers—the perimysium around fascicles and the epimysium around the whole muscle. These ECM components play essential mechanical roles. This study presents a 3D microscale muscle model using explicit finite element analysis (FEA) to explore how fascicle and ECM affect muscle behavior. Fascicle geometries were generated using Voronoi tessellation, and muscle mechanics were modeled using a Hill-type hyperelastic constitutive framework [1]. The framework simulates both passive and active muscle states using user-defined subroutines in Abaqus, enabling anatomically realistic muscle responses under dynamic loading.

METHODS: To replicate observed muscle tissue architecture, synthetic muscle microstructures were generated using Voronoi tessellation [2] to model fascicles as irregular polygons based on histological cross-sections [3,4]. Fascicles were embedded within an ECM matrix composed of perimysium and epimysium (endomysium was excluded). A series of 3D representative volume elements (RVEs) were constructed to reflect different fascicle morphologies and ECM volume fractions (ECM ratio), mimicking conditions such as aging or disease (e.g., duchenne muscular dystrophy, cerebral palsy) with increased ECM [5]. Each fascicle was modeled as a fiber-reinforced composite using a hyperelastic strain energy formulation accounting for both matrix and fiber contributions [1,6]. The constitutive model was implemented via a custom VUMAT subroutine in Abaqus/Explicit. Cohesive interactions between fascicles and ECM ensured continuous contact while allowing relative sliding. To evaluate the mechanical response, both passive and active elongation tests were simulated. Boundary conditions applied a 10% uniaxial stretch to one face of the RVE, with the opposing face fixed (Fig. 1). RVEs were generated with varying numbers of Voronoi cells and ECM ratios to assess their impact on overall muscle stiffness and behavior.

RESULTS SECTION: The model successfully generated muscle microstructures that reflect physiological variability in fascicle arrangement and ECM content. Simulations showed that ECM volume fraction and fascicle morphology significantly affect stress distribution and force transmission. Active and passive muscle states exhibited distinct mechanical responses, with stress concentrations shifting between ECM and fascicles depending on activation (Fig. 2). Higher ECM ratios increased stiffness but altered load-sharing, especially in the active state. Variations in Voronoi cell number (i.e., fascicle density) also influenced force output, underscoring the impact of microstructural organization on muscle behavior.

DISCUSSION: This microscale modeling framework offers a powerful tool to study the mechanical interplay between fascicles and ECM in skeletal muscle. By capturing both passive and active behavior in anatomically inspired geometries, the model provides insights into how structural changes affect functional output. While the current approach focuses on single muscle units, scaling to multiple muscles or multiscale systems will require further computational enhancements and model adaptations. Future work will incorporate material property variations to simulate age- or disease-related degeneration.

SIGNIFICANCE/CLINICAL RELEVANCE: This work contributes to the development of computational "digital twins" of skeletal muscle by linking microstructure to mechanical performance. The framework offers a foundation for simulating patient-specific muscle responses, which could inform personalized rehabilitation, surgical planning, or implant design. By enabling detailed analysis of fascicle-ECM interactions, this model may also aid in understanding muscle degeneration in aging or neuromuscular disorders, ultimately improving clinical assessment and intervention strategies.

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IMAGES AND TABLES:

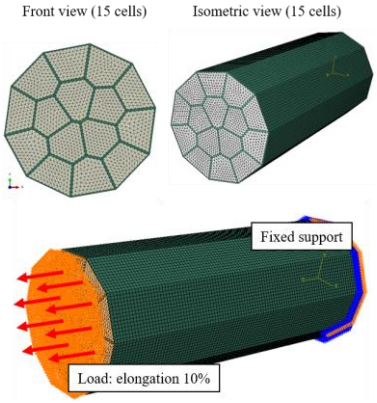

Fig. 1. Model morphology and boundary conditions: schematic showing fascicles embedded in perimysium and wrapped by epimysium, with applied loading and constraints.

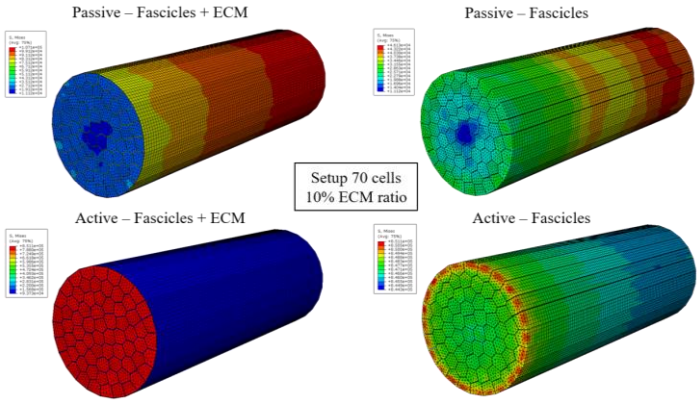

Fig. 2. Comparison of simulation results for a muscle RVE in passive and active states, using a sample model with 70 fascicles and 10% ECM volume fraction.