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EFFECT OF FIBER ARCHITECTURE ON TISSUE FAILURE DYNAMICS: A FINITE ELEMENT STUDY

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INTRODUCTION

Fiber-reinforced tissues experience large, complex loads during daily activities. Failure of these tissues often results in debilitating pain and reduced mobility. Understanding the failure behavior of tissues with limited self-healing capabilities, such as the meniscus in the knee and annulus fibrosus (AF) in the intervertebral disc, is of particular importance, as their failure alters the stress distribution throughout the tissue and adjacent tissues. Increased stresses result in tissue remodeling and may lead to a degenerative cascade [1].

Unfortunately, the failure mechanics of fiber-reinforced tissues, particularly those with fibers oriented off-axis from the applied load, is not well understood. Previous studies have suggested that this lack of understanding is due to limited specimen sizes and high strains at the testing grips, which may cause unpredictable tissue failure [2, 3]. Recent work by Peloquin *et al.* identified five different failure modes in meniscus specimens, with less than 25% of specimens failing at the mid-substance [3]. Unpredictable failure behavior may be responsible for the large variation of failure properties reported in the literature.

The fiber architectures of load-bearing, fiber-reinforced soft tissues vary greatly. For example, tendon is considered a unidirectional composite with fibers aligned primarily along the loading direction (Fig. 1a). Meniscus (Men.) is considered a cross-ply laminate composed of alternating layers in which the fibers are oriented at 0° and 90° relative to each other (circumferential and radial fibers, Fig. 1b, c). The AF is considered an angle-ply laminate containing alternating layers of fibers oriented between ±30° and ±45° to the transverse plane (Fig. 1d) [4].

While fiber orientation is known to affect sub-failure mechanical properties [3, 5], few studies have quantified the effects of fiber architecture on failure behavior [6]. Therefore, the objective of this study was to investigate the effects of various fiber architectures on the predicted failure location of fiber-reinforced tissues in uniaxial tension using finite element analysis. Our analysis also considered the effect of applied compression at the grips. The results from this model help explain large variations in failure behavior reported in the literature.

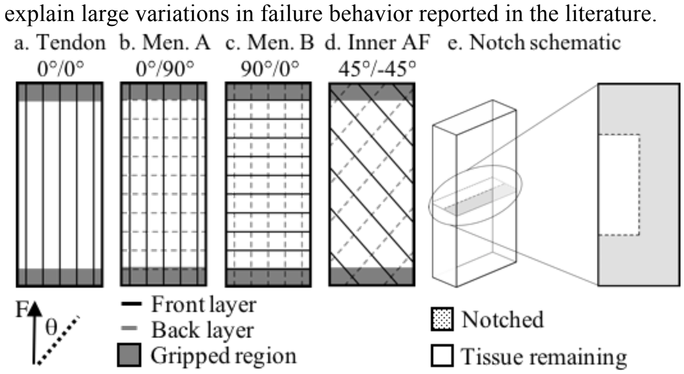

Figure 1: (a - d) Schematic front view of specimens showing fiber architectures and (e) schematic of notched geometry.

METHODS

Finite element models (FEMs) were developed representing fiber-reinforced tissue specimens (PreView 1.19.0; FEBio 2.5.2, ~180k nodes, ~170k hexahedral elements). Bulk tissue dimensions were defined to be 4.8 mm x 2 mm x 0.8 mm, which is proportional to experimental specimens from our previous work [7]. Four 200 µm-thick, welded-interface lamellae were included [4]. Full-width sandpaper grips were simulated to cover 0.4 mm of the tissue at both ends (Fig. 1a-d – grey region). A homogeneous, hyperelastic material description was used [8], with material coefficients based on data obtained from preliminary experiments on AF specimens in tension (ρ= 1 g/cm^3, C_1= C_2= 0.1 MPa, C_3= 0.02 MPa, C_4= 30, C_5= 25 MPa, k= 50 MPa, λ= 1.15). While FEMs were developed based on AF material properties, these methods can be applied to other fiber-reinforced tissues as well.

Tendon specimens were modeled with layers of fibers aligned to the loading direction (Fig. 1a). Meniscus specimens were modeled with layers of fibers alternating between 0° and 90° relative to loading. Meniscus A refers to a sample with front layer fibers aligned with loading (‘0°/90°’, Fig. 1b), while Meniscus B refers to a sample with front layer fibers oriented at 90° with respect to loading (‘90°/0°’, Fig. 1c). Inner AF specimens were modeled with alternating layers of fibers oriented at ±45° from loading (Fig. 1d), while outer AF specimens were modeled with alternating layers of fibers at ±30°.

In addition to the intact models described above, a notched specimen geometry, which increased the likelihood of mid-substance failure, was included [7]. In these cases, elements were removed at the mid-substance (MS) such that one quarter of the original cross-sectional area remained (Fig. 1e). Loading was simulated by first applying 10% compressive strain at the grips, followed by uniaxial tension to 30% global engineering strain along the length. Grip boundary conditions were fixed to represent no slipping between the grips and the sample.

Local strains for each node in the mid-substance and at the grip-line were sorted in descending order, and the average strain for each region was calculated as the average of the top 35 nodes. The MS:grip strain ratio was calculated as the average local mid-substance strain divided by the average local grip strain (i.e. MS:grip ratio greater than 1.0 indicates higher local strain at mid-substance). An average local strain of 50% served as an estimate of bulk failure initiation: failure was predicted at the location reaching this strain threshold earliest in the simulation.

RESULTS

Average local strains reached 50% at either the mid-substance or at the grip-line for all simulations. For all intact simulations, local strains were always higher at the grip-line than at the mid-substance, so these specimens are predicted to fail at the grips. For all notched simulations except Meniscus A, the MS:grip ratio at predicted failure was at least 1.10 (Fig. 2a, 2c-e – front, white arrows; Fig. 3), so mid-substance failure is predicted in these samples. Notched Meniscus A was predicted to fail at the grips because the maximum local strain at predicted failure was at the grip-line (Fig. 2b – back, white arrows).

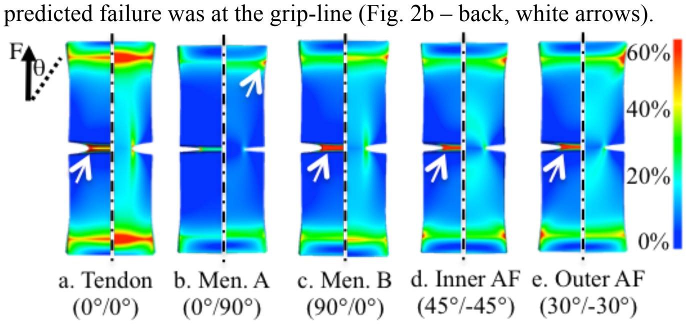

Figure 2: Strain map (front | back) at predicted failure initiation. Arrows indicate maximum local strains.

DISCUSSION

In this study, we used FEMs to investigate the effect of fiber architecture on the predicted failure location of various fiber-reinforced soft tissues. The results of this study indicate that the fiber angle relative to the loading direction and the relative fiber orientation between layers both have a significant effect on the predicted failure location under uniaxial tension. Our results also reinforce the importance of modeling compressive strains caused by gripping when investigating failure properties. Additionally, this study further validates the effectiveness of the described notched geometry for inducing mid-substance failure of fiber-reinforced soft tissues [7].

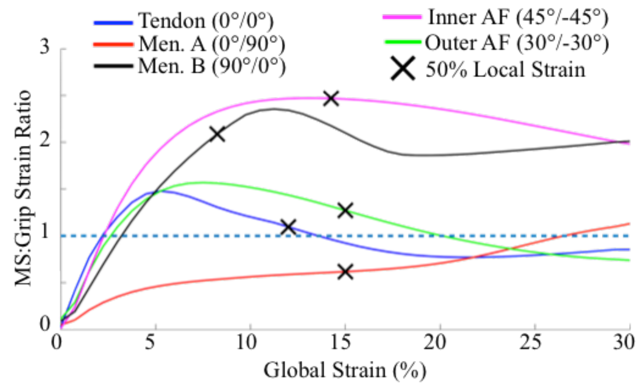

Figure 3: MS:grip ratio versus global strain for four fiber architectures (all Notched). X denotes predicted failure.

We found that increasing fiber alignment towards the loading direction increased the likelihood of failure at the grip-line. For example, the MS:grip strain ratio of notched tendon specimens was close to 1.0 when the maximum local strain reached 50% (Fig. 3 – blue line). The simulations also suggest that mid-substance failure was more likely in notched specimens taken from the inner AF, where fibers are less aligned with loading (Fig. 3 – pink line), than the outer AF, where fibers are more aligned with loading (Fig. 3 – green line).

Predicted failure location differed greatly between the two Notched meniscus cases (Fig. 3– red and black lines), where the models differed only by the fiber orientation of the layer adjacent to the notch. The model strongly predicted mid-substance failure for Meniscus B (90° layer at front of notch), but suggested grip-line failure for Meniscus A (0° layer at front of notch). The 0° fiber layer is stiffer, so it develops higher local stresses, whereas the 90° layer develops higher local strains. This dependency on specimen alignment helps explain the large variation in reported meniscus failure properties [3].

While it is not well understood whether tissue failure is a stress- or strain-based phenomenon, we chose 50% local strain as a threshold to predict tissue failure. Furthermore, our model did not include a description for damage, which may cause differences in global failure strain predictions. Finally, it is likely that local failure behavior depends on tissue composition; therefore, future work will utilize a heterogeneous model to describe the extrafibrillar matrix separate from the collagen fibers in order to better investigate tissue failure mechanisms [8].

This study expands upon our previous work that aimed to ensure repeatable mid-substance failure of fiber-reinforced tissues in uniaxial tension [7]. We found that both the notch geometry and fiber architecture have a significant impact on predicted failure location for such specimens. These observations are valuable for guiding time-intensive experimental studies. Moreover, as electrospun scaffolds are explored for biological repair strategies of fiber-reinforced materials, the findings of this study emphasize the importance of replicating the native fiber architecture to maintain native stress distribution throughout the tissue [9].

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