Modulus of Fiber-Reinforced Tissues is Sensitive to Specimen Dimensions

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Introduction

Mechanical testing of fiber-reinforced tissues has been performed using a wide range of specimen dimensions; however, previous studies showed that annulus fibrosus (AF) Young's modulus increases with a decrease in specimen width [1,2]. Computational models often rely on a homogenized description of fibers and extrafibrillar matrix, and our recent work showed that this approach is not sufficient for describing the changes in tissue mechanics with changes in specimen dimensions [3]. Models that describe fibers as a separate material (SEP) are capable of replicating experimental observations, allowing for a high-throughput analysis of tissue mechanics. Therefore, the objective of this study was to use a series of SEP models to investigate the effects of specimen dimensions on bulk tissue modulus.

Methods

Hyperelastic SEP models were developed to represent circumferential-axial outer AF specimens (n=30) [3]. A range of specimen dimensions were assessed: length=4.8-9.6mm; width=2-4.8mm; aspect ratio (AR)=1-9.6. Each model consisted of 4 lamellae with a modified dog-bone shape [2]. The matrix was modeled as a Neo-Hookean material with parameters curve-fit to data in [4]. Collagen fibers were modeled using a Holmes-Mow description with exponential-linear fiber functions and parameters were fit to data in [5]. A 20% uniaxial tensile stretch was applied and modulus was evaluated at 15% stretch [5]. A multivariate linear regression was used to investigate the effects of tissue width and length on modulus. Pearson's correlation was performed to determine a relationship between modulus and specimen dimension.

Results

Modulus did not depend on specimen length (Fig.1A-blue; $p>0.2$). There was a strong linear correlation between modulus and specimen width (Fig.1B). The modulus plateaued for AR values below ~2.5(Fig. 1A-red & Fig.1B-oval), and was relatively consistent for high ARs (above ~6.5) (Fig.1A-blue dots & Fig.1C); however, there was a large variation in modulus within range of ARs suggested by ASTM guidelines for synthetic materials (Fig.1C-red box) [6].

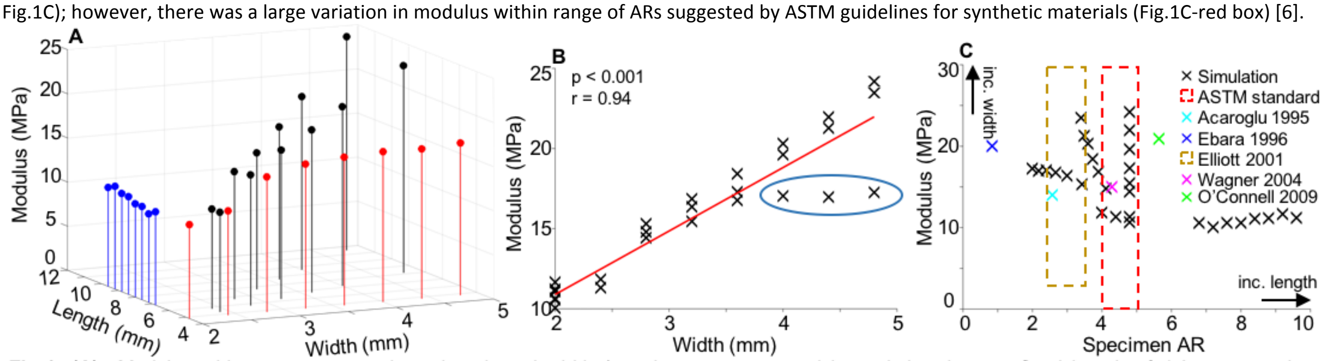

Fig.1: (A) Modulus with respect to specimen length and width (specimens represented by red dots have a fixed length of 4.8 mm; specimens represented by blue dots have a fixed width of 2 mm). **(B)** Correlation between modulus and specimen width; the data points highlighted by the blue ellipse demonstrates the modulus stabilization when specimen aspect ratio (AR) dropped below 2.5. **(C)** Modulus with respect to specimen AR. The red box represents the range of AR suggested by ASTM standards. Data from the literature is shown by colored 'x's and the golden box.

Discussion

Young's modulus of fiber-reinforced materials highly depended on specimen width, agreeing with previous experimental observations [1,2]. ASTM guidelines suggest a minimum length:width AR of 4.0 for uniaxial tensile specimens. However, this study demonstrated high variability in modulus (Fig.1C-red box), suggesting that these guidelines may not be ideal for fiber-reinforced tissues with fibers oriented off-axis from the loading direction. These findings can guide future experimental studies and reduce variability in experimental data (e.g., Fig.1C-golden box). It should be noted that simulations were limited to specimens with fibers oriented at $\pm 30^{\circ}$ and may not be applicable to tissues with highly aligned fibers. Future work will establish a generalized description that incorporates the role of fiber orientation on fiber engagement and tissue tensile mechanics.

Reference

1. Adams,M.A.+, *Eur Spine J*(1993)
2. Werbner,B.N.+, *JBME*(2017)
3. Zhou,M.+, *ORS*(2017)
4. Fujita,Y.+, *JOR*(1997)
5. Holzapfel,G.A.+, *BMMB*(2005)
6. ASTM(2004)