An Integrated Opto-Mechanical System for Quantification of Dynamic Microstructure and Mechanics of Heart Valve Leaflets

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Background: Collagen in Tissues

- Collagen is an abundant protein in the body and the primary constituent of tissues such as tendon, skin, and heart valve (HV) leaflets [1].
- On sub-fiber scales, collagen exhibits a nested organization (**Fig. 1a**), but on a tissue scale, fibers form complex architectures (**Fig. 1b**) to support tissue function.
- Due to the tensile strength of the individual fibers, these collagen fiber architectures (CFAs) govern the mechanical behavior in connective tissues such as HV leaflets [3].

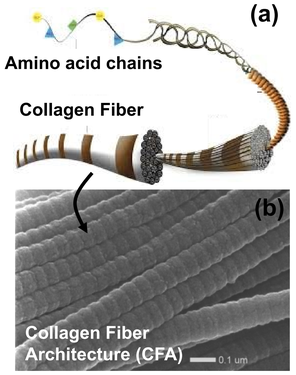

Figure 1. (a) Diagram of nested fiber[1] and (b) image of example CFA [2].

Dynamic Collagen Architecture under Mechanical Loading

- CFAs exhibit a ***dynamic*** response to applied mechanical loading due to deformations and rotations of the internal collagen fibers (**Fig. 2**).

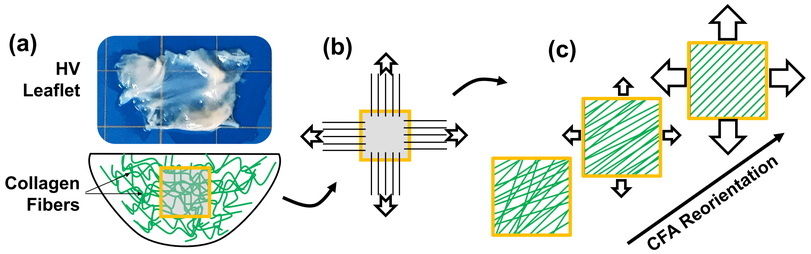

Figure 2. Schematic diagrams depicting (a) an HV leaflet with representative **CFA**, (b) biaxial mechanical loading of HV sample, and (c) reorientation of the CFA under various load magnitudes.

Collagen, Mechanics, and Disease in Heart Valve Leaflets

- CFAs can be degraded in HV diseases such as stenosis or regurgitation, further altering the mechanical behavior of the valve tissues and impairing function [4].
- The ***motivation*** for this study is the lack of understanding of how the *dynamic* CFA governs tissue mechanics in HV leaflets. Our ***objective*** is to develop a device to investigate the relationship between CFA and mechanics to shed light on how disease-driven CFA changes can affect function.

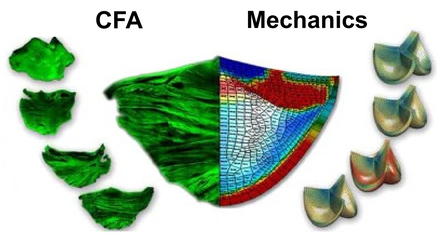

Figure 3. Schematic diagrams depicting the deterministic relationship between the CFA and the mechanical behavior of the HV leaflet tissues [5].

System Instrumentation, Design, and Theory

- We use polarized spatial frequency domain imaging (pSFDI) to extract fiber ***orientation*** (θ_{fiber}) and ***concentration*** (κ_{fiber}) from optical anisotropy.

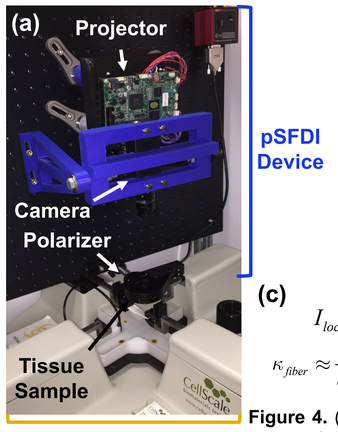

Figure 4. (a) Image of the system, (b) optical anisotropy of example fiber at θ_{fiber} = 90°, and (c) extraction of $\theta_{fiber}(x, y)$ and $\kappa_{fiber}(x, y)$.

System Verification Testing on Tendon Tissues

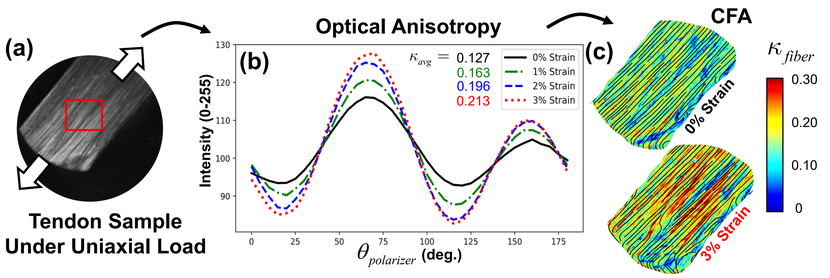

Figure 5. (a) Image of the tendon sample with ROI in red. (b) The average optical response over the ROI at various strains, and (c) fiber orientation (–) and concentration maps over the sample.

Integrated Biaxial Testing and Imaging on HV Leaflet

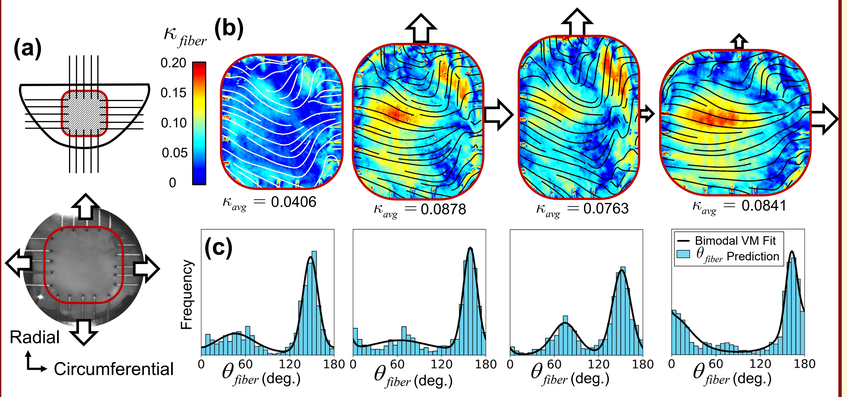

Figure 6. (a) The mounted leaflet tissue showing ROI, (b) fiber orientation (–) and concentration maps and (c) fiber distribution histograms over the ROI with Bimodal Von-Mises fit at various loads.

Applications in the Clinical Setting

- This integrated opto-mechanical system renders a novel and valuable tool for assessing the microstructural similarity of the HV replacement biomaterials compared to the native tissues.
- By comparing the *dynamic* CFA between healthy leaflets and valve replacement biomaterials, an improved understanding of functional distinctions can be gained (**Fig. 7**).

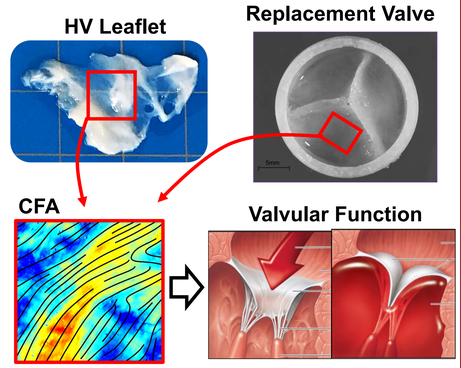

Figure 7. Depictions of CFA equivalence in native and replacement HV materials to promote functional mechanical similarity between the healthy and replaced valve [1].

Future Research Extensions

- The quantification of dynamic CFA in HV leaflets can also be utilized to improve predictions of leaflet mechanics through development of structurally-based constitutive models of leaflet mechanics (**Fig 8a**).
- These material models can be applied to improve fidelity of computational models for examining how diseases impair valvular function (**Fig. 8b**).

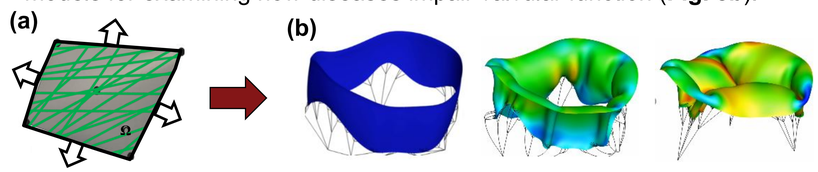

Figure 8. (a) The development of a structurally-based constitutive model to describe leaflet mechanical behavior applied in (b) computational models of the valvular function and closure [6].

Acknowledgments

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References

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