Different Anisotropic Biomechanical Behavior of Left and Right Ventricles in Adult Sheep

Michael Nguyen-Truong[1] (mnguyent@colostate.edu), Wenqiang Liu[1], Kevin Labus[1], Elisabeth Gray[1,2], Kirk McGilvray[1,3], Christian M. Puttlitz[1,3], Zhijie Wang[1,3]

[1]School of Biomedical Engineering, [2]Department of Chemical & Biological Engineering, [3]Department of Mechanical Engineering, Colorado State University, Fort Collins, CO, USA

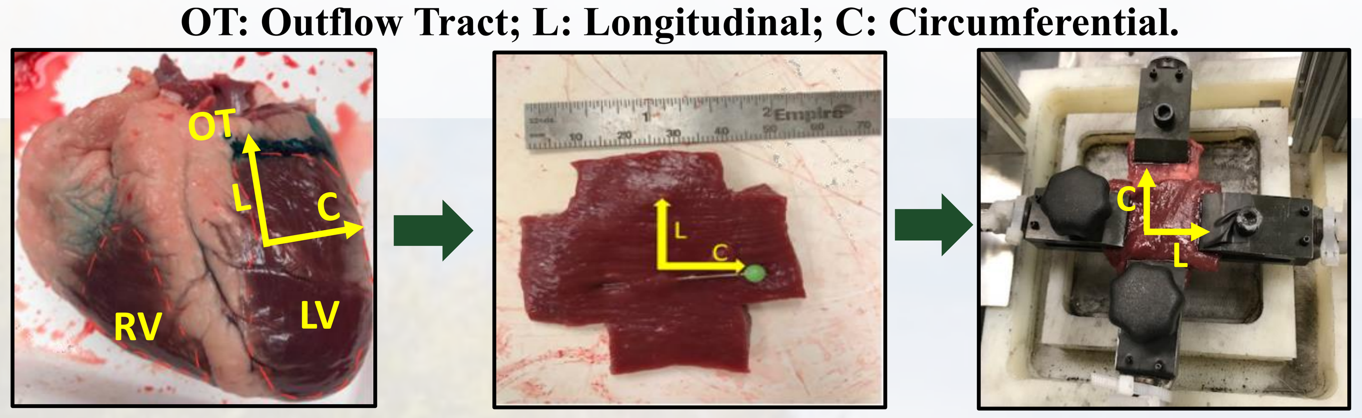
Cardio Vascular Biomechanics

Background

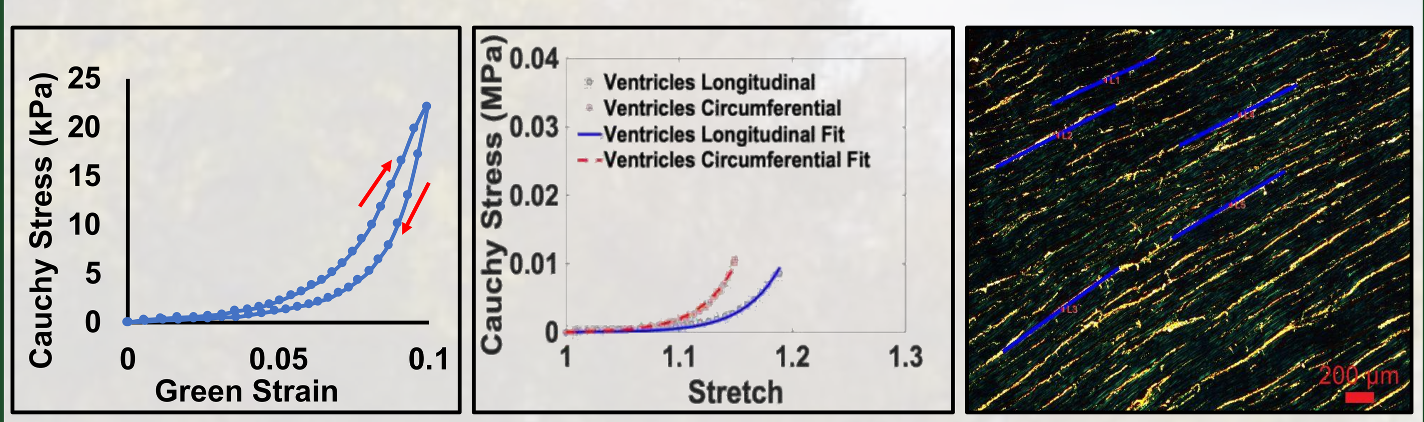
- Ventricular dysfunction is the most common cause of heart failure, which contributes significantly to the mortality and morbidity in the modern society[1].
- It is well accepted that the right ventricle (RV) is distinct from the left ventricle (LV) in embryologic origin, anatomy and function[2]. However, the differences in biomechanical behavior of the RV and LV are not well understood.
- The Ogden constitutive model has been found to provide better fits for soft materials than other models (e.g., the Neo-Hookean and Mooney-Rivlin models)[3]. However, it has not been applied for cardiovascular tissues like myocardium.
- ***Our goal*** was to characterize and compare the biaxial mechanical properties of RVs and LVs from healthy adult sheep via both experimental and computational approaches.

Methods

OT: Outflow Tract; L: Longitudinal; C: Circumferential.



Tissue Harvest — Cruciform Section — Biaxial Mechanical Test



Stress-Strain Curve — Model Fitting — Histology Analysis

Methods: Fresh hearts (n=7) were harvested from 4+ year-old female sheep without known cardiovascular diseases or defects. Within several hours of sacrifice, biaxial mechanical tests were performed at three displacement ratios (2:2, 2:1 and 1:2) in random order after the preconditioning cycles, using similar methods described previously[4]. Elastic modulus (E) was obtained as the slope of the stress-strain curves. Moreover, stress-strain data was fitted by a modified Ogden constitutive model[4]:

$$W = \frac{2\mu}{\alpha^2}\left({\lambda_1}^{\alpha} + {\lambda_2}^{\alpha} + {\lambda_3}^{\alpha} - 3\right) + \frac{2k\mu}{\alpha^2}\left(I_4^{\frac{\alpha}{2}} + 2I_4^{-\frac{\alpha}{4}} - 3\right)$$

$$I_4 = a_0 \cdot C \cdot a_0 \qquad C = F^T F \qquad |a_0| = 1$$

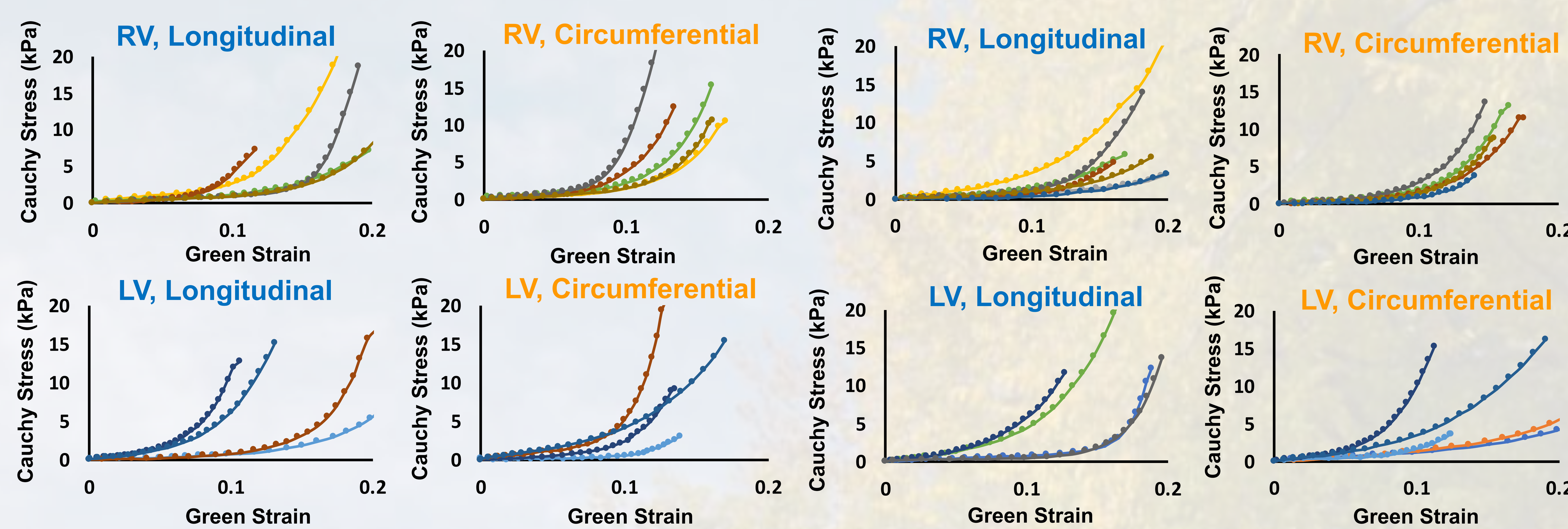
$$Cauchy\ Stress\!: \sigma = 2J^{-1}F \cdot \frac{\partial W}{\partial C} \cdot F^T;\ F = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}$$

W: Strain Energy Density Function; λ: stretch; I_4: stretch invariants; a_0: referential unit vector;
***α*: nonlinearity; *k*: anisotropy; *μ*: infinitesimal shear modulus;**
C: right Cauchy-green strain tensor; J: Jacobian of the deformation, J=det(F); F: deformation gradient tensor

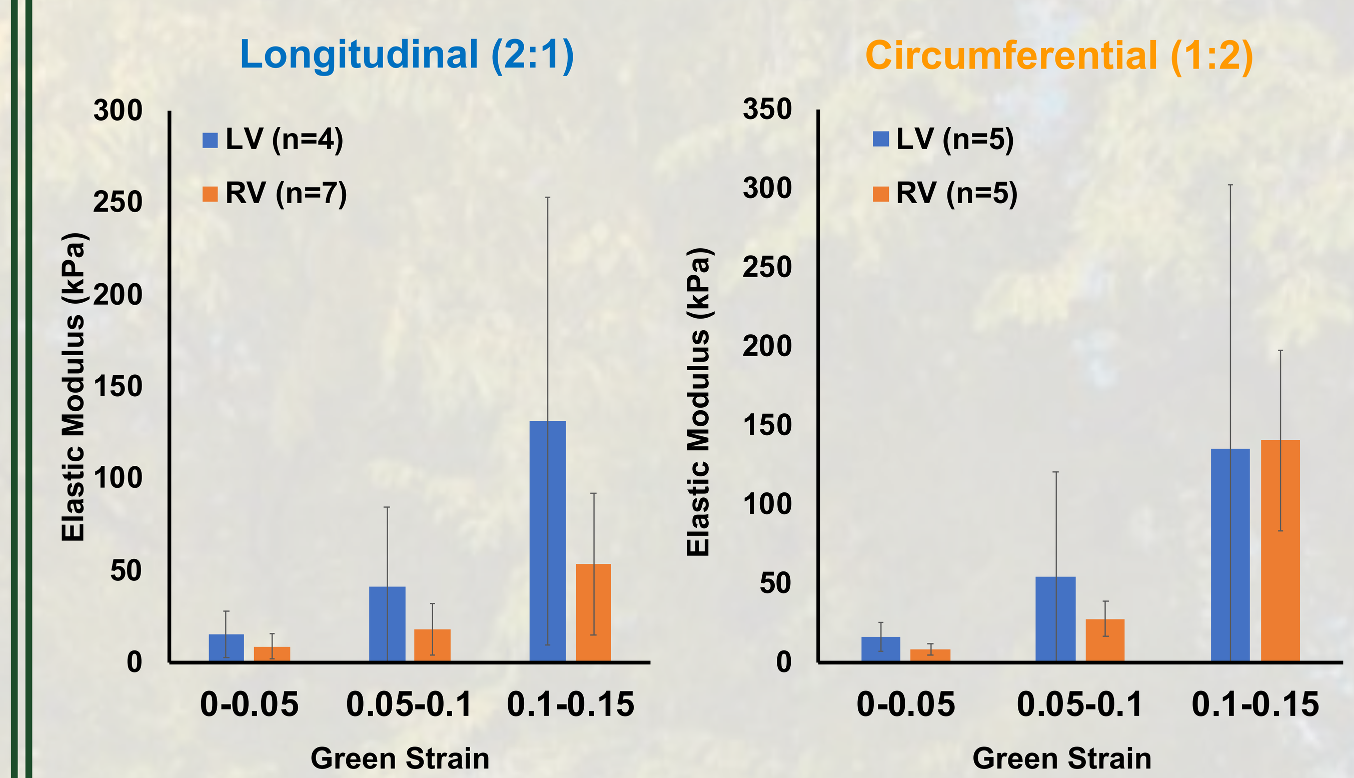
Histology was performed with picrosirius red staining to measure collagen fiber orientation and content (n=4-5 per group). Student's t-test was used and all results are mean±SD.

Experimental and Model Fitting Results

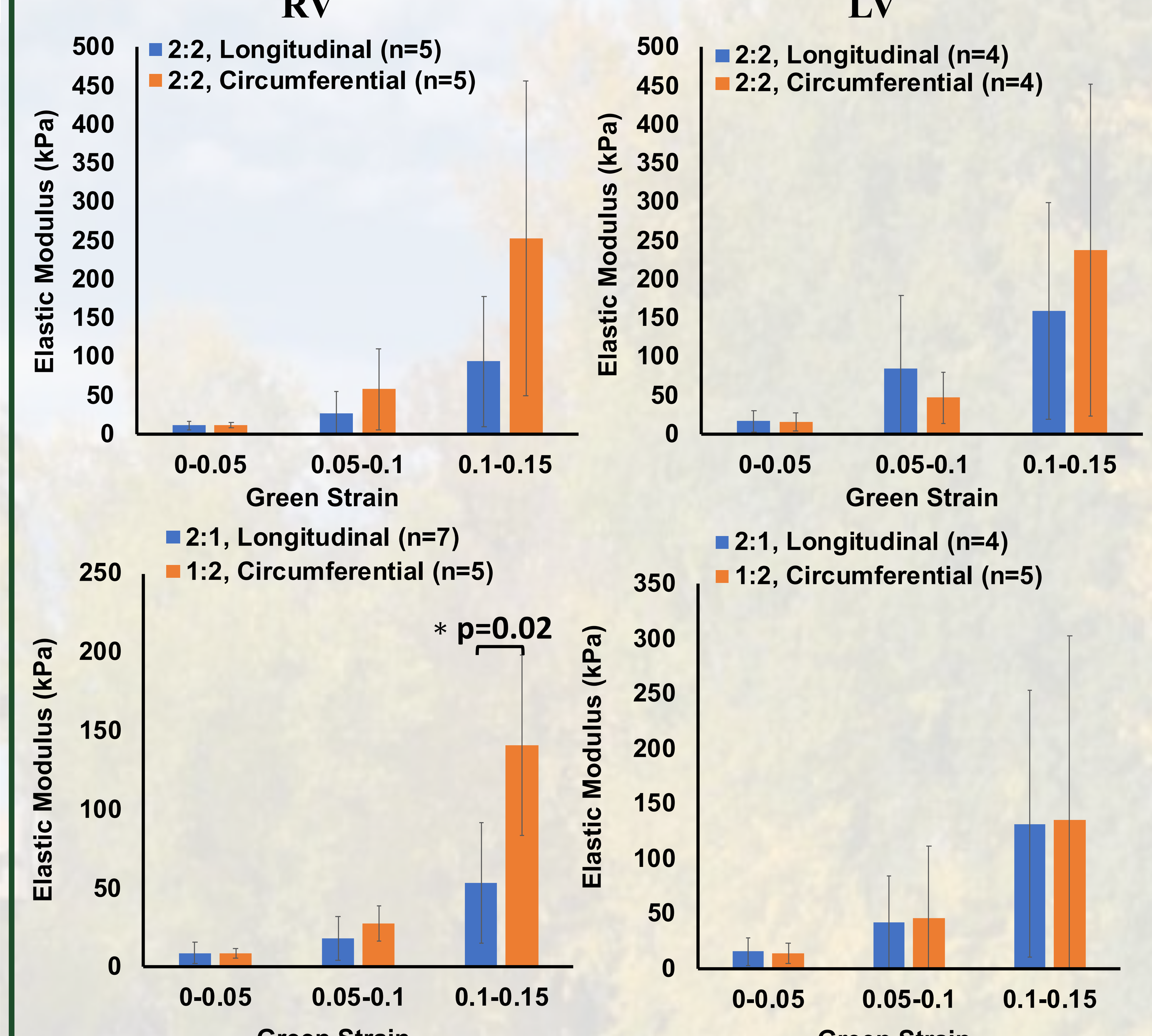
Experimental stress-strain curves of all samples obtained at different ratios



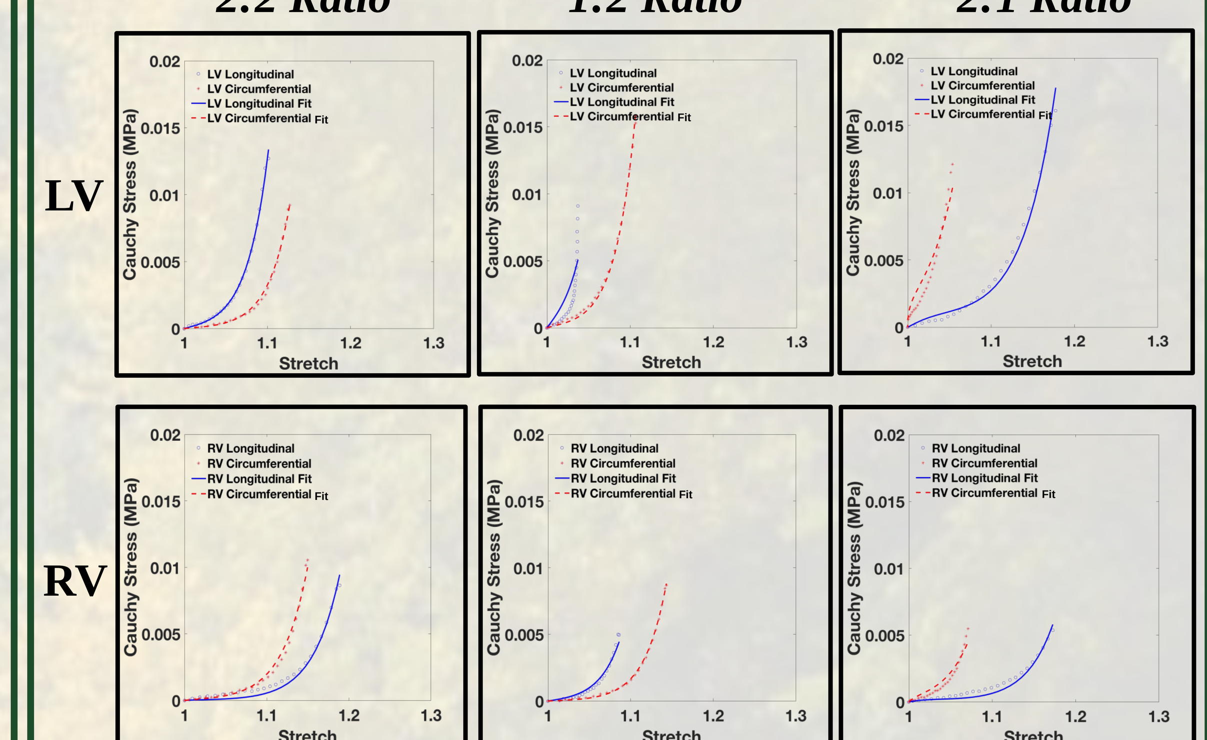
Similar elastic moduli between LVs and RVs



Anisotropic behavior in RVs vs. Equibiaxial strength in LVs



Individual ratio of model fitting

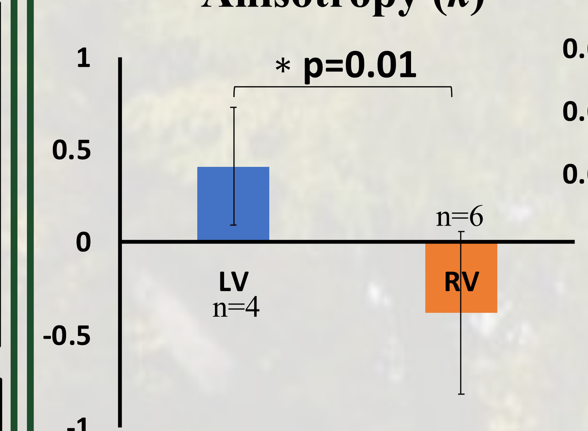


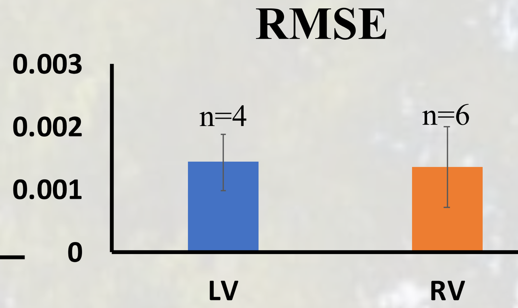
	Ratio	Shear Modulus μ (Pa)	Nonlinearity α	Anisotropy k	R^2(L)	R^2(C)
LV	2:2 (N=4)	1950± 1245	37± 11	0.63± 1.71	0.99± 0.00	0.97± 0.45
	1:2 (N=5)	2159± 2064	33± 13	13.83± 16.54	0.79± 0.11	0.98± 0.03
	2:1 (N=4)	1580± 1909	41± 11	0.44± 1.96	0.98± 0.02	0.88± 0.08

	Ratio	Shear Modulus μ (Pa)	Nonlinearity α	Anisotropy k	R^2(L)	R^2(C)
RV	2:2 (N=5)	1340± 365	42± 10	-0.32± 0.72	0.98± 0.02	0.99± 0.10
	1:2 (N=5)	857± 385	41± 5	3.56± 2.32	0.91± 0.12	0.99± 0.00
	2:1 (N=7)	745± 5076	48± 11	-0.89± 0.16	0.96± 0.04	0.83± 0.14

k>0: stiffer in the longitudinal direction.
k<0: stiffer in the circumferential direction.

Simultaneous model fitting for all ratios

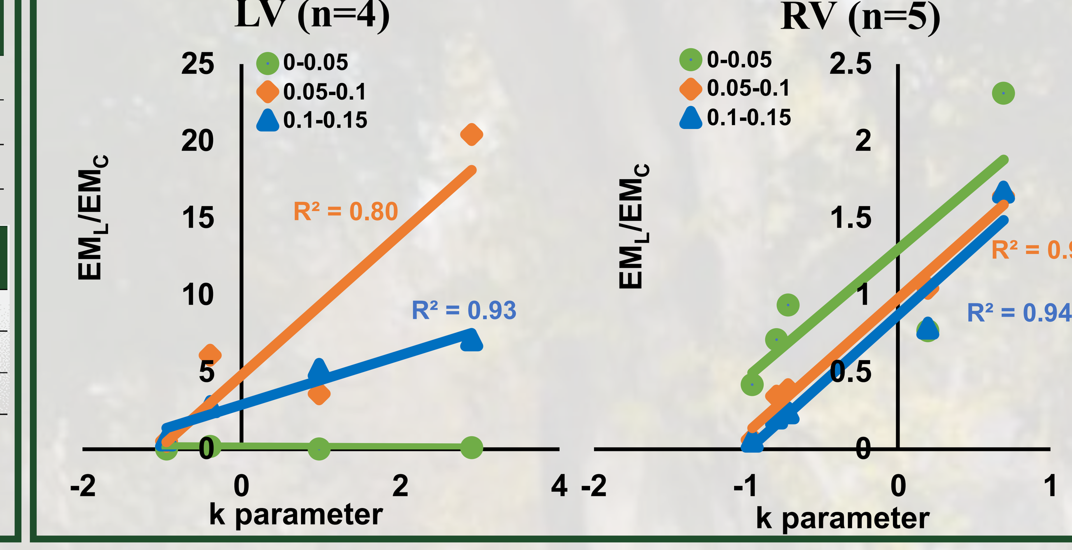




RMSE: Root Mean Square Error. A measure of how well the model fits the experimental data.

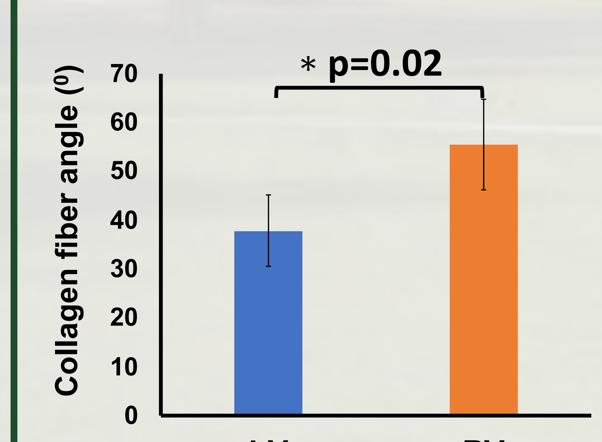
Correlation Analysis

Correlations between k and EM_L/EM_C in high strain regions (at 2:2 ratio)

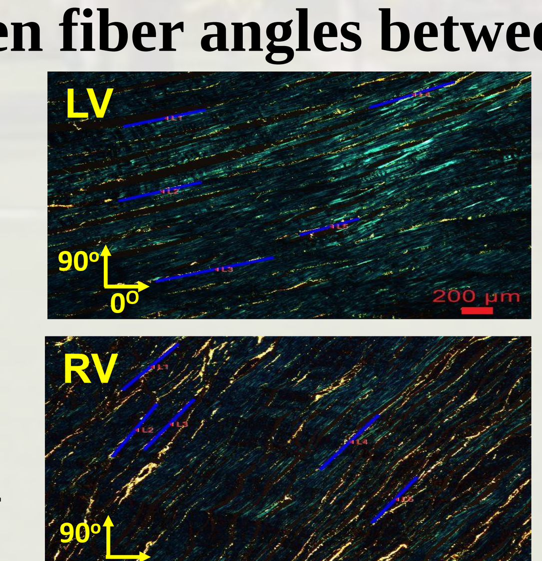


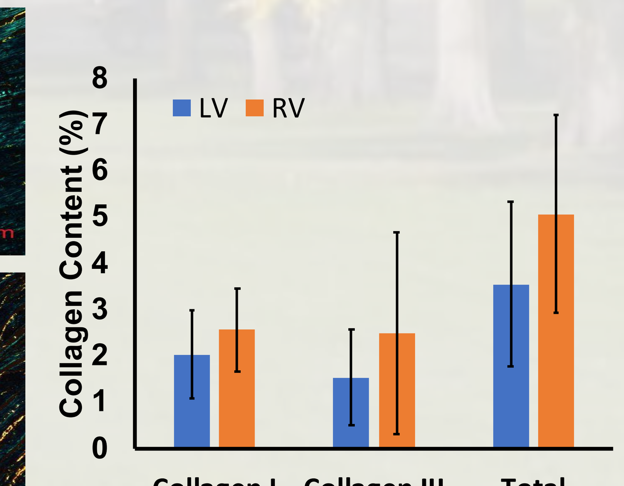
Collagen Fiber Angle and Content

Different collagen fiber angles between the LV and RV



0°: Longitudinal direction
90°: Circumferential direction





Conclusions

- We did not observe differences in intrinsic mechanical properties between LVs and RVs.
- In the high strain region, the RV was stiffer in the circumferential direction compared to the longitudinal direction (p<0.05). The LV, however, showed comparable stiffness in both directions in all strain regions. The difference in anisotropic behavior can be partly attributed to the different collagen fiber orientations between the two ventricles.
- The modified Ogden model provided a good fit and correlation to the experimental data.

References

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4. Labus, K.M., Puttlitz, C.M. *Journal of the Mechanical Behavior of Biomedical Materials* **62**, 195-208 (2016).

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