Planar biaxial testing of porcine heart valves

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Introduction

Background

- Valvular heart disease refers to any condition affecting any of the four heart valves
- Long-term treatments can be divided into repairing the faulty valves such as valvuloplasty or replacing the valve; both of which require extensive knowledge of soft tissue properties
- Soft tissues are difficult to characterize due to their 3D geometry and microstructures
- New biaxial tissue testers are replacing uniaxial ones to more accurately test soft tissues

Properties of soft tissues

- Soft tissue is a complex composite of cells and basic functional groups
- Soft tissue is nonhomogeneous and anisotropic
- It is viscoelastic, exhibiting behaviour based on both time and history, such as creep, stress-relaxation, and hysteresis [1]
- Hysteresis reflects the different stress-strain curves obtained from deformation tests when loading and unloading the tissue

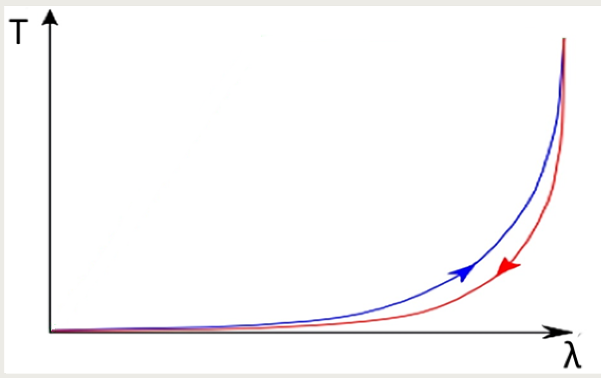


Fig. 1. Stress-strain curves of a general soft tissue. Blue and red curves represent the loading and unloading of soft tissue.

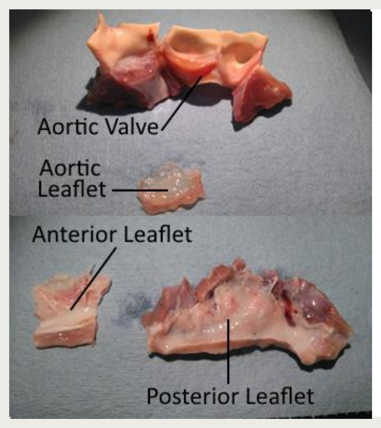
Objectives

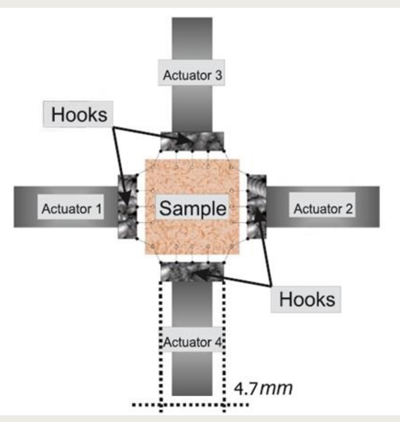
1) Validate the efficacy of our biaxial method for soft tissue characterization
   a. Confirm existing material properties of fresh porcine heart valve leaflets
   b. Test material properties of previously frozen porcine heart valve leaflets
2) Refine existing methodology in preparation for testing with human valves and blood vessels

Methods

Leaflet mounting

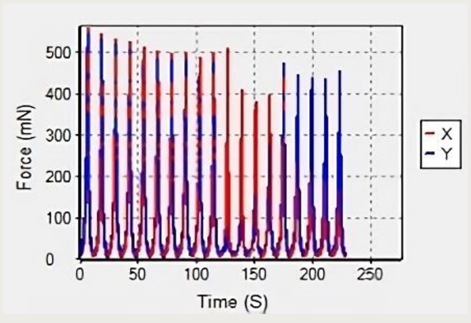
- Fresh aortic and mitral valves were obtained from five pig hearts
- Half of the valves were frozen at −18°C
- The three aortic and two mitral leaflets were excised and cut into squares
- Samples were mounted on the rakes of a biaxial Biotester machine (Cellscale)





Preconditioning

- Leaflets were equibiaxially preconditioned for ten cycles to elicit stable mechanical responses
- A saline bath at 37°C was used to ensure sample hydration and to provide a controlled environment



Displacement-controlled testing

- Nine protocols with various radial to circumferential displacement ratios were carried out starting from 1:5 circumferential to radial displacement and ending with 5:1
- The x and y directions represent the circumferential and radial orientations, respectively
- The two highest red and blue peaks represent the ten preconditioning cycles ; the others show the nine protocols
- To avoid any camera glare that would affect the image analysis, the testing was done outside the saline bath

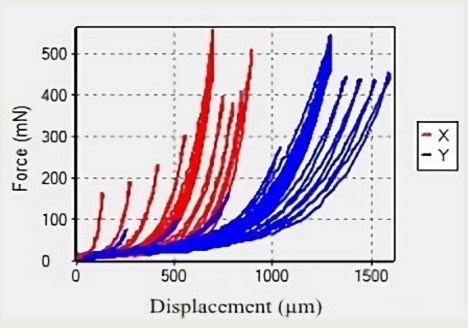
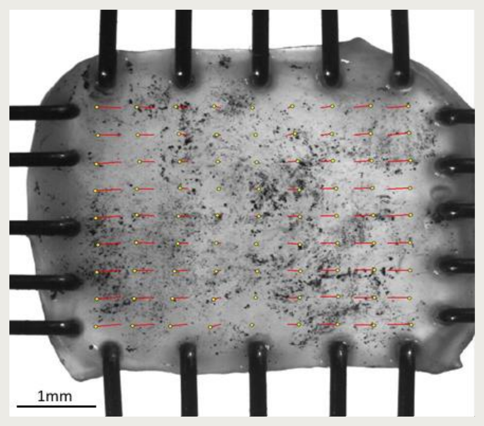


Image analysis

- 81 points were tracked on each leaflet sample from a digital video camera; only four points were used for determination of the material constants of the constitutive model below
- Yellow dots represent the final position after loading
- Red lines represent the displacement over seven seconds



Material model

- The generalized Fung constitutive equation [2] was used to obtain the stress-strain curves

$W = \frac{1}{2}c(e^Q - 1)$ *where* W is the strain energy function

b_{ijkl}, and c are material constants

$Q = b_{ijkl}E_{ij}E_{kl}$ E_{ij} is the Green strain tensor

Results

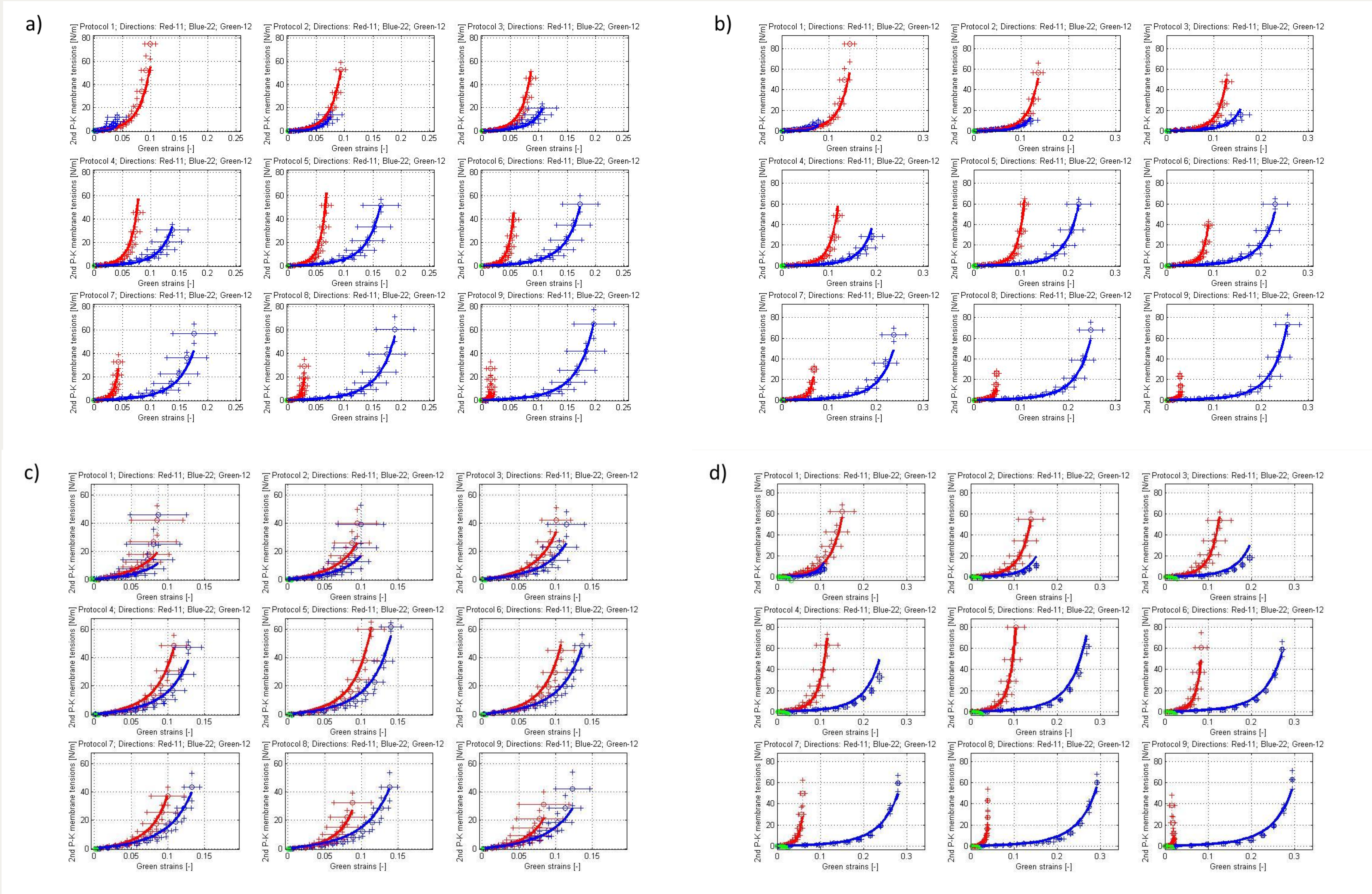


Fig. 2. Stress-strain curves generated from porcine valve tissue biaxially tested using nine displacement-controlled protocols. The circumferential direction is represented in red and the radial direction is represented in blue. Experimental data is shown in red and blue points. **a)** and **b)** show data collected from the left, right, and non-coronary aortic valve leaflets of fresh and frozen hearts, respectively. **c)** represents data collected from the anterior leaflets of fresh mitral valve and **d)** represents data collected from the posterior leaflets of fresh mitral valve.

Conclusions

- All tissue samples from the aortic and mitral leaflets were stiffer in the circumferential direction compared to the radial direction
- No significant difference was observed in the mechanical behaviour of the left, right, and non-coronary leaflets of the aortic valve
- The mitral leaflets behaved differently under similar loads with the anterior leaflet displaying similar stress-strain curves in both circumferential and radial directions, while the posterior leaflet was shown to have a greater radial deformation
- In fresh porcine tissue, experimental stress-strain curves obtained were comparable to those reported by other groups [1]
- Tissue processing methods were consistent and accurate
- Previously frozen heart valve tissue exhibited unrealistic compliance compared to fresh tissue, suggesting that tissue storage at −18°C should not be used

Future Research

- Test material properties of human heart valves and blood vessels instead of using animal models
- Use collected data with finite element analysis to generate three-dimensional models for use as surgery simulators
- Expand research to the actual human valves to gain insight on treating diseases such as aortic and mitral insufficiency
- Modify the methodology to incorporate a saline bath during the displacement-controlled stage without negatively impacting the quality of image analysis
- Link the mechanical properties of soft tissues to connective tissue fibers to refine our constitutive model for determining material constants
- Determine suitable materials to construct biosynthetic valves

References

[1] Heyden, S., Nagler, A., Bertoglio, C., Biehler, J., Gee, M., Wall, W. and Ortiz, M., 2015, "Material modeling of cardiac valve tissue: Experiments, constitutive analysis and numerical investigation", J Biomech., 48., pp. 4288.

[2] Fung. Y., 1984, "Structure and Stress-Strain Relationship of Soft Tissues", American Zoologist, 24. 1. pp. 13-22.

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