Rigid rakes outperform hooks and pulleys as attachments in testing of anisotropic hyperelastic materials: experiments and simulations

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Introduction

Planar biaxial testing has been used to study biological tissues and biomaterials whose mechanical properties are directionally dependent. It enables the exploration of forces or displacements applied in two orthogonal directions on an approximately square membrane-like specimen. The specimen can either be attached using a force-balanced system of suture lines, hooks and pulleys (Fig. 1a), or with CellScale BioTester BioRakes (Fig. 1b) [1,2]. The suture/pulley system are designed to simulate uniformly distributed loads applied to the edges of the specimen, whereas the BioRakes are designed to simulate uniformly distributed displacements.

Loading conditions are well understood when the specimen principal axis (typically parallel to the fiber orientation) is aligned/perpendicular with the two testing axes. Misalignment of the specimen with respect to the testing axes may result in uncontrolled shear deformation and forces developing in the specimen. The objective in this work is to evaluate which attachment system yields the most consistent results.

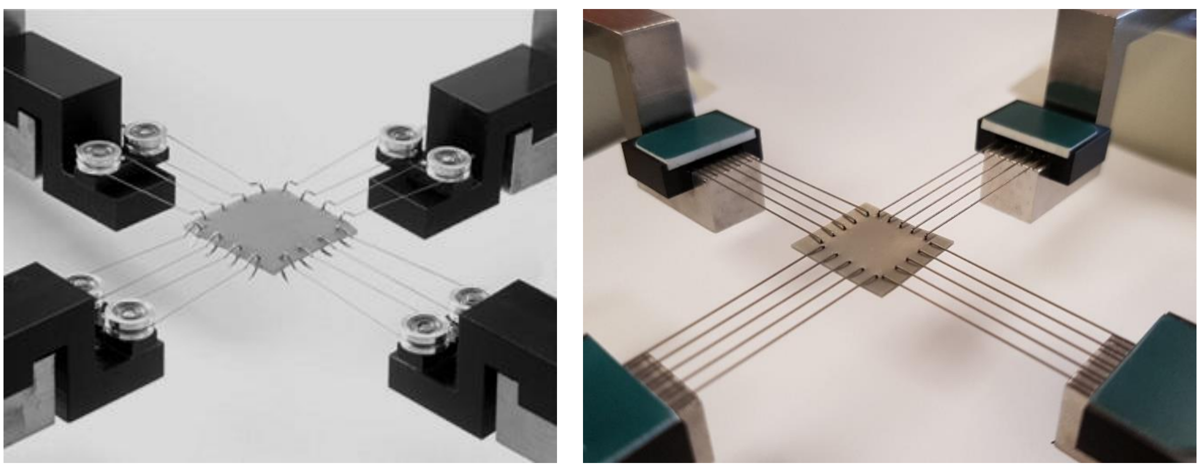

Figure 1. (a) Specimen attachment using sutures, hooks, and pulleys. (b) Specimen attachment using BioRakes.

Methods

An isotropic soft silicone rubber was chosen as the test material for the study. The strip of the material was tested uniaxially to determine the material properties of the rubber. A 20×2×0.5 mm strip of this material was subjected to displacement-controlled uniaxial testing using custom clamps. The maximum imposed displacement was selected to reach up to 5 N of applied force. Three load-unload cycles were applied, and the data from the last cycle was analyzed to fit a hyperelastic Ogden model using ANSYS 16.1 (ANSYS, Canonsburg, PA, USA).

To create an anisotropic (directionally dependent) material, the rubber was molded into a flat membrane with a ribbed structure (Fig. 2). The dimensions of the ribs were measured using a profilometer (ST400, Nanovea, Irvine, CA, USA). Specimens were cut with ribs running either parallel or at 45-degrees to the test axes. The specimens with parallel ribs were designed to minimize the occurrence of shear strains under biaxial testing [2], while the specimens with 45-degree ribs were designed to maximize shear strains.

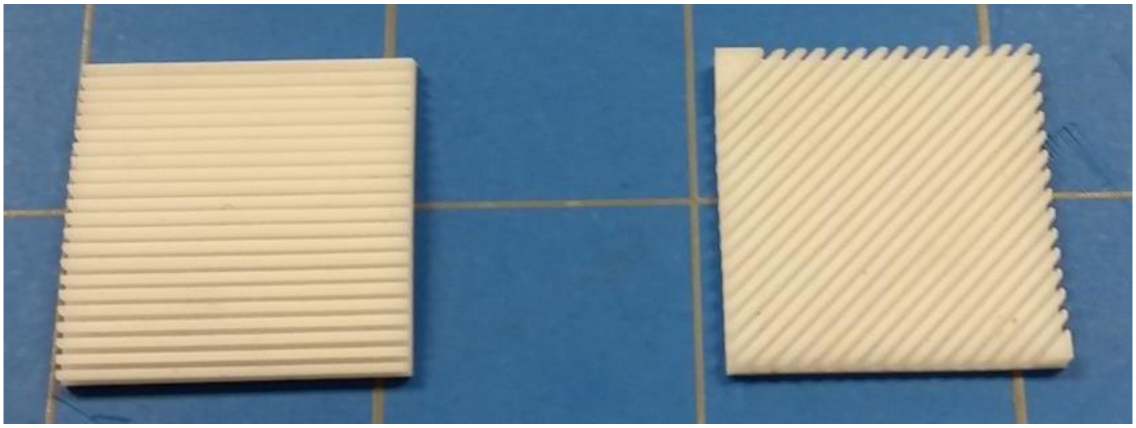

Figure 2. Anisotropic specimens created from silicone rubber.

Four experimental conditions were tested including 0- and 45-degree ribs with both sutures/pulleys and BioRake attachments. In all 4 conditions, a series of nine displacement-controlled protocols were run to explore the anisotropic behaviour of the specimens. These protocols generated up to 20% strain and spanned X/Y displacement ratios ranging from 0.17 to 6.00. Sacks' anisotropic hyperelastic material model was fitted to the experimental data according to numerical procedures detailed in [3].

Finite element (FE) models of the specimens were created in ANSYS and assigned bulk isotropic hyperelastic material properties as determined from the uniaxial test. The models included approximately 100,000 ten-noded tetrahedral Solid285 (mixed u-P) FE suitable for large deformations with nearly-incompressible hyperelastic materials. The simulations of the suture/pulley systems were accomplished with distributed forces applied to the nodes of mounting holes, while multiple nodes in the centre of the specimens were restricted from moving in all directions. The simulation of the BioRake system was accomplished by applying a displacement condition to the nodes of the mounting holes and, in addition, preventing the middle holes on each side of the specimen from moving in the direction perpendicular to the corresponding side.

Results

A second-order Ogden model provided an excellent fit to the uniaxial experimental data. The stress-strain results from the experimental biaxial testing of all nine displacements protocols for all 4 experimental conditions were calculated. The 2nd Piola-Kirchhoff membrane tensions were derived from the forces measured by the BioTester and the Green strains were obtained from digital image correlation (DIC) of the textured surface of the specimens' central region. The experimental data were used to generate material constants in a Sacks' material model.

FE simulations of the physical biaxial tests produced strain maps that agreed well with the DIC data for both the 0- and 45-degree configurations under equibiaxial conditions. In addition, it was possible to compare the imposed displacements and resulting forces during the physical tests and the same data from the numerical simulations. For all experimental conditions, the average percent error from the numerical simulations was less the 10%.

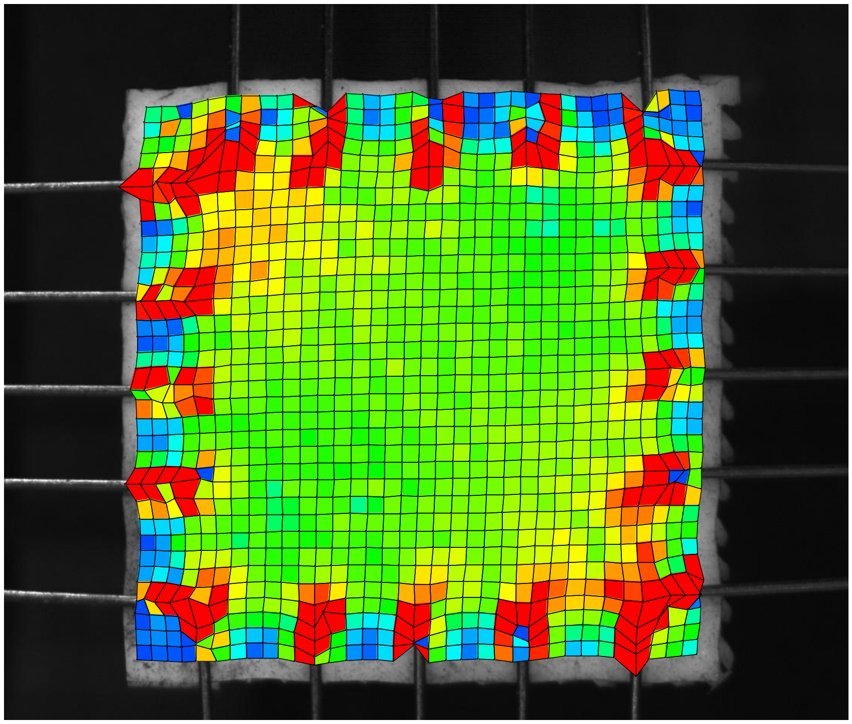

Figure 3. DIC strain tracking of an equibiaxially stretched ribbed specimen attached using BioRakes.

Discussion

The material model determined from the biaxial experimental tests with suture/pulleys and BioRake attachment systems were both successful in modelling real-world experiments.

During the physical biaxial tests, the suture/pulley attachment system was considerably more difficult and time-consuming to use than the BioRakes. Setting adequate lengths for all the suture lines to ensure minimal tension in the undeformed specimen was challenging. The orientation of the hooks with respect to the specimen was unstable and required many adjustments. On the other hand, the tines of the BioRakes were evenly distributed and the setup was simple and fast.

Conclusion

The excellent match (less than 10% error) between the experiments and the simulations across all the testing protocols and geometric configurations, combined with a remarkable ease of use in experiments and simulations, strongly suggest that rigid rakes outperform sutures/pulleys for testing specimens of this nature.

References

1. Sacks, M.S. A method for planar biaxial mechanical testing that includes in-plane shear. *Journal of Biomechanical Engineering*, 121:551–555, 1999.
2. Eilaghi, A., Flanagan, J.G., Brodland, G.W., Ethier, C.R. Strain uniformity in biaxial specimens is highly sensitive to attachment details. *Journal of Biomechanical Engineering*, 131(9):091003-1–091003-7, 2009.
3. Labrosse, M.R., Jafar, R., Ngu, J., Boodhwani, M. Planar biaxial testing of heart valve cusp replacement biomaterials: Experiments, theory and material constants. *Acta Biomaterialia*, 45:303–320, 2016.