Assessment of Anterior Spinal Artery Blood Flow during Active Compression in Spinal Cord Injury

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Spinal Cord Injury

- Spinal cord injury (SCI) incidence in the US is approximately 12,000 individuals annually[1]
- Compressions causing <35% canal stenosis are not considered clinically significant[2]
- Increased force beyond certain thresholds or prolonged compression of the spinal cord result in progressive ischemia[3]

Relative Ischemia

- Most current research focuses on clinical assessment of spinal cord injury
- The state of spinal blood flow at subclinical forces has not been well understood

Purpose

- Characterize the relative extent to which various modes of compressive mechanical loading compromise blood flow in the anterior spinal arterial supply.

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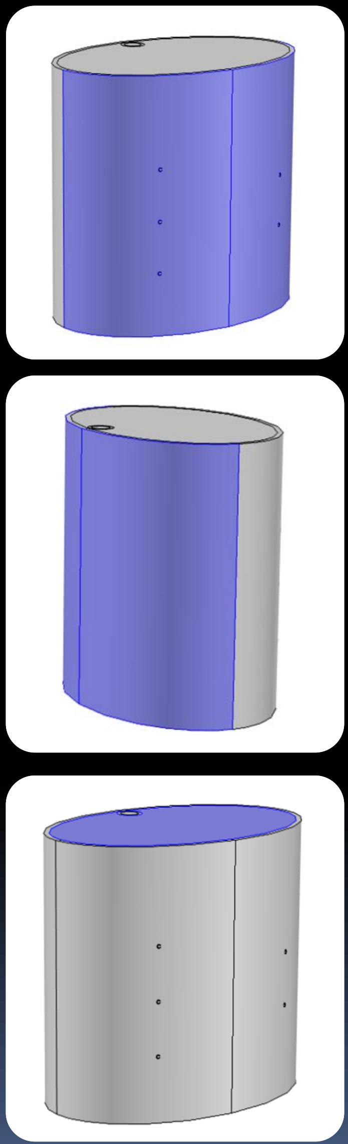
Theory & Methods

- 3-D finite element model of the cervical spinal cord was developed using Comsol Multiphysics 4.0a
- Fluid-structure interaction physics module
- Quantifying changes in outlet flow as a result of compression
- Applied Loads based on the most common spinal injuries: Anterior, Posterior, Axial
- Changes in Mechanical properties: Spinal cord elastic modulus, anterior spinal artery elastic modulus

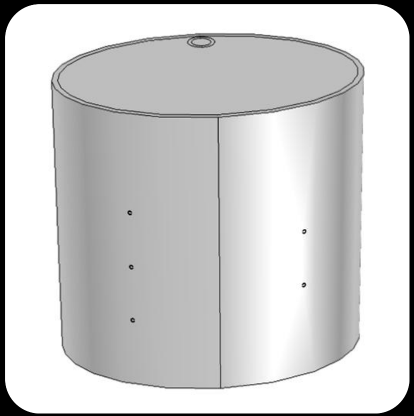


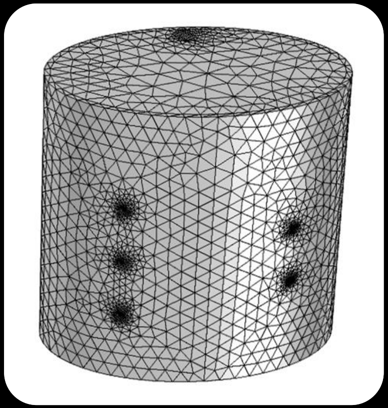
Theory & Methods (2)

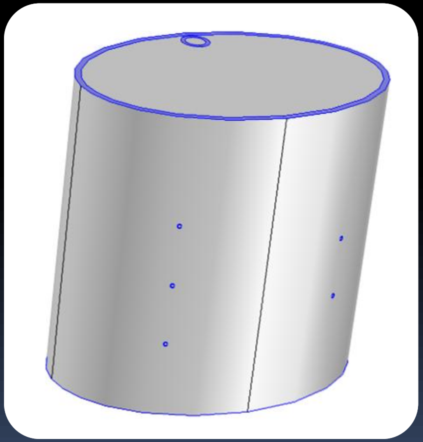
- Model includes a 1 cm segment of the cervical spinal cord, surrounding dura mater, the anterior spinal artery, and 5 arterial branches
- Measurements based on bovine and porcine experiments
- May be extrapolated to human studies

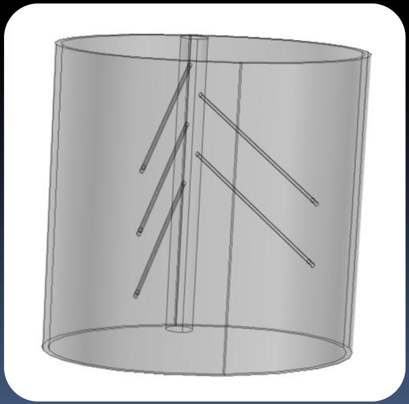
Model Design

- All materials in the model were characterized as linear elastic materials
- Blood was modeled as a Newtonian fluid with a density of 1060 kg/m^3 and a dynamic viscosity of 5e-3 Pa.s.
- Blood flow was induced with an average inlet velocity of 0.3 m/s
- Adaptive free-tetrahedral meshing





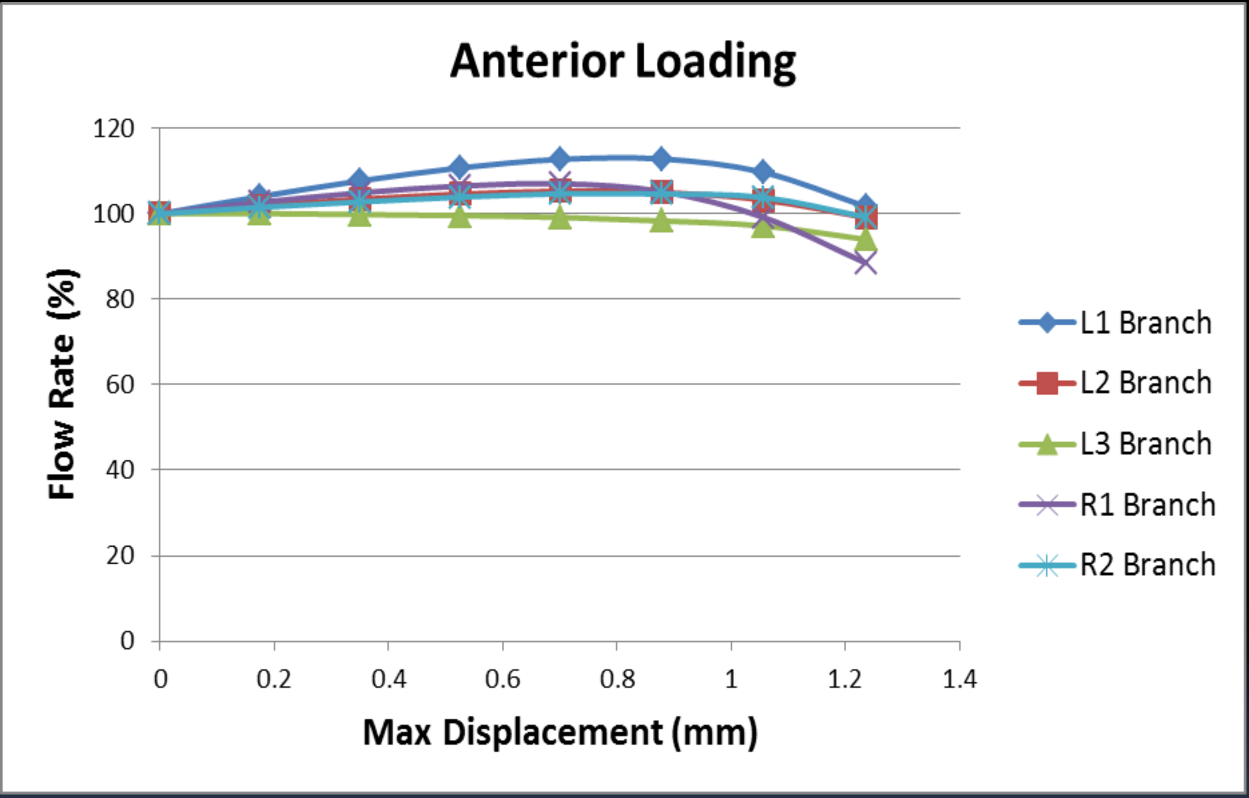


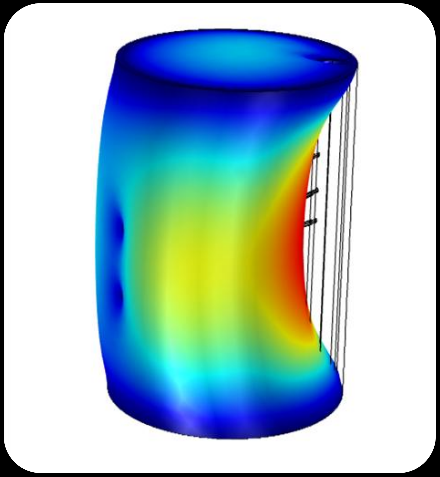


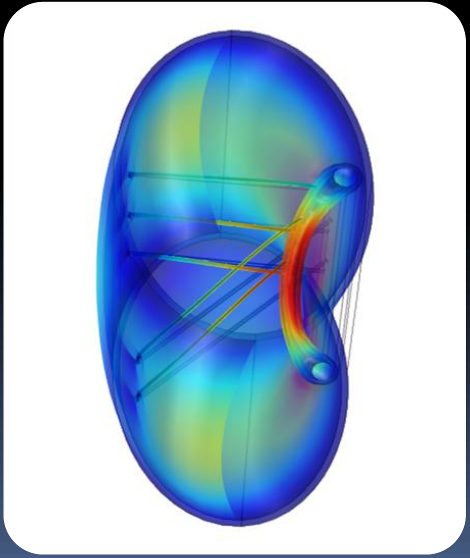
Mechanical Properties

Material	Size (mm)	Elastic Modulus (Pa)	Poisson's ratio	Density (kg/m^3)	Other
Cervical spinal cord	1-1.5 cm (5) Width: 1.5 cm Length: 1.0 cm	1.4e6 (6)	0.40 (7)	1050 (8)	
Dura mater	0.3-0.4 (9) 0.3	8e7(10)	0.49 (10)	1000 (11)	
Anterior spinal artery	Diameter: 1.5 (12) Thickness: 0.25 D: 1.4, T: 0.2	1e6 (13)	0.45 (13)	1000 (14)	
Vascular branches	Diameter: 0.1 Thickness: 0.02	1e6	0.45	1000	4.6 branches/cm of spinal cord (5)

Results: Perfusion - Anterior Loading







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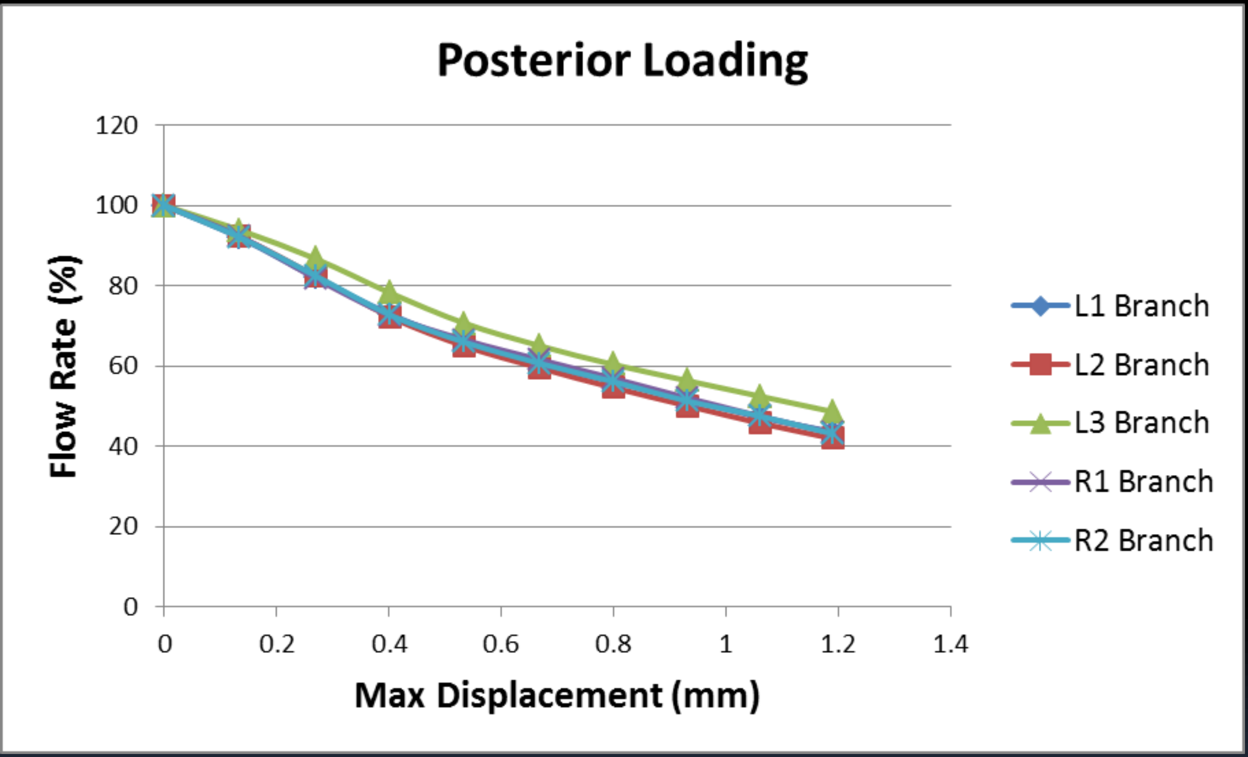
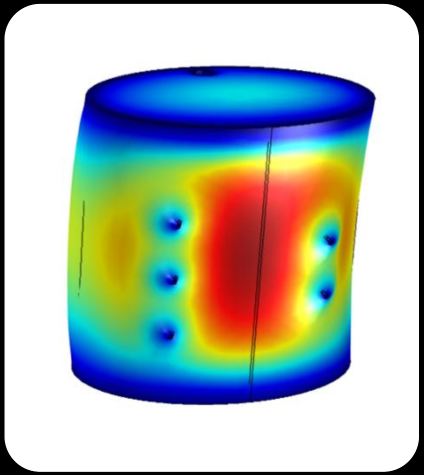
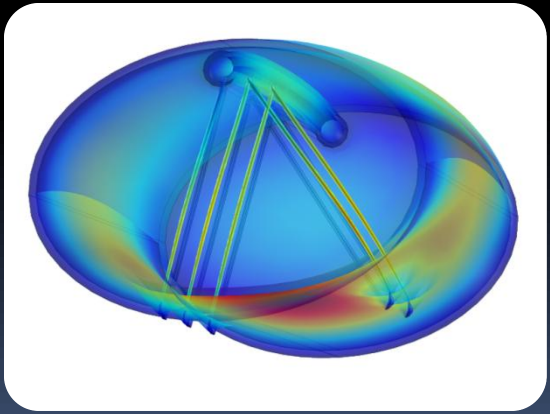
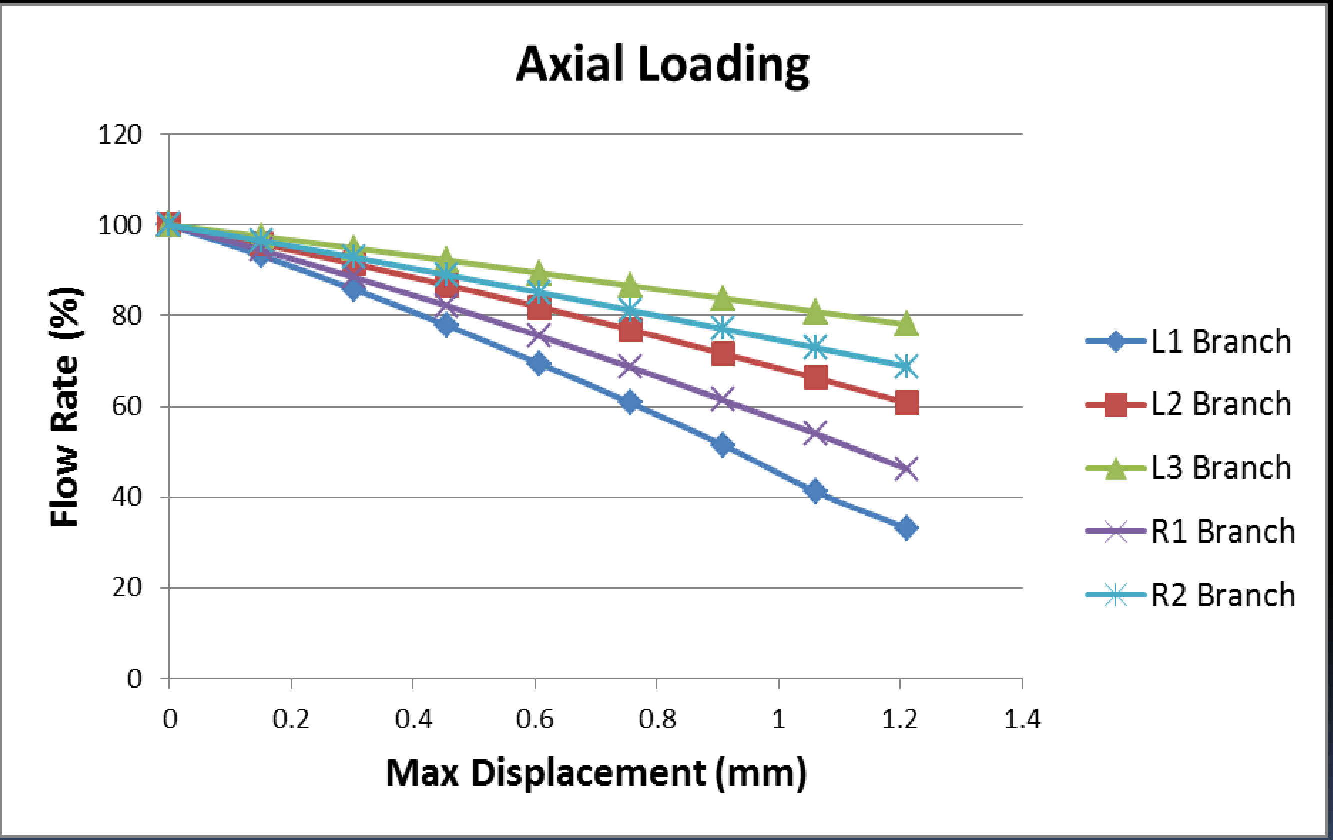
Results: Perfusion - Posterior Loading

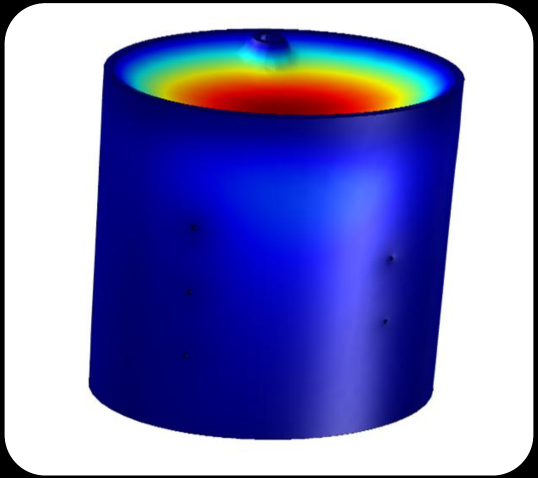


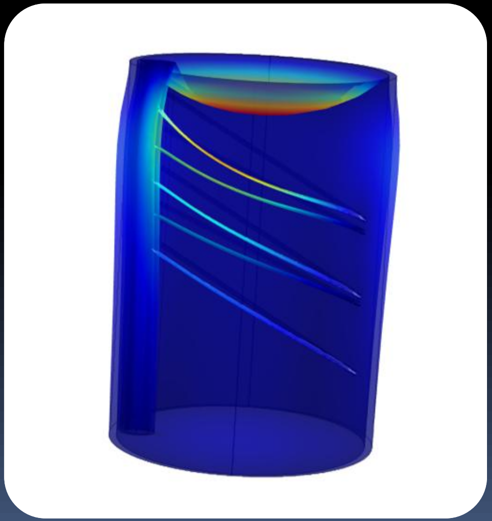




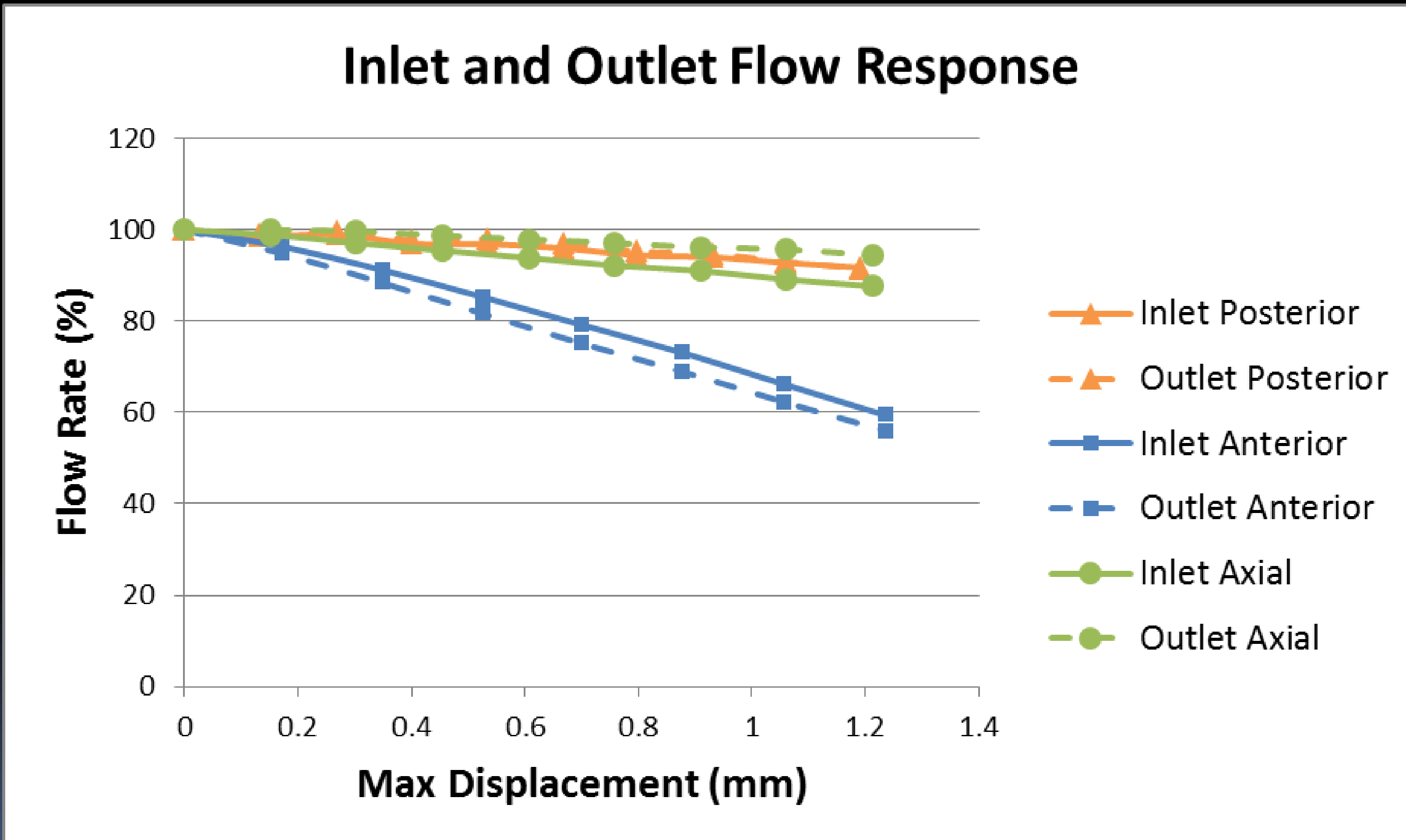
Results: Perfusion – Axial Loading







Results: ASA - Inlet & Outlet Flow



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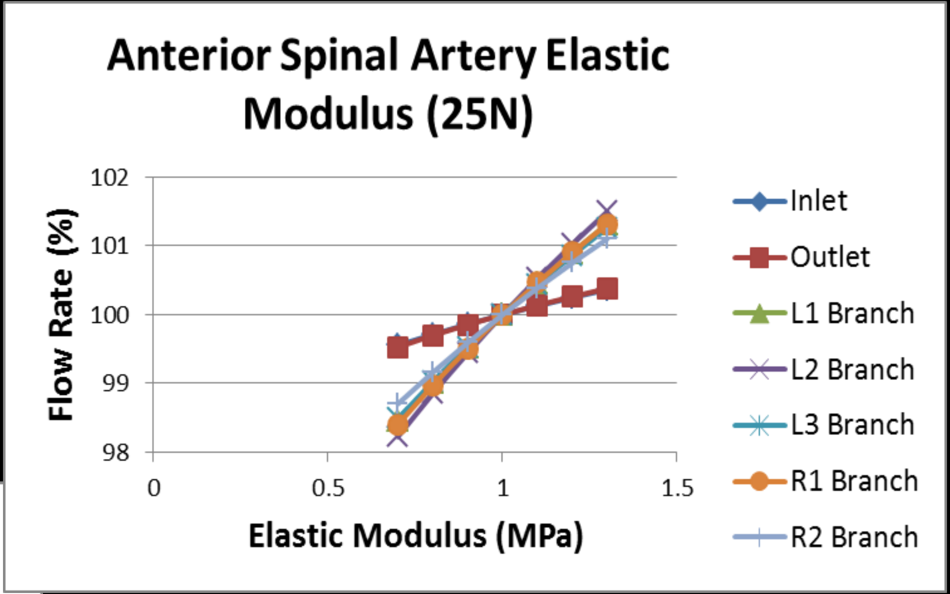
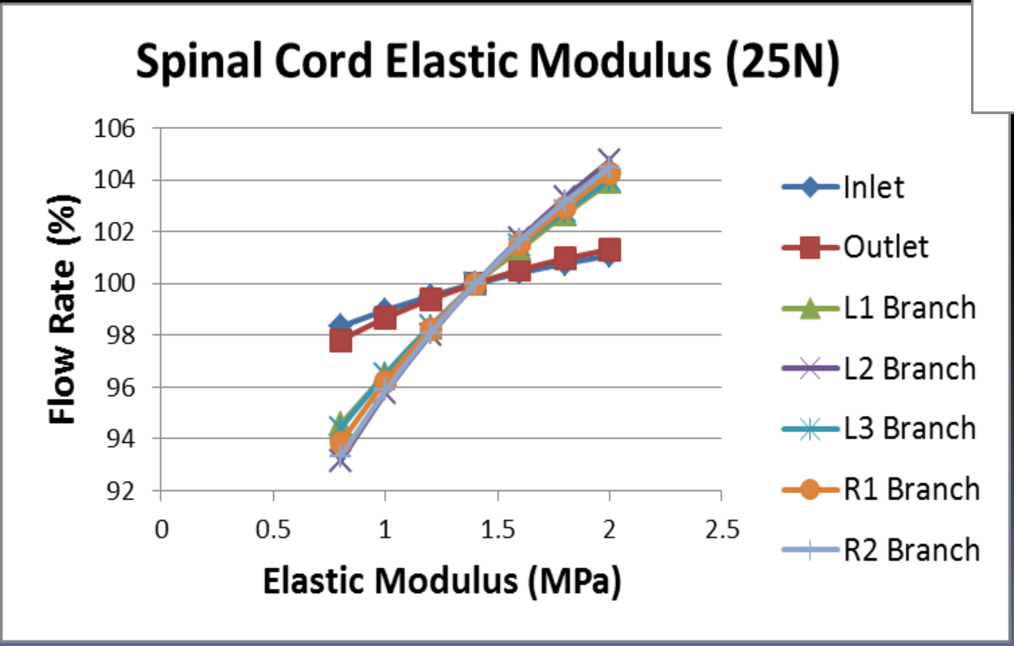
Results: Alteration in Mechanical Properties





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Limitations

- Cannot induce acute mechanical damage
- Spinal cord vascular auto-regulation is not simulated
- Linear Elastic Material used to model materials
- Lack of a cerebrospinal fluid layer
- Newtonian fluid & steady state flow for blood flow
- Collateral circulation & posterior spinal arteries were not included

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Discussion

- Anterior loading results in reduced flow and increased deformation in the ASA.
  - may induce maladaptive vascular remodeling
  - may disrupt auto-regulation mechanism
- Posterior loading reduces perfusion substantially within the spinal cord
  - limits blood flow in the arterial branches
  - minimally affects the ASA
  - may lead to ischemia of the supplied tissues
- Axial loading affects arterial branches predominantly in proximity of the loading site.
- Decreased blood flow caused by spinal compression may contribute to progressive ischemia of the spinal cord.

Future Work

- Passive and active mechanical testing of anterior spinal artery
- Ex-vivo testing of compressive loading on spinal cord
- Update model using constitutive equations for vascular tissue for quantitative analysis

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