Finite Element Modeling of the Posterior Eye in Microgravity

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Purpose

Visual impairment and intracranial pressure (VIIP) syndrome is a major health concern for astronauts on long-duration missions[1]. VIIP syndrome results in altered visual acuity and ocular anatomical changes persisting after returning to earth (Figure 1).

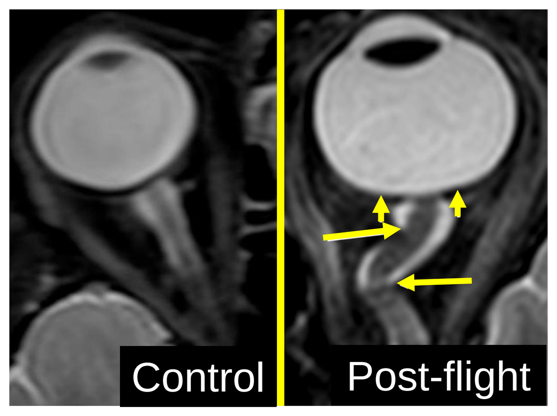

Figure 1: Left: MR image of a normal eye and optic nerve. Right: MR image of an eye from an astronaut with VIIP, showing 'kinking' (long arrows) of the optic nerve and posterior globe flattening (short arrows)[2].

It is hypothesized that the cephalad (headward) fluid shift occurring in microgravity elevates intracranial pressure (ICP) acting on the optic nerve head (ONH) and over time leads to visual impairment.

Goal: To develop a finite element (FE) model that simulates elevation of ICP and accounts for inter-individual variation. This model will allow us to understand how ICP affects the strains in the lamina cribrosa (LC), which are hypothesized to play a role in other ocular diseases (e.g. glaucoma) and thought to play a role in VIIP syndrome.

Model Overview

- Developed a geometric model of the posterior eye and optic nerve sheath (Figure 2).
- For static IOP (15 mmHg), applied various magnitudes of ICP to simulate the effects of the upright position (low ICP), supine position (moderate ICP) and microgravity – assumed to result in an elevated ICP.
- Examined the peak tensile and compressive strains in the LC, defined as the 95th and 5th percentile of the first and third principal strains, respectively.

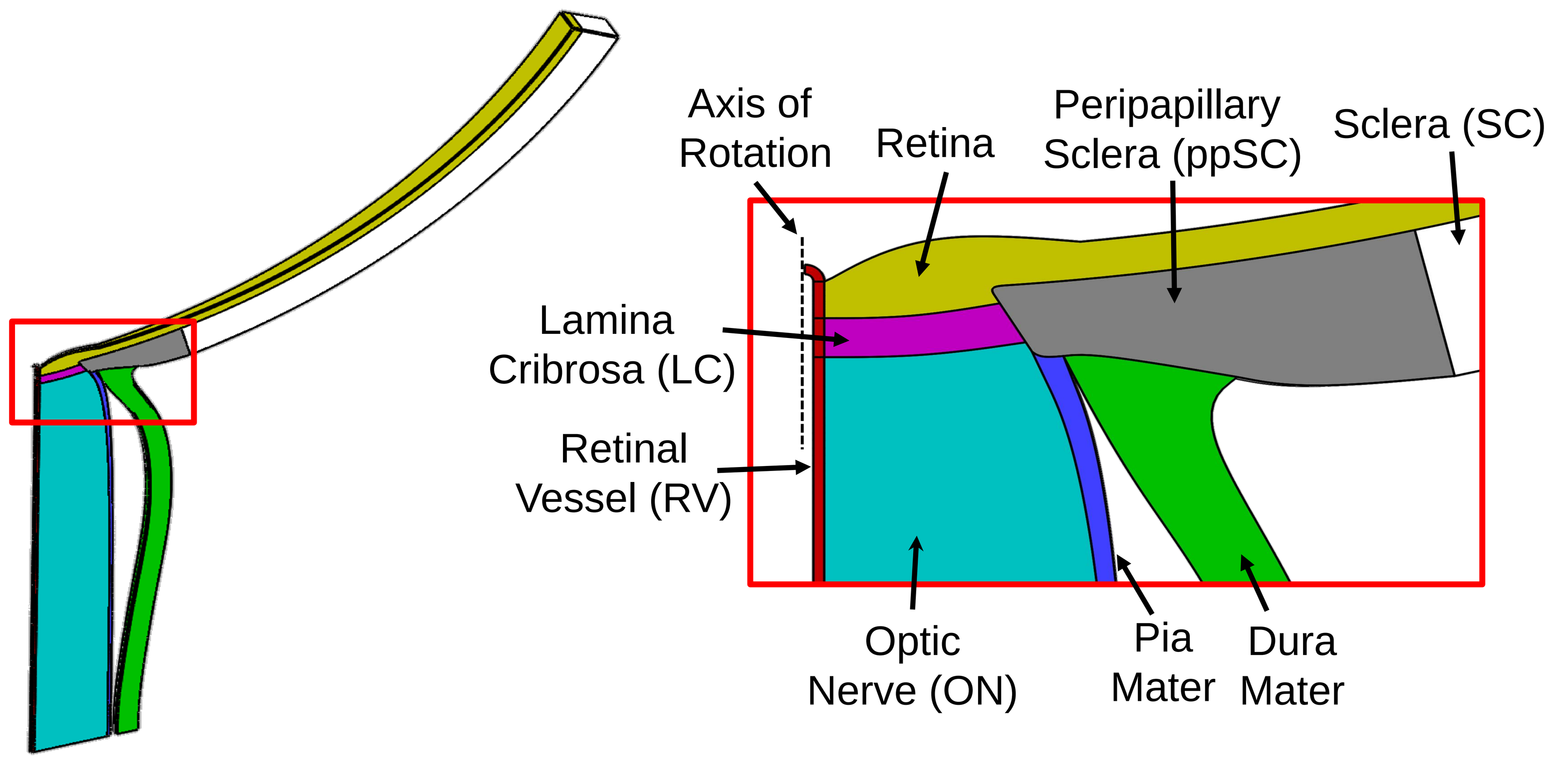

Figure 2: The 3D geometry was created in Gmsh[2] and all simulations were performed in the FE solver FEBio[3]. Left: Our geometric model that built on existing models of the posterior eye[4]. Right: A zoomed image of the ONH (boxed region on the left).

References

1) Kramer et al. *Radiology*, 2012. **2)** Geuzaine, CR, et al., Int J Num Method Eng, 79(11):1309-31, 2009. **3)** Maas, SA, et al., J Biomech Eng. 134(1):011005, 2012. **4)** Sigal, I et al., IOVS, 45(12):4378-87, 2004.

Latin Hypercube Sampling (LHS)

- LHS generates model inputs that represent inter-individual variations in the ONH pressures and material properties (Figure 3).
- We compared the peak tensile and compressive strains using cumulative distribution functions (CDFs), derived from the histograms of the peak strains.
- We calculated the percentage of simulations in microgravity experiencing extreme strains in the LC – i.e. strains above the supine threshold.
- After identifying models with extreme strains in microgravity, we used a Mann-Whitney test to examine the material properties of ONH tissues that associated with this condition.

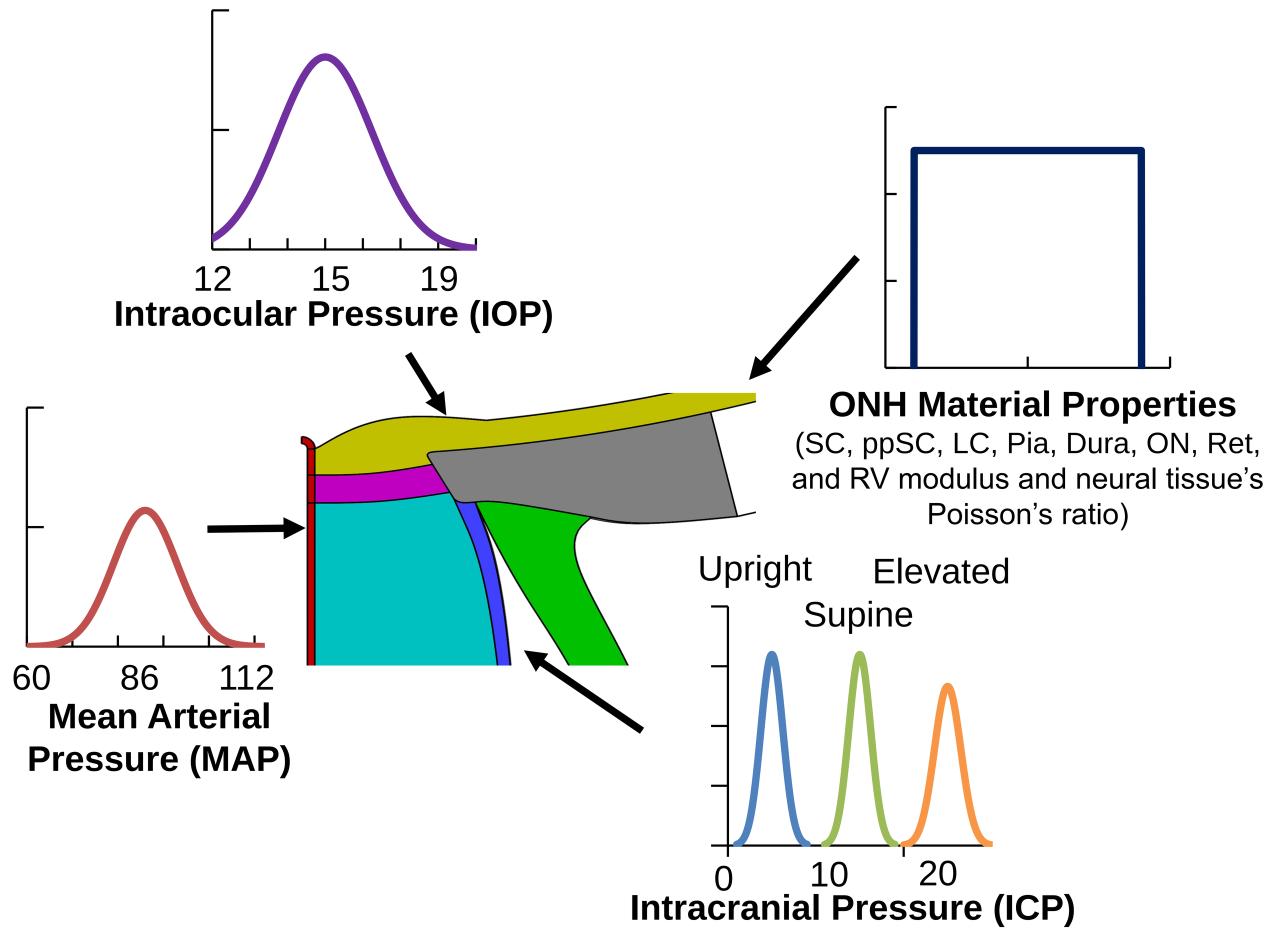

Figure 3: Input parameters for the LHS approach. ONH pressures followed truncated normal distributions, and tissue mechanical properties followed uniform distributions. LHS allowed us to simulate the entire parameter space in a minimum number of simulations (100 simulations per ICP condition).

Elevating ICP - Results

- Elevating ICP while assigning all other material properties to "Baseline" values altered the distribution of strain in the lateral region of the LC and anterior optic nerve (Figure 4).
- The magnitude of tension and compression in the LC only modestly increased as ICP was elevated.

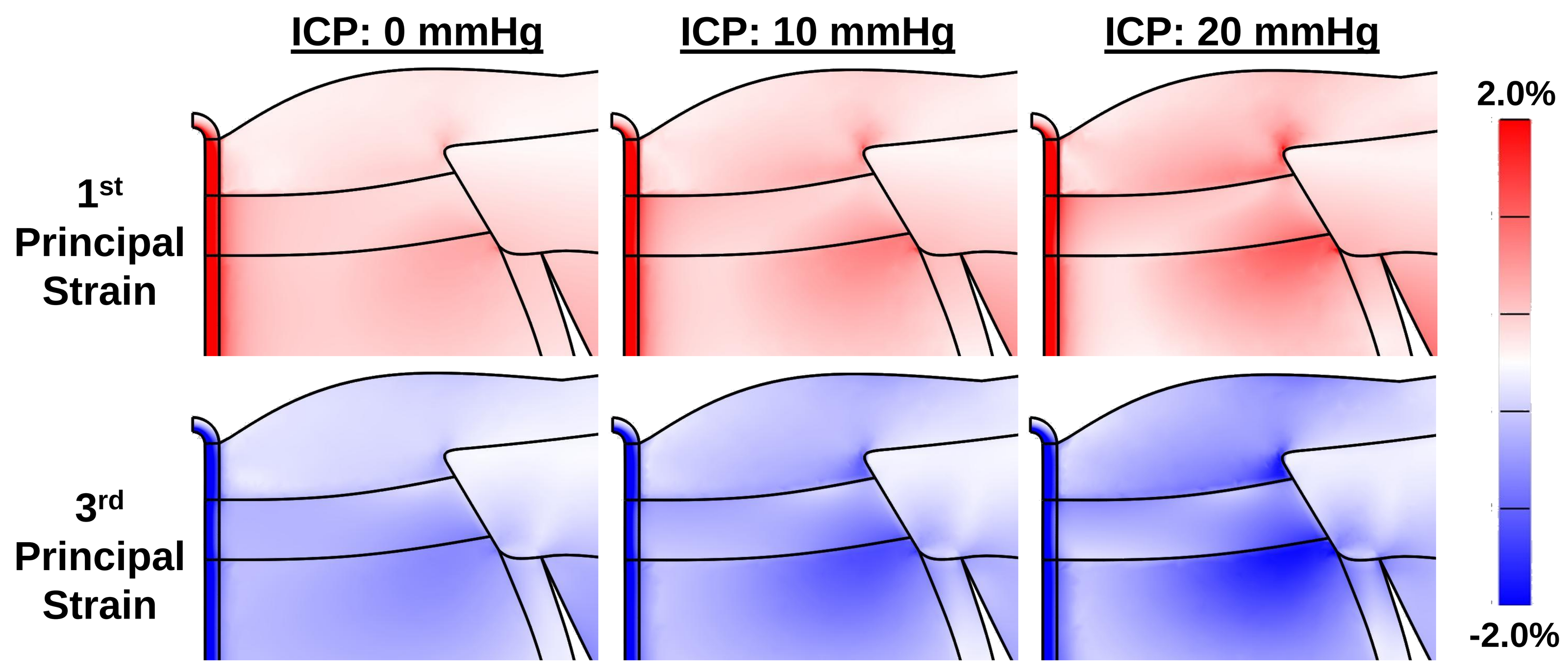

Figure 4: Contour plots of the computed 1st and 3rd principal strains in the ONH tissues as ICP was varied between 0, 10 and 20 mmHg. Tissue extension (tension) is shown in red and compression is shown in blue.

Inter-individual Variation - Results

- Incorporating inter-individual differences from our LHS approach led to large variations in LC strains (Figure 5).
- 5-8% of the simulations in the elevated ICP condition experienced strains greater than the supine threshold.
- LC stiffness was significantly lower in elevated ICP simulations that experienced extreme strains.

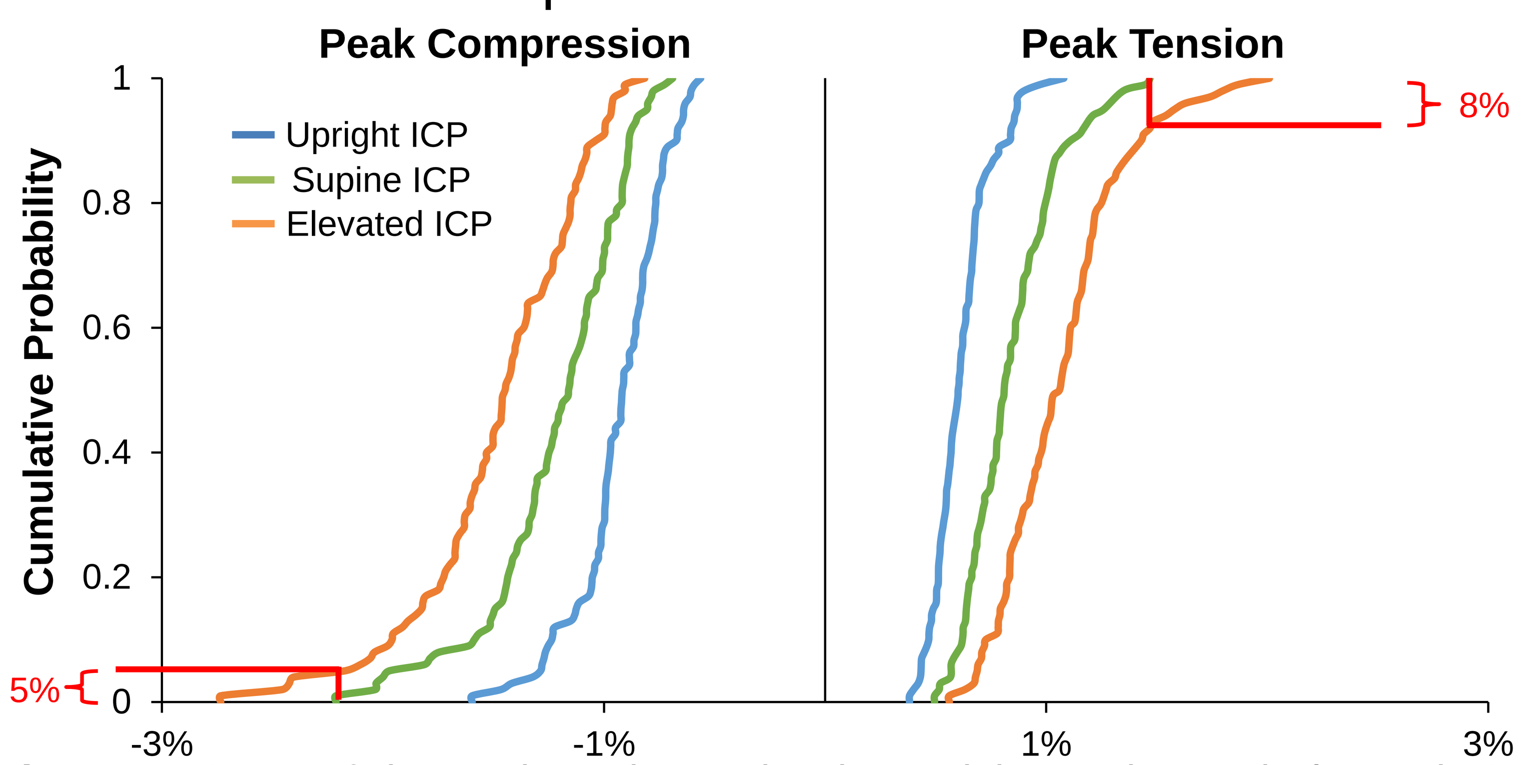

Figure 5: CDFs of the peak strains under the upright, supine and elevated ICP conditions. The vertical red lines illustrate the peak strains experienced on earth, and the corresponding percentages indicate the percentage of individuals experiencing strains above the terrestrial threshold.

Summary

- Inter-individual variations in pressures and tissue mechanical properties significantly affected LC peak strains.
- A less stiff LC was a risk factor for experiencing extreme strains in the LC under simulated microgravity.
- Experiencing these extreme strains may activate local mechanosensitive cells and induce tissue remodeling.

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