Validation of Spherical Indentation Methodology to Characterize Material Properties of Brain Tissue

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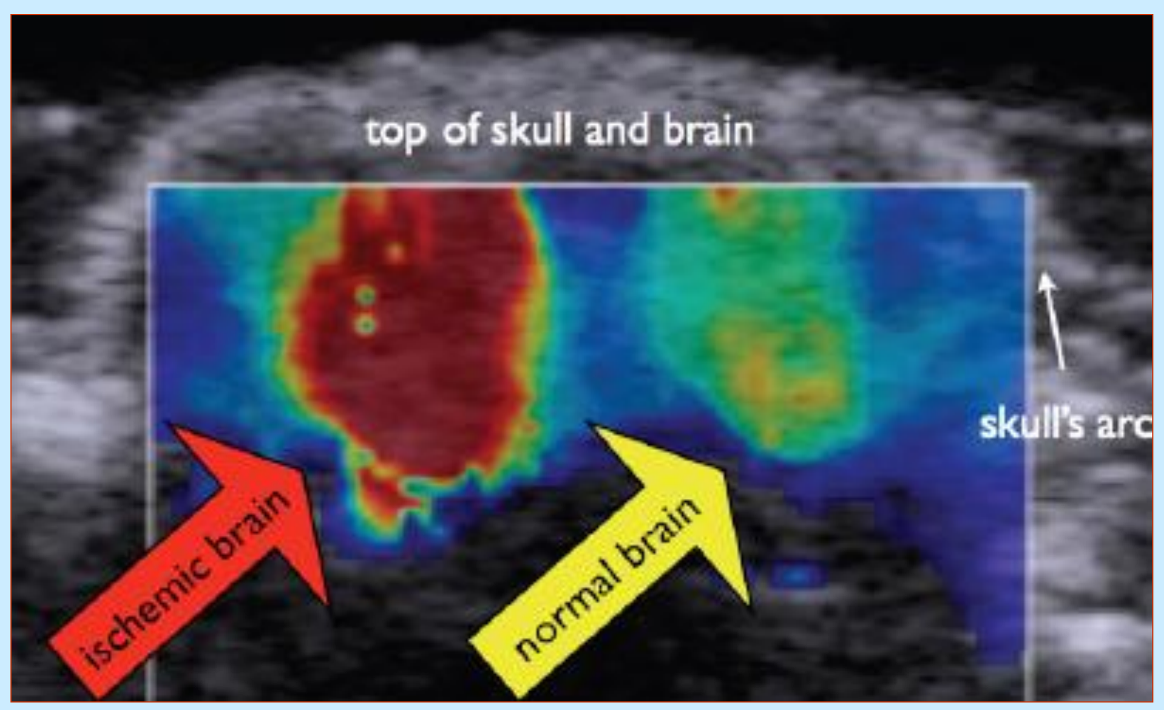
Motivation

Roughly 1.7 million people sustain a Traumatic Brain Injury (TBI) every year. These injuries include, but are not limited to, contusions, edema, hemorrhage, intracranial bleeding, and traumatic axonal injury. Among the leading causes of clinically treated cases are blunt traumas to the head resulting from falls, automotive collisions, and assault. On the battlefield, improvised explosive devices have led to TBI in as many as 62% of soldiers sustaining head injuries (Owens et al. 2008 Combat wounds in Operation Iraqi Freedom and Operation Enduring Freedom. J. Trauma 64(2):295-299.). In some of these cases, TBI victims are either unaware of their condition or unable to receive adequate treatment before permanent brain damage has occurred, thus reducing the quality of life of the individual. Situations like these reveal critical gaps in patient care, both in the clinical and battlefield settings.

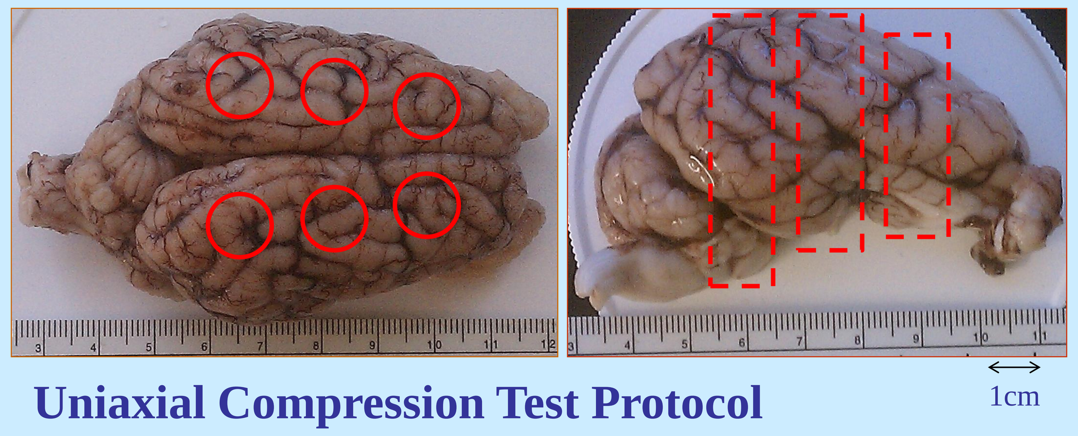
Background



One method of accurately diagnosing TBI severity involves an imaging technique that can discern changes in the mechanical response of brain tissue following injury. Such a technique would utilize stereotactic comparison between contemporary medical imaging systems and the intrinsic mechanical response of brain tissue. To achieve this, mechanical testing is necessary to quantify and map the local material properties down to the various substructures of the brain at different levels of injury. Spherical indentation is a practical choice capable of determining material parameters with the resolution necessary to develop a detailed stiffness map of both injured and uninjured brain tissue. However, there are limitations associated with spherical indentation. The contact surface between indenter tip and specimen does not remain constant and can be problematic. Furthermore, the mathematical formulation of indentation is based on an elastic half space and hence substrate thickness under the indenter will affect accurate determination of material parameters. To address these limitations and validate the indentation methodology, both compression and indentation tests are conducted on porcine brain tissue. The indentation data is then used to model the viscoelastic response of the brain tissues using quasilinear viscoelastic theory.

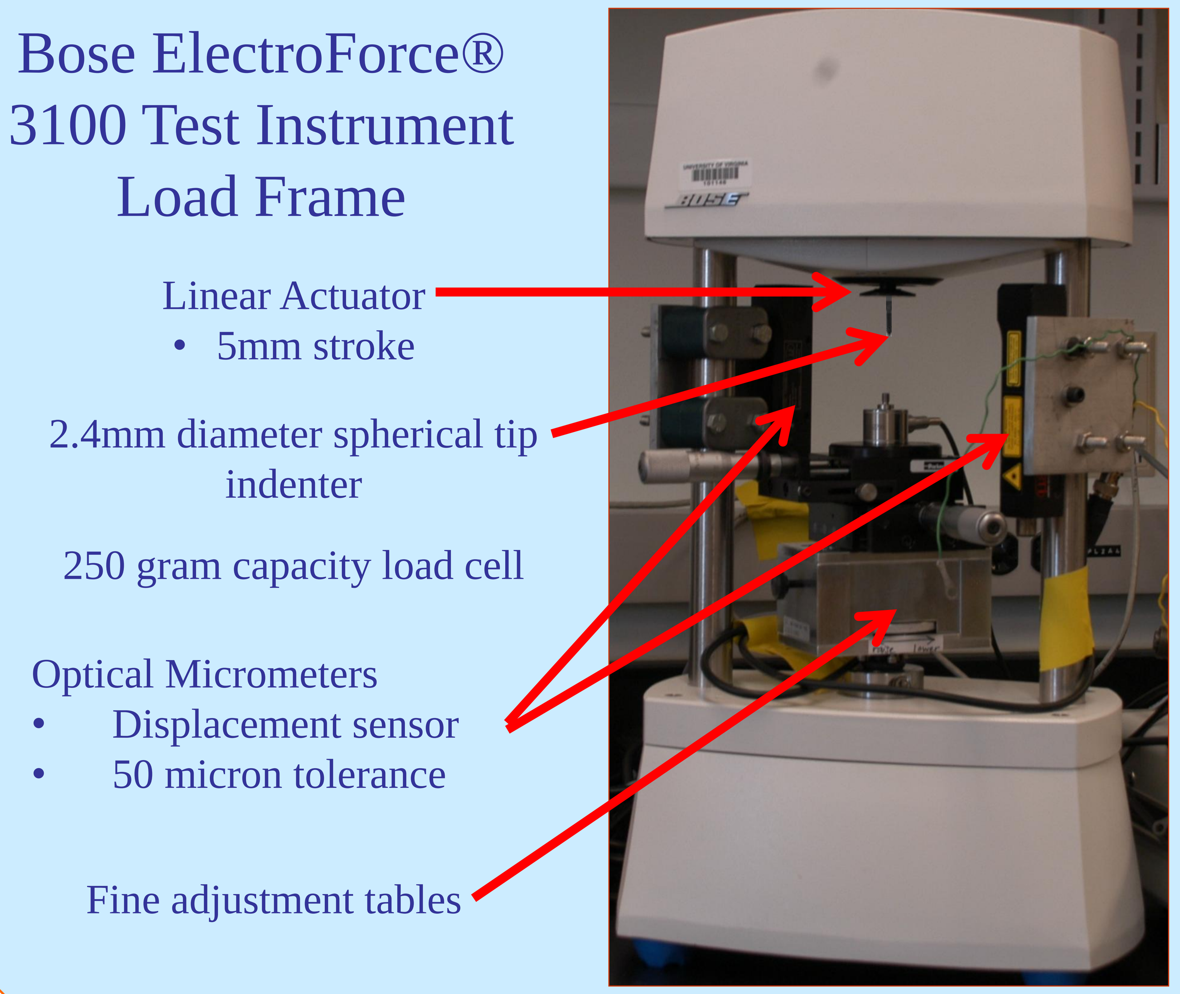
Methodology

- 30 cylindrical samples were obtained from 10 whole porcine brains from six locations (circled in red);
- Each sample resulted in a right circular cylinder 10mm height and 10mm diameter;
- Samples are assumed homogeneous, incompressible, isotropic, and predominately white matter;
- Both indentation and compression tests were performed on each sample (indentation proceeding compression).



Uniaxial Compression Test Protocol
- Ramp-hold, Stress Relaxation Tests;
- Load platen ramped at 50mm/s for strain amplitudes ranging between 5-30%;
- 5% pre-compression was applied;
- Saline was continuously applied to the sample.

Bose ElectroForce® 3100 Test Instrument Load Frame



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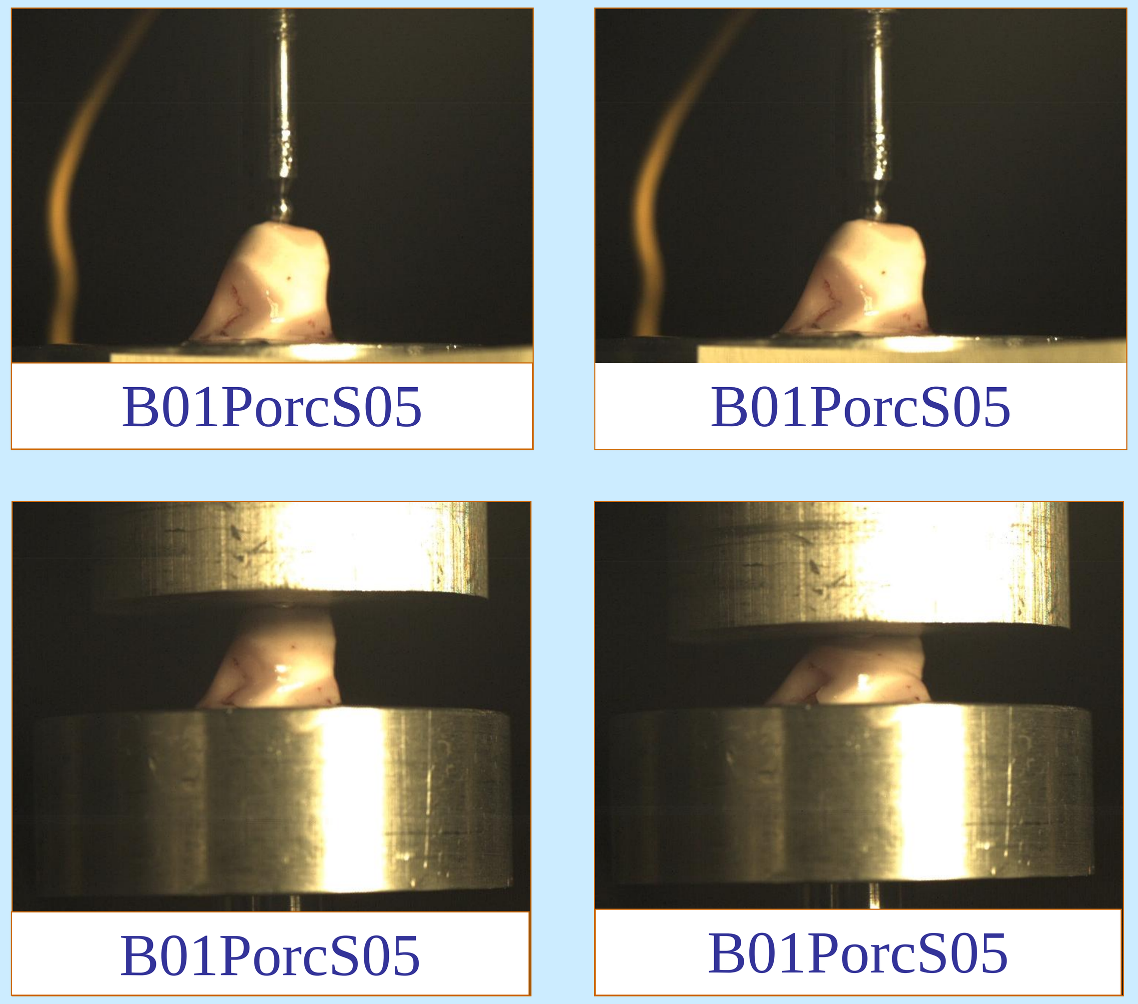
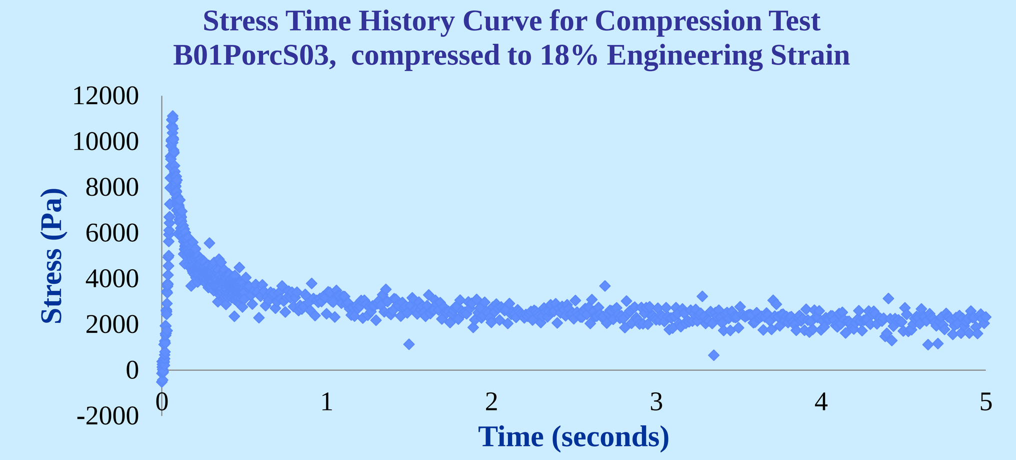
Indentation Test Protocol
- Ramp hold, Stress Relaxation Tests;
- 2.4mm diameter spherical tip was used to indent the top surface of each cylindrical sample at a speed of 50mm/s;
- Maximum indentation depth h was prescribed between 0.4 and 0.9mm below the level of the contact surface;
- Indenter tip was held at the maximum depth for 20s;
- Contact between indenter tip and sample surface was verified with the use of an electric circuit.

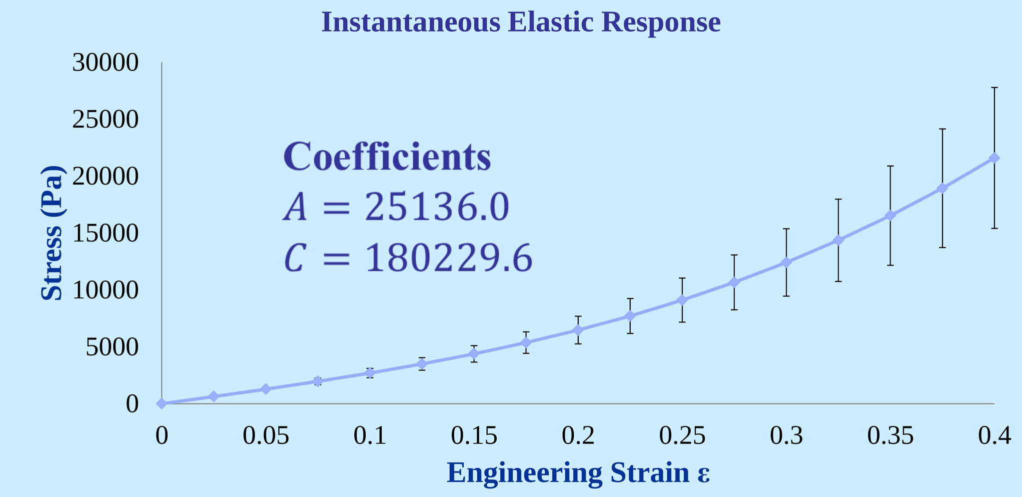


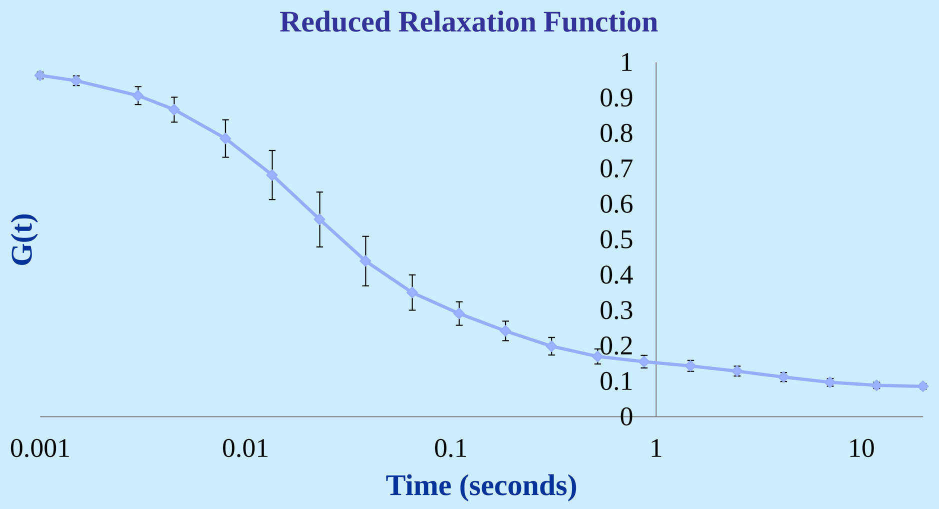
Constitutive Modeling
- Quasi-linear Viscoelasticity, Fung 1993
- $K(\varepsilon, t) = G(t)\sigma^e(\varepsilon)$

Compression Tests
- Polynomial hyper-elastic material model
- $\sigma^e(\varepsilon) = A\varepsilon + B\varepsilon^2 + C\varepsilon^3, B = 0$
- $G(t) = G_\infty + \sum_{i=1}^{3} G_i e^{-\beta_i t}$
- Indentation Tests
- Assumed form for the instantaneous response
  - $F^e(h) = Dh^{\frac{3}{2}} + Eh^{\frac{7}{2}}$
- $\phi(t) = \phi_\infty + \sum_{i=1}^{3} \phi_i e^{-\upsilon_i t}$

Analysis and Results





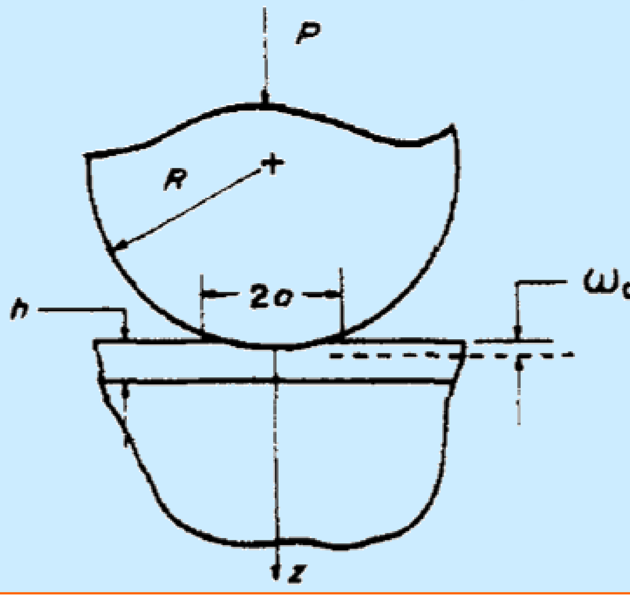


Coefficients
$G_\infty = 0.085$
$G_1 = 0.579$
$G_2 = 0.241$
$G_3 = 0.089$
$\beta_1 = 51.816$
$\beta_2 = 6.481$
$\beta_3 = 0.288$

The above graphs are results for the compression tests performed on 5 brain samples strained from 5% to 30% Engineering strain. Note the nonlinear stress strain behavior in the instantaneous elastic response. This indicates that brain tissue exhibits spatial nonlinear behavior. Data was filtered using an 8 pole Butterworth filter at 1650Hz (CFC 1000) according to the specifications of SAEJ211 REV.MAR95

Discussion

Difficulties and Limitations
- Low signal to noise ratio in force data;
- Limited time post-mortem for tissue viability;
- Ensuring flat loading surface on tissue;
- Mapping in vitro mechanical response to in vivo response;



Assumptions
- Brain tissue is assumed to be homogenous, isotropic, and incompressible. This assumption based on findings in the literature: Pamidi and Advani, 1978, Miller et al. 1997-2002, Takhounts et al. 2003, among others;
- For compression testing samples are assumed to have a cylindrically symmetric geometry;
- Hertzian contact mechanics are assumed to hold for indentation testing

Future Work

- To obtain a higher signal to noise ratio a lower capacity load cell will be instrumented to the experimental setup;
- A 3D model of a cylindrical brain sample will be constructed and modeled using finite elements. An inverse finite element analysis will be performed to compare the results of the indentation and compression tests and validate the methodology.

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