Regional and Directional Differences in the Material Properties of Porcine Brain Tissue

Sowmya N. Sundaresh, John D. Finan, Barclay Morrison III

I. INTRODUCTION

Traumatic brain injury (TBI) presents a major health concern; there were 2.5 million emergency visits, hospitalisations and deaths related to TBI in the US alone in 2010 [1]. Finite element (FE) models are used to understand and predict the brain's mechanical response to TBI for multiple applications including designing preventative measures [2]. However, the appropriate constitutive properties are required to inform these FE models so that the predicted responses are biofidelic. Studies have shown the brain to be an anisotropic material exhibiting viscoelastic behaviour [3]. This anisotropy could be due in part to the structural and mechanical differences between grey and white matter [4]. Porcine brain tissue is often used to study these mechanical properties due its similarity to human brain tissue in gross neuroanatomy and brain mass [5]. This study investigates the regional differences of the mechanical properties of porcine brain tissue on the sagittal and horizontal planes.

II. METHODS

Brain tissue samples were excised from euthanised pigs and transported in ice cold oxygenated artificial cerebrospinal fluid (aCSF) supplemented with glucose. Tissue slices of 2 mm thickness were cut in the sagittal and horizontal planes. The samples were adhered to plastic dishes and then maintained in CO_2 independent medium supplemented with 4 mg/mL glucose at physiological pH. All testing was performed within a postmortem time of three hours. Indentation testing was conducted using a custom designed microindentation device [6]. Each tissue sample was placed on a 10 g load cell (GSO-10, Transducer Techniques, Temecula, USA). The indentation was made using a 250 μm radius flat ended cylindrical punch (National Jet Company, Cumberland, USA) mounted to a linear actuator (M-227.10, Physik Instrumente, Karlsruhe, Germany), which displacement was monitored by a capacitive sensor (capaNCDT 6100, Micro Epsilon, Ortenburg, Germany). For a 10% strain, the depth of indentation was 40 μm. The load and displacement data were collected at 10 kHz using a custom LabVIEW code (LabVIEW 8.6, National Instruments, Austin, USA). Indentation tests were conducted in multiple locations within each anatomical region tested.

The velocity history and the relaxation function were convolved using the following Boltzmann hereditary integral,

$$P(t) = \frac{4R\kappa}{1-\nu}\int_0^t G(t-\tau)\left(\frac{d\delta}{d\tau}\right)d\tau \quad (1a)$$

where R is the radius of the cylindrical punch, κ is the correction factor for finite thickness effects, ν is the Poisson's ratio, G is the shear modulus, and δ is the indentation depth. The relaxation function was expressed as the following Prony series,

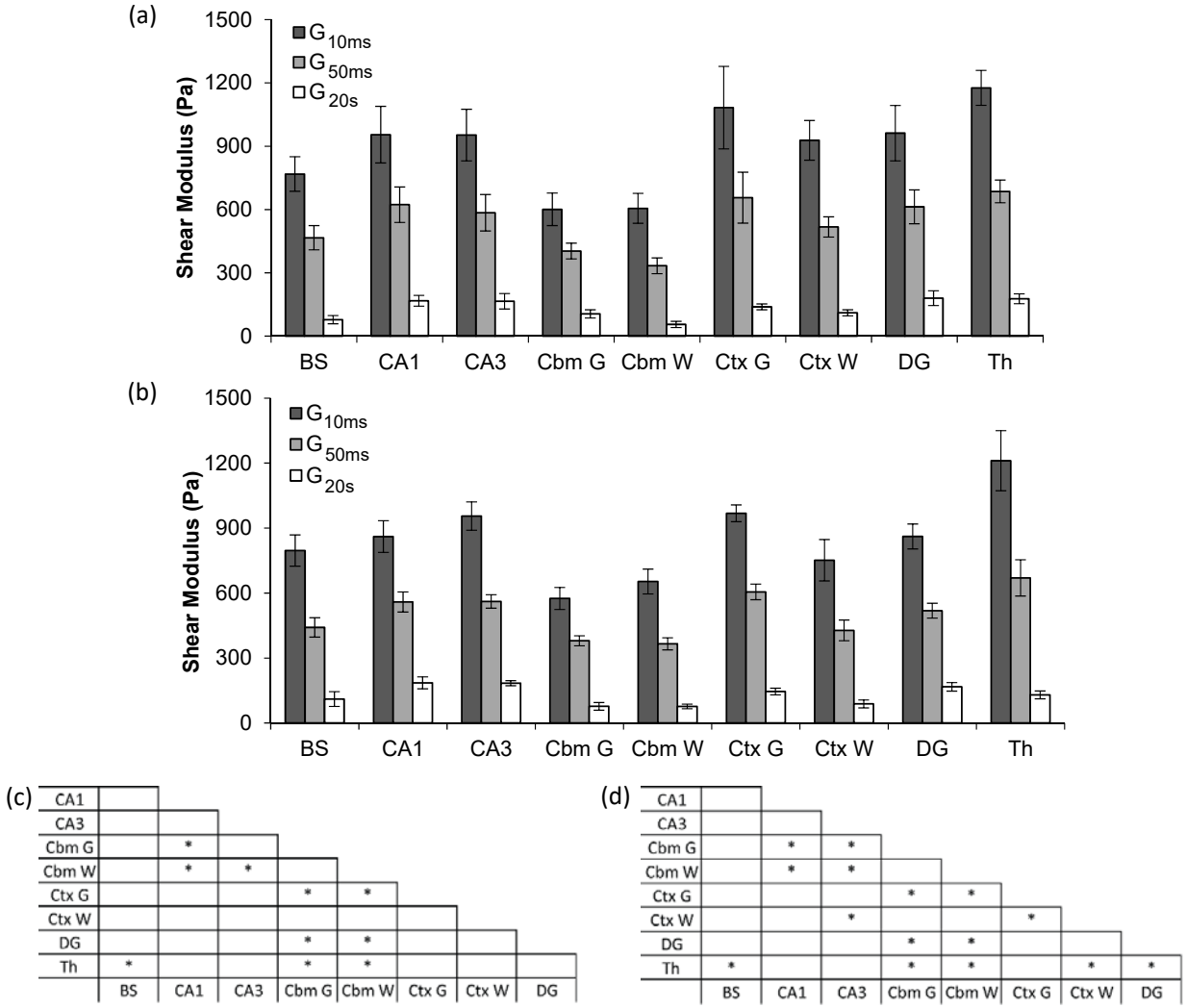
$$G(t) = G_\infty + \sum_i G_i e^{-\frac{t}{\tau_i}}. \quad (1b)$$

The coefficients in this function were used to calculate the shear modulus at 10 ms, 50 ms, and 20 s for statistical comparison. The optimal number of terms used in the Prony series was determined using the F-statistic [7]. ANOVA and Bonferroni post hoc tests were used to determine significant differences in the time-dependent shear moduli. A p-value less than 0.05 indicated statistical significance.

S. N. Sundaresh is a PhD student in Biomedical Engineering at Columbia University in New York, NY, USA (Phone +1 212-854-2823, sns2164@columbia.edu). J. D. Finan is a Research Scientist in Neurosurgery at NorthShore University Health System in Evanston, IL, USA. B. Morrison III is an Associate Professor of Biomedical Engineering and Vice Dean of Undergraduate Programs (Engineering) at Columbia University in New York, NY, USA.

III. INITIAL FINDINGS

For each indentation plane, the shear moduli were calculated in the brainstem, hippocampus (CA1, CA3, DG), cerebellum (white and grey matter), cortex (white and grey matter), and thalamus (n = 5-7 for each region). The time dependent moduli were calculated at 10 ms, 50 ms, and 20 s in the aforementioned regions in the sagittal and horizontal planes (Figure 1a, b). Within each plane, there were various statistical differences amongst the regions (Figure 1c, d). The shear moduli of the cerebellum grey and white matter were significantly lower than most regions on both the horizontal and sagittal plane. The thalamus was significantly stiffer than most regions on the horizontal plane. The regions within the hippocampus (CA1, CA3, and DG) did not differ in stiffness on either directional plane.



(c)	BS	CA1	CA3	Cbm G	Cbm W	Ctx G	Ctx W	DG
CA1								
CA3								
Cbm G		*						
Cbm W		*	*					
Ctx G				*	*			
Ctx W								
DG				*	*			
Th	*			*	*			

(d)	BS	CA1	CA3	Cbm G	Cbm W	Ctx G	Ctx W	DG
CA1								
CA3								
Cbm G		*	*					
Cbm W		*	*					
Ctx G				*	*			
Ctx W			*			*		
DG				*	*			
Th	*			*	*		*	*

Fig. 1. Time-dependent moduli for different regions (BS = brainstem, Ctx = cortex, Cbm = cerebellum, DG = dentate gyrus, Th = thalamus, G = grey, W = white) of porcine brain tissue in the (a) sagittal and (b) horizontal planes (mean ± SEM, n = 5-7). Table of statistics using the Bonferroni *post hoc* test in the (c) sagittal and (d) horizontal planes (*$p < 0.05$).

IV. DISCUSSION

We determined that there are regional differences in the shear moduli of pig brain tissue in both the sagittal and horizontal planes. The homogeneity within the hippocampus was previously observed in human tissue [7]. This analysis might be limited by the anisotropy present in different directions within each plane which could be caused by the direction of axonal fiber orientation in white matter. Future work will compare the directional difference in the mechanical properties for each anatomical region. We will also extend this analysis to larger deformations of 30% strain.

V. REFERENCES

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