Mechanical Properties of Male and Female Calvaria in Four-Point Dynamic Impact Bending

Kevin Adanty, Kapil B. Bhagavathula, Karyne N. Rabey, James D. Hogan, Dan Romanyk, Samer Adeeb, Simon Ouellet, Thomas A. Plaisted, Sikhanda S. Satapathy, Christopher R. Dennison

I. INTRODUCTION

Quasi-static bending tests are used to determine the flexural mechanical properties of human calvaria and calvaria surrogate models [1-2]. However, the mechanical properties derived from quasi-static testing may not be appropriately assumed to be comparable to properties for impact. This is because real-world traumatic head impacts observed in military operations, and civilian activities are abrupt and occur at a high-loading rate [3]. To date, limited studies have quantified the mechanical bending properties of calvaria under dynamic impact bending [4]. This loading regime is most pertinent to real-world traumatic head impacts and ought to be considered when validating a calvarium surrogate model for impact biofidelity. The main purpose of this short communication was to report on preliminary findings of the mechanical properties of male and female calvaria subjected to 4-point dynamic impact bending. The following null hypothesis was tested: no significant differences in mechanical and geometrical properties between sex. This work is a critical step forward in our future effort to develop a frangible surrogate model of the calvarium.

II. METHODS

Specimens

This work was approved by the University of Alberta Research Ethics Board (ID: Pro00089218). From 10 embalmed cadavers 5 male (79 ± 11 years old) and 5 female (86 ± 10 years old) frontal calvaria was used for testing. The calvaria center thickness (T) (M: 5.4 ± 0.9 mm; F: 6.8 ± 0.8 mm), center width (M: 8.4 ± 0.4 mm; F: 8.2 ± 0.3 mm), length (L) (M: 52.1 ± 2.4 mm; F: 52.3 ± 1.9 mm), and 2nd moment of inertia (M: 1.3E-10 ± 4.0E-11 m^4; F: 1.9E-10 ± 3.5E-11 m^4) were measured using BoneJ (Fig 1b).

4-Point Bending Impact Experiments

4-pt bending impacts were performed in an effort to create bending for which fracture is attributed to a bending stress as opposed to a complex stress-state containing bending and shear induced in a conventional 3-pt bending test. Impacts were carried out on a guided linear drop tower using custom-built 4-pt impact fixtures (Fig 1a). The velocity of the top impact fixture (mass: 2.62 kg) was 0.86-0.89 m/s, thus, impact kinetic energy was 0.97-1.04 joules. The instrumentation included two piezoelectric force transducers to measure impact force (impact prong 1 and 2) (Fig 1a) and surface-mounted fibre Bragg Gratings (FBGs) to quantify outer (compression) and inner cortical (tension) surface strain (Fig 1b). FBGs are strain transducers embedded within optical guides where strain induced on the FBGs can be quantified based on proportional changes in a Bragg wavelength ($\Delta\lambda_B$). Bending stress was estimated by applying the Euler-Bernoulli beam theorem and its assumptions.

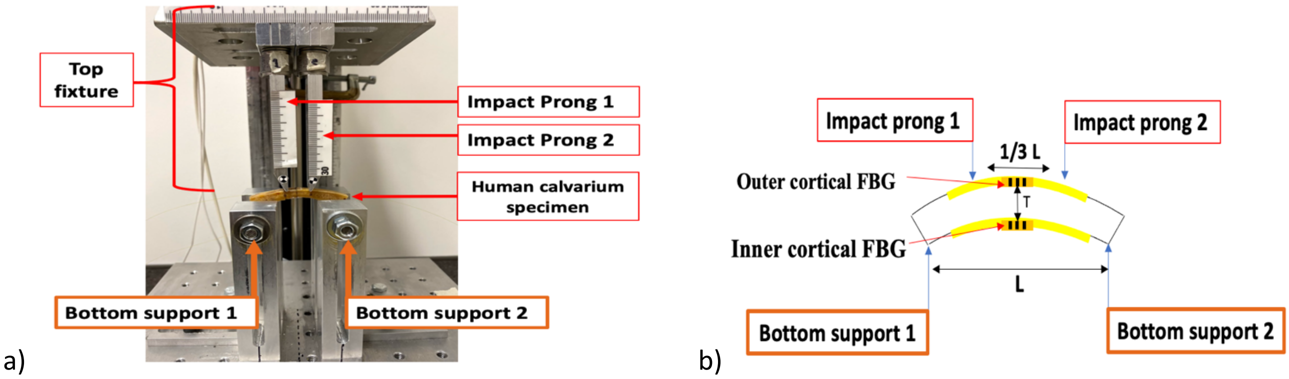

Fig 1. a) 4-pt bending impact. b) 2-D schematic of the surface mounted FBGs on a specimen. The equation to compute strain is: $\mu\varepsilon = \Delta\lambda_B / S_\varepsilon$, where $\mu\varepsilon$ is micro strain and S_ε is the FBG sensitivity (1.21 pm/ $\mu\varepsilon$).

K. Adanty (adanty@ualberta.ca) is a PhD candidate, K. B. Bhagavathula is a PhD candidate, J. D. Hogan is an Assistant Prof., D. Romanyk is an Assistant Prof. and C. R. Dennison is an Associate Prof., all in Mechanical Engineering, University of Alberta, Canada. S. Adeeb is a Full Prof. in Civil and Environmental Engineering, University of Alberta, Canada. K. N. Rabey is an Assistant Prof. in Medicine and Dentistry at the University of Alberta, Canada. S. Ouellet is with Defence Research and Development Canada at Valcartier Research Centre. T. A. Plaisted and S. S. Satapathy are with US Army Combat Capabilities Development Command - Army Research Laboratory.

III. INITIAL FINDINGS

Table 1 presents the preliminary findings on the mechanical properties of the calvaria. An effective bending modulus was estimated at three regions on the stress-strain plot (E1, E2 and E3) (Fig 2) to account for the non-constant strain rates experienced by the calvaria for the duration of the impact. From an independent samples t-test, the 2nd moment of inertia was significantly different between sex ($p<0.05$). There were no significant differences in thickness, length, and width between sex ($p>0.05$). From Table 1, there were no significant differences in mechanical properties between sex ($p>0.05$).

Table 1. Average effective bending moduli (shaded blue) and fracture properties (shaded orange) of the calvaria. ** indicates a Mann-Whitney U-test was performed due to violation of normality.

Mechanical properties	Human: male (SD) N=5	Human: female (SD) N=5	p-value and F-statistic
Tensile modulus (GPa)	E1: 6.46 (3.30) E2: 12.53 (5.86) E3: 16.37 (3.87)	E1: 4.98 (3.86) E2: 11.51 (4.32) E3: 18.16 (11.82)	P=0.535, F=0.914 P=0.763, F=0.393 P=0.756, F=1.939
Compressive modulus (GPa)	E1: 6.88 (3.87) E2: 12.46 (3.45) E3: 20.35 (5.70)	E1: 5.41 (5.40) E2: 11.25 (8.19) E3: 16.53 (4.65)	P=0.700, F=0.701 P=0.819, F=2.781 P=0.564, F=0.001
Compression: Outer cortical surface fracture strain (%)	-0.22(-0.08)	-0.18 (0.13)	P=0.658, F=0.439
Compression strain rate (s^{-1}) for E2	-5.50 (3.22)	-3.23 (1.93)	P=0.284, F=0.297
Tension: Inner cortical surface fracture strain (%)	0.28 (0.04)	0.29 (0.08)	P=0.664, F<0.001
Tension strain rate (s^{-1}) for E2	6.36 (1.85)	5.87 (1.67)	P=0.651, F=0.090
Tensile fracture stress (MPa)	32.42 (5.90)	25.16 (7.11)	P=0.211, F=0.843
Compressive fracture stress (MPa)	31.94 (7.06)	27.00 (7.98)	P=0.421**
Fracture moment (N.m)	1.48 (0.27)	1.56 (0.70)	P=0.841**

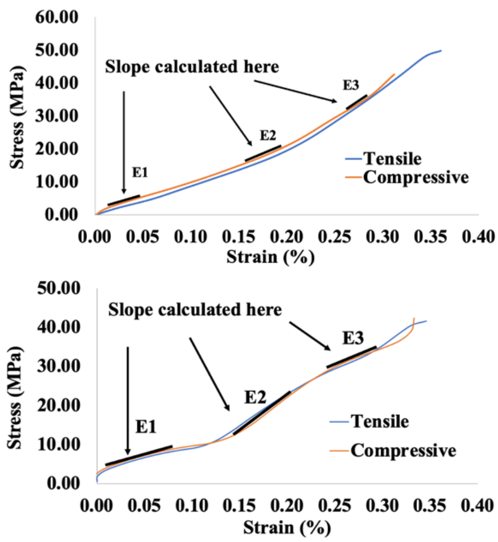

Fig 2. An example of a tensile and compressive stress-strain plot for a male (top) and female (bottom) calvarium.

IV. DISCUSSION

There were no significant differences in mechanical properties between sex, thus, failing to reject the null hypothesis. These early findings may suggest a single calvarium surrogate is sufficient to model head impact or fracture regardless of sex. Though, testing on additional calvaria is required to strengthen this conclusion. Motherway et al. reported a tensile elastic modulus of 4.87 ± 1.93 GPa for 3-pt dynamic bending on fresh-frozen frontal calvaria [4]. This average is comparable to the tensile E1 values reported in the present work (4.98 to 6.46 GPa). They reported a greater tensile rupture stress (102.60 ± 36.20 MPa) compared to the present work (25.16 to 32.42 GPa) which may be attributed to differences in specimen morphology and specimen conditions (i.e. fresh-frozen versus embalmed) [4]. Auperrin et al. reported a lower modulus of elasticity (3.81 GPa) compared to E1, E2, and E3 in this work, however, their study performed 3-pt quasi-static bending on fresh calvaria [1]. Our initial findings are important because they present mechanical properties that can be available as a reference to ensure our future calvarium surrogate model yields comparable moduli and fracture properties during impact.

V. ACKNOWLEDGEMENTS

This research was sponsored by the Army Research Laboratory and was accomplished under Cooperative Agreement Number #: W911NF1920336. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either express or implied, of the Army Research Laboratory or the U.S Government.

VI. REFERENCES

[1] Auperrin A et al, *J Biomech*, 2014.
[2] Roberts J et al, *Front Bioeng Biotech*, 2013.
[3] Van Lierde D et al, *J. Appl. Biomater. Biomech*, 2003.
[4] Motherway, J., et al, *J Biomech*, 2009.