On the Ability of Morphometric Indices of Skull Diploë to Explain Variation in Bone Fracture Force and Fracture Strain in Four-Point Bending: A Preliminary Step Toward A Simulant Fracture Model

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I. INTRODUCTION

The diploë of the calvarium has complex morphometric properties defined by density, porosity and geometrical parameters describing trabecular microarchitecture. It is reasonable to speculate, therefore, that the mechanical response to an external load, and fracture tolerance, of the calvarium, is related to geometric, morphometric and mechanical properties [1-2]. A recent study suggests that ascertaining the correlation between characteristics such as sex, age and morphometry of the human skull with fracture response can advance the development of subject-specific injury (fracture) models [3]. Data for morphometric properties, such as bone mineral density (BMD), porosity and trabecular structure, in addition to mechanical properties, could allow the development of physical surrogates that can effectively model skull fracture [4]. Currently, there is limited data quantifying geometric, morphometric and mechanical properties for diploë in association with fracture [2]. In this study, our objective was to report on preliminary work investigating whether morphometric properties of diploë can predict variation in measurements at fracture using linear regression analyses. We hypothesised that the variability in diploë morphometry can statistically predict the variability in measurements at fracture. This work is part of a broader program on calvarium fracture that comprises the development of simulants on the bases of geometry, morphometry and mechanical properties.

II. METHODS

All protocols were approved by the University of Alberta Research Ethics Board (ID: Pro00089218).

Specimens

From 25 embalmed cadavers (Male: 13; Female: 12), two specimens were extracted from the calvarium using a Mopec autopsy saw, one in the frontal and one in the parietal region (N=50). In this study, we reported on a subset of n=9 male specimens (Age: 81 ± 9 years old) from the parietal region (Fig. 1a)). The average dimensions (mm) of the specimens were bottom length (L): 55.7 ± 1.3, centre thickness (T): 5.5 ± 0.6 and centre width (W): 8.6 ± 0.4 (Fig. 1b), c)). All specimens were free from bone-related disease.

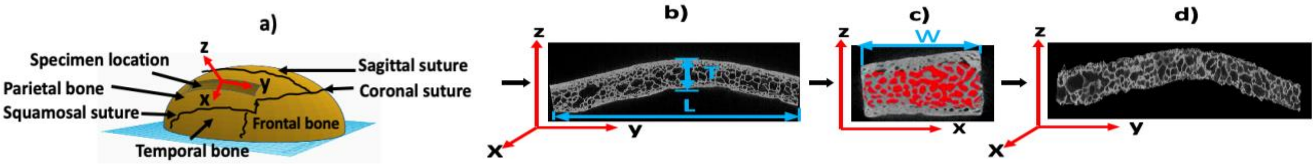

Fig. 1. a) Parietal specimen location on the calvarium. b) Micro-CT scanned specimen. c) Diploë region of interest (ROI) per cross-section (shaded red). d) Resultant diploë volume of interest (VOI) for morphometric analysis.

Micro Computed Tomography (Micro-CT)

Specimens were Micro-CT scanned at a resolution of 18 µm (Bruker-Skyscan 1176) (Fig. 1b)) along with calibration phantoms with known concentrations of calcium hydroxyapatite (HA). Each scan was reconstructed and analysed using CT-Analyser software. Delineating the diploë ROI from the cortical regions was achieved manually on a slice-by-slice basis (Fig. 1c)). In the diploë VOI (Fig. 1d)), the average morphometric variables were determined and used as predictors for linear regression analyses: BMD, porosity, trabecular thickness (Tb.Th), trabecular separation (Tb.Sp) and trabecular number (Tb.N). Tb.Th is the average thickness of trabeculae, Tb.Sp is the average distance between trabeculae, and Tb.N is the average number of trabeculae per mm.

Quasi-Static 4-point Bending

Symmetrical 4-point bending on the specimens were carried out using an Instron E3000 (Fig. 2a)). This configuration generated as close as possible a state of pure bending at the mid-region of the specimens, thus,

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fracture was mainly due to bending stress as opposed to a complex stress-state comprising of both bending and shear. Each test was displacement controlled at 2 mm/min. Two mechanical response variables were measured until fracture and were used as the dependent variables for the linear regression analyses: (1) Outer and inner cortical surface strain (%) using Fiber Bragg Gratings (FBGs); and (2) Force (N) applied by the inner fixtures recorded using a 5 kN Dynacell. FBGs are strain transducers embedded within optical guides. Perturbations on the FBG, such as strain, can be quantified based on proportional changes in a Bragg wavelength ($\Delta\lambda_B$) (Fig. 2b)).

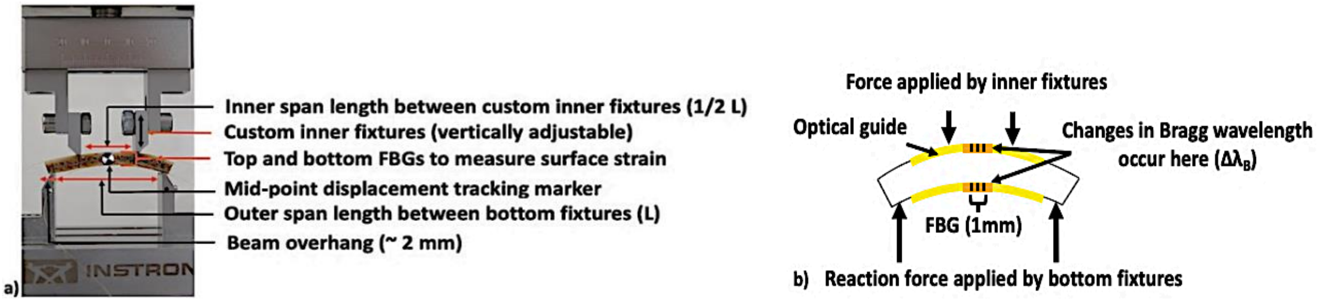

Fig. 2. a) 4-point bending test. b) 2-D schematic of the mounted FBGs on a specimen using cyanoacrylate. Equation to compute strain**:** $\mu\varepsilon = \Delta\lambda_B / S_\varepsilon$ where $\mu\varepsilon$ is micro strain and S_ε is the FBG sensitivity (1.21 pm/ $\mu\varepsilon$).

III. INITIAL FINDINGS

Linear regression analyses (SPSS) determined that Tb.Sp explained 33% and 34% of the variation in outer and inner cortical surface strain (Fig. 3), respectively. 42% and 41% of the variation in fracture force was explained by BMD and porosity, respectively (Figs. 4 and 5). Tb.Th and Tb.N explained less than 30% of the variation in fracture force and strain. None of the regression models in this study was significant, therefore we did not have evidence to reject the null hypothesis, which states that the slopes of the models are equal to zero (p>0.05).

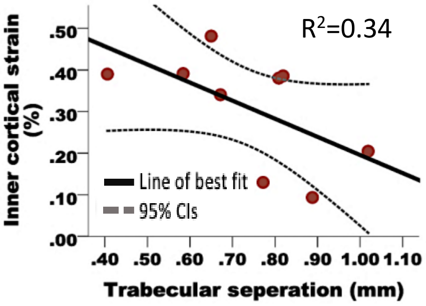

Fig 3. Linear regression model of Inner cortical strain vs. Tb.Sp.

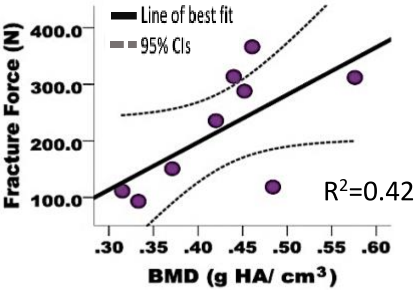

Fig 4. Linear regression model of Fracture force vs BMD.

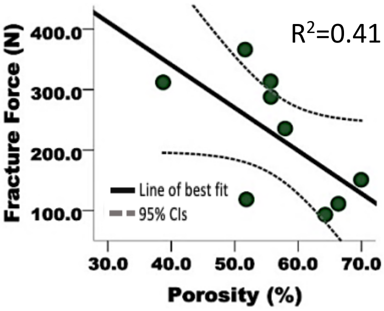

Fig 5. Linear regression model of Fracture force and porosity.

IV. DISCUSSION

Additional experiments leading to larger sample sizes are required to infer whether these regression models explain fracture better than chance. The mean fracture strains (outer: -0.30 ± -0.12% and inner: 0.31 ± 0.13%) are consistent with previous literature, which reported inner cortical strains between 0.33% and 0.76% [5]. In compression tests of cranial bone [2], fracture force scaled with BMD and scaled inversely with porosity. The findings in the present work convey similar scaling relationships. In future work, we will present data that will comprise a greater sample size and embalmed and fresh-frozen tissue loaded at both quasi-static and dynamic rates. This data will inform our efforts to design simulant material models appropriate for skull fracture in impact.

V. ACKNOWLEDGEMENTS

This work was financially supported by US Army Research Labs through contract #: W911NF1920336.

VI. REFERENCES

[1] Wood, J., *J Biomech*, 1971.
[2] McElhaney, J., et al., *J Biomech*, 1970.
[3] De Kegel, D., et al., J *Mech Behav Biomed*, 2019.
[4] Roberts, J., et al., *Front Bioeng Biotech*, 2013.
[5] Hubbard, R., et al., *J Biomech*, 1971.