Large Animal Model of Impact Induced Traumatic Brain Injury: Apparatus Development and Head Mechanics Characterisation

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I. INTRODUCTION

Traumatic brain injury (TBI) is the leading cause of death in people under 45 years and is the most common cause of disability across all age groups [1]. Clinically, most TBIs are caused by head impact without skull penetration [2-3], and animal modelling has shown that rapid rotation of the head causes brain pathology in the absence of skull penetration [4-5]. The mechanism by which head rotation damages the brain tissue is not well understood [2], which limits the development of improved injury prevention strategies and interventions. Large animal models of TBI can be used to explore associations between head biomechanics and resultant brain pathology. Modelling clinically relevant injury mechanisms, and rigorously characterising mechanical inputs and head biomechanics, is crucial for studying injury mechanisms and informing computational modelling [2][5][6]. The aims of this study were to develop and characterise an apparatus for an ovine model of non-penetrating impact induced TBI, and to characterise the resulting head mechanics, using recently deceased sheep.

II. METHODS

A custom elastic energy injury device was developed to provide mechanical insults to the heads of sheep. An impact piston (2.26 kg) with rounded tip (40 mm diameter) was seated in a guiding cylinder (Fig. 1A). Elastic cord (16 mm diameter) was threaded between two mounting plates, one at the rear of the piston, and the other fixed to the guiding cylinder. The piston was retracted with a winch to the desired draw distance, increasing the tension in the shock cord and providing graded nominal impact velocities. The piston was then released to impact the interface plate attached to the head, causing sagittal plane rotation of the head (Fig. 1B-C). The animal was placed on its left side and its head was secured via a bite plate to a planar motion constraint with a fixed axis of rotation (Fig. 1A). An aluminium sensor array (78 g) comprising three angular rate sensors and four tri-axial accelerometers was fixed to the skull, caudal to the bregma, via a mantle of methacrylate resin and unicortical screws. Landmarks on the head and sensor array were digitised to provide head kinematics in an anatomical coordinate system with its origin at the approximate head centre of mass [7] (Fig. 1A). A contoured interface plate of aluminium, steel, and neoprene rubber (526 g) was strapped to the head at the impact site. Impact force was measured with a load cell on the piston. Piston position and velocity were measured with a linear encoder. All sensor data were synchronously acquired at 50 kHz. Two high-speed cameras recorded the impact event at 11 kHz for qualitative analysis. Thirty-eight impact tests were completed on 10 specimens, at three piston draw distances (40%, 60% and 80% shock cord extension). Six specimens received repeated impacts (3-7) of varying severities. Four specimens were impacted once each; subsequent computed tomography (CT) images were obtained to assess cranium damage. Linear mixed-effects models (LMM) were used to assess if apparatus and head mechanics were associated with piston draw distance; Bonferroni-corrected post-hoc pair-wise analyses were performed, and p-values and conditional R^2 are reported. Repeatability of impact velocity and impact force was assessed with coefficient of variation (CoV) analysis.

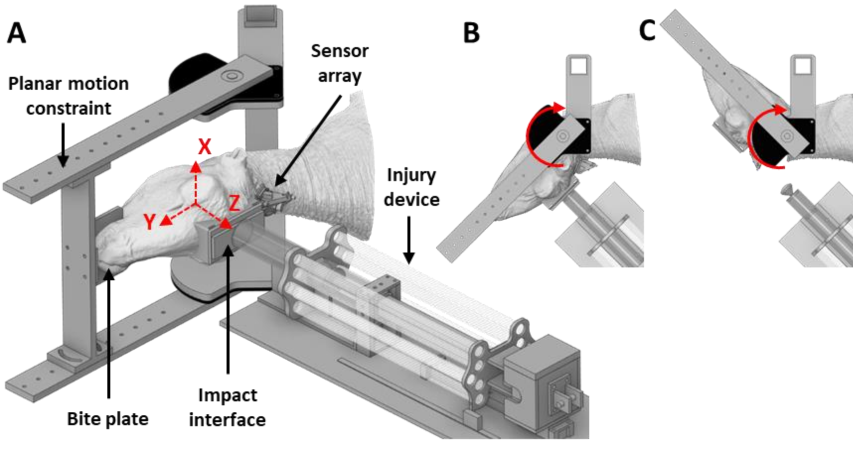

Fig. 1. **A**) Schematic of impact injury model with head mounted in planar constraint and positioned prior to impact. Anatomical coordinate system overlayed in red (dashed). Top view of the injury model, **B**) pre-, and **C**) post-impact. Rotational direction in red.

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III. INITIAL FINDINGS

There were no fractures of the cranial vault in any of the specimens that received a single impact. Head rotation was predominantly in the sagittal plane (exemplar, Fig. 2); the mean (± standard deviation) contribution of peak sagittal velocity and acceleration to peak resultant values 93 ± 7 % and 82 ± 17%, respectively. The relationship between draw distance and impact velocity was linear ($p<0.001$, $R^2 = 0.986$) (Fig. 3A). Similarly, linear relationships were observed between draw distance and impact force ($p<0.001$, $R^2 = 0.722$) (Fig. 3B), and peak resultant angular velocity ($p<0.001$, $R^2 = 0.586$) (Fig. 3C). Impact velocity CoV was 5.3%, 4.2%, and 3.0% at 40%, 60%, and 80% draw distance, respectively. Mean impact force intra-animal CoV was 9.4% (across all draw distances) and inter-animal CoV was 17.0%, 9.1%, and 27.0%, at 40%, 60%, and 80% draw distance, respectively.

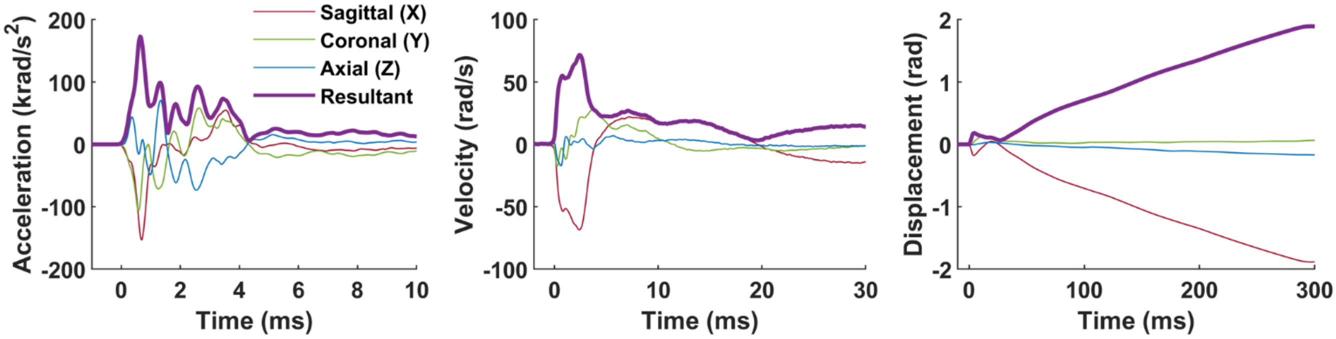

Fig. 2. Exemplar head angular acceleration, velocity, and displacement in anatomical coordinate system, versus time, for 60% draw distance, with a piston impact velocity and impact force of 11.7 m/s and 21.3 kN, respectively. Acceleration and velocity trace timescales trimmed to impact event; displacement trace shows full head motion. Sagittal, coronal, axial direction and signs are defined as rotations about the X, Y and Z axes, respectively.

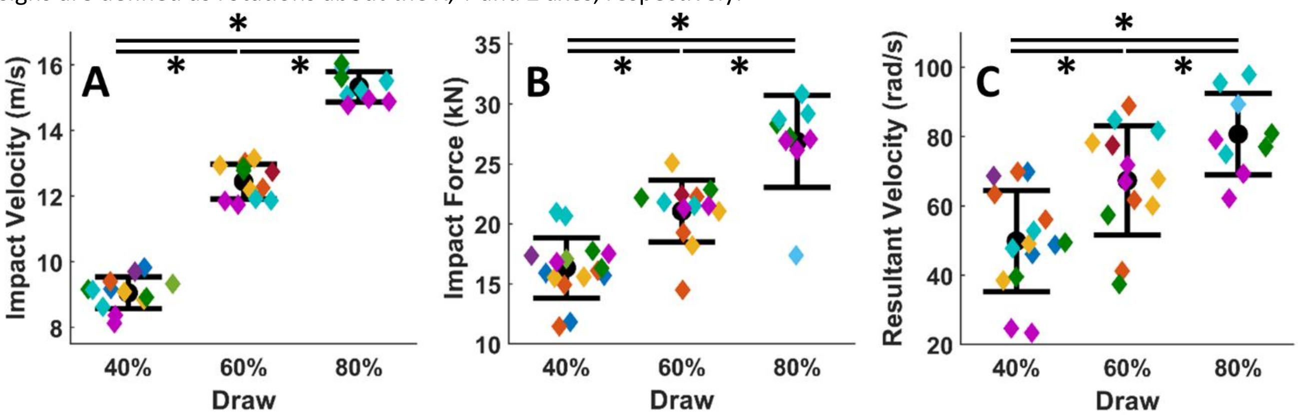

Fig. 3. Scatter plots of piston impact velocity (**A**), impact force (**B**) and peak resultant angular velocity of the head (**C**). Black circle and whiskers are mean and standard deviation, respectively. Diamonds are single impacts coloured by specimen. * indicates p < 0.05 for pair-wise post-hoc comparisons.

IV. DISCUSSION

The apparatus produced high-rate head impacts without penetrating the skull, as required for a non-penetrating impact model of TBI. The planar constraint apparatus restricted, but did not eliminate, non-sagittal plane rotations of the head. Impact velocity was linearly related to draw distance and was repeatable. Impact force and peak head angular velocity were also positively associated with draw distance but had greater variation than impact velocity. Further evaluation of the apparatus will be conducted with anaesthetised sheep to determine the pathological outcomes in this proposed head impact model.

V. REFERENCES

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