How does Pre-impact Head Rotation affect Impact-induced Brain Strain?

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I. INTRODUCTION

Rotation-induced brain strains are thought to be an important mechanism of concussive brain injury [1]. The brain's relatively large inertia and low shear stiffness mean that rapid skull rotations during a head impact create differential rotation both between the skull and brain and between superficial and deep regions of the brain. Differential motion within the brain can stretch axons and other neuronal structures, which can then experience transient or permanent dysfunction. Rapid head rotations can also develop immediately before a direct head impact in car crashes [2] and football contacts [3]. The effect of these pre-impact head rotations on the resulting impact-induced brain strain has not been well studied, and thus our goal was to explore how pre-impact head rotation affects the brain strain that develops during a subsequent head impact.

II. METHODS

We relied on a single-degree-of-freedom (sDOF) mechanical model linking skull rotational kinematics to maximum principal strain (MPS) in the brain [4]. This model is essentially a uni-axial component of the Diffuse Axonal, Multi-Axis, General Evaluation (DAMAGE) metric [5], and its closed-form solution permits a simple parametric exploration of different impact scenarios with no loss of generality. The model's response correlates better than other rotational kinematic-based injury metrics with MPS (95^{th} percentile) predicted by a finite-element (FE) model [4]. The skull input kinematics we used consisted of three sequential half-sinusoid pulses (see P1, P2 and P3 in Fig 1a). P1 was a long-duration *pre-impact* angular acceleration in one direction, followed by P2, a short-duration *impact* angular acceleration in the opposite direction, followed by P3, a long-duration *recovery* angular acceleration in the same direction as P1. The position and speed of the model's brain with respect to the skull at the end of one input pulse served as its initial conditions at the start of the next input pulse. One oscillation of free vibration was added after P3 to ensure that the model's maximum response was captured.

The peak amplitude and duration of each input pulse was based on prior work. Peak P1 accelerations were chosen to reach peak angular velocities observed before ground contact in football head impacts (mean 14 rad/s, range 5 to 54 rad/s) over durations up to 100 ms [3]. We considered a range of peak P2 accelerations (0 to 13 krad/s^2) and velocity changes (0 to 80 rad/s) to characterise the baseline response [4], but focused the pre-rotation analyses presented here on a P2 pulse with a peak amplitude of 5.0 krad/s^2 and duration of 13 ms, which generated a 42 rad/s speed change [6] (see red dot in Fig 1e). Peak P3 acceleration was set to one-quarter of the peak P2 acceleration to ensure peak model response was generated by the impact pulse and not the recovery pulse. The duration of P3 was adjusted to return the skull's angular velocity to zero.

All analyses were performed using the natural period (44.9 ms), damping ratio (0.466), and scale factor (2.59) previously optimised to fit FE-predicted MPS's about the mediolateral (y) axis [4]. We first calculated MPS's with no pre-impact rotation (Base condition). We then added pre-impact skull rotation but assumed no restitution effects on P2 acceleration or duration (condition R0). We then added restitution (e=0.20 [7]) and increased peak P2 acceleration to increase the P2 angular velocity change ($\Delta\omega_2$) in proportion to the terminal angular velocity of P1 (ω_1). Since the skull's velocity change during impact depends on both the restitution and the inertia of the object it strikes, we considered two cases: two similar objects colliding, i.e., a head-to-head impact, where $\Delta\omega_2$ equals $((1+e)/2)\cdot\omega_1$ (condition RA), and a barrier or ground impact where $\Delta\omega_2$ equals $(1+e)\cdot\omega_1$ (condition RB). For the three pre-rotation conditions (R0, RA and RB), we considered terminal angular velocities from ω_1=0 to 60 rad/s developing over 100 ms or less [3].

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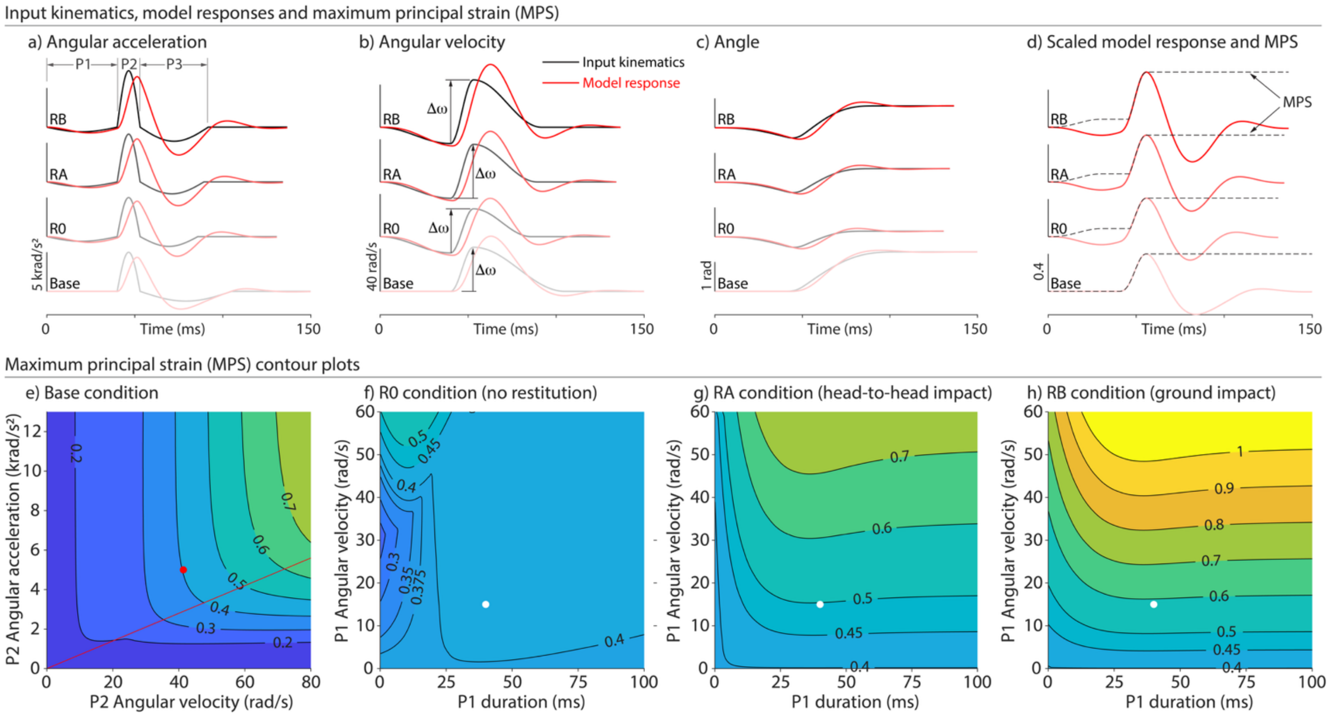

Fig. 1. Skull input kinematics and model responses (a-d) and MPS (d-h) for the baseline condition with no pre-impact rotation (Base condition) and for the three conditions with pre-impact rotation (no restitution - R0 condition), head-to-head impact (RA condition), and head-to-ground impact (RB condition). Individual graphs show: (a) angular acceleration, (b) angular velocity, and (c) angular position of the skull (black lines) and model response (red lines) for each condition; (d) scaled model responses and MPS (dashed line) in each condition; and (e) MPS for different combinations of peak angular acceleration and peak angular velocity with no pre-impact rotation. The red dot depicts the Base condition (P2: 5 krad/s^2, 42 rad/s, 13 ms) shown in the top graphs. The red line depicts the natural period of the sDOF system (44.9 ms). For the Base condition, the MPS's that develop for different combinations of pre-impact (P1) angular velocities and pulse durations are shown in (f) without restitution, (g) with restitution in head-to-head impacts, and (h) with restitution in head-to-ground impacts. The white dots depict the pre-rotation condition (P1: 15 rad/s, 40 ms) shown for R0, RA and RB in the top graphs.

III. INITIAL FINDINGS

The Base condition (P1: absent; P2: 5 krad/s^2, 42 rad/s, 13 ms, Fig 1a-d) generated an MPS of 0.40 (red dot, Fig 1e). Adding pre-impact rotation increased the peak kinematics and MPS (Fig 1a-d), except for short duration P1 pulses (<25 ms) when ignoring restitution (Fig 1f). Adding pre-impact rotation of 42 rad/s developed over 40 ms to the Base condition without including restitution only increased MPS from 0.40 to 0.41 (white dot, Fig 1f). Accounting for restitution in a head-to-head impact increased MPS to 0.50 (white dot, Fig 1g), and accounting for restitution in a head-to-ground impact further increased MPS to 0.59 (white dot, Fig 1h).

IV. DISCUSSION

Using a previously validated sDOF model linking skull input kinematics to MPS, we found that simply adding pre-impact rotation to the model without considering restitution, i.e., with considering how pre-impact rotation increases the subsequent impact severity, had only a small effect on MPS for pre-impact rotations that developed over periods greater than 25 ms. When the potential effects of restitution are included, however, MPS generally increases with increasing levels of skull angular velocities at impact. While further work is needed using kinematic data from more realistic multi-axial impacts, these initial results suggest that pre-impact rotation in isolation has less effect on MPS than the increased impact-related angular velocity change ($\Delta\omega$ in Fig 1b) it can generate due to restitution effects and a higher initial impact velocity.

V. REFERENCES

[1] Kleiven, Frontiers Bioeng Biotech, 2013.
[2] Siegmund *et al.*, Traffic Inj Prev, 2005.
[3] Kent *et al.*, J Biomech, 2020.
[4] Gabler L *et al.*, J Biomech Eng, 2018.
[5] Gabler L *et al.*, Ann Biomed Eng, 2019.
[6] Bonin S *et al.*, IRCOBI, 2018.
[7] DeMarco A *et al.*, Accid Anal Prev, 2016.

Note: No AI agents were used in this research project.