Assessment of Head Injury Mechanisms in Side Impacts considering Posture, Anthropometry and Loading Conditions

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I. INTRODUCTION

Side-impact injury outcome depends on multiple interlinked factors, including loading configuration, occupant anthropometry and seating posture. Current evaluation procedures typically assess occupant protection using nominal upright seating positions and limited occupant representations, while real-world occupants frequently adopt alternative postures and present significant variability in size and geometry. Previous studies have shown that both occupant posture and anthropometry influence kinematics and injury outcome in side impacts [1-4]. In addition, barrier and pole impacts generate different loading conditions, leading to distinct load transfer mechanisms and occupant responses [5]. However, these factors are often investigated independently, while their combined influence on injury mechanisms remains less explored. Human body models (HBMs) allow simultaneous assessment of anatomical response and restraint interaction across multiple occupant conditions [1-2]. The objective of this study is to perform a multifactor assessment of head injury mechanisms considering seating posture, occupant anthropometry and lateral loading configuration using HBMs.

II. METHODS

A generic finite element (FE) vehicle subsystem model representing a C-segment SUV structure was used. The model included deformable side structures, interior trim components, seat and an integrated restraint system consisting of a head-thorax side airbag and a seat-integrated three-point seat belt with pretensioner and load limiter. The deployment time-to-fire for both systems was set to 6 ms. Simulations were performed using LS-DYNA version R13.1.0. Three THUMS HBMs were used to represent anthropometry variability: a 50th percentile male (AM50); a 50th percentile female (AF50); and a 5th percentile female (AF05). Models were positioned using gravitational settling prior to impact. Three seating configurations were evaluated: a nominal seating posture with a 21° seat-back angle (Scenario 0); a reclined posture with a 35° seat-back angle (Scenario 1); and a reclined posture with a 45° seat-back angle combined with 120 mm rearward seat displacement (Scenario 2). Each configuration was evaluated under Euro NCAP side barrier and oblique pole impact conditions (Fig. 1). A total of 18 simulations were performed.

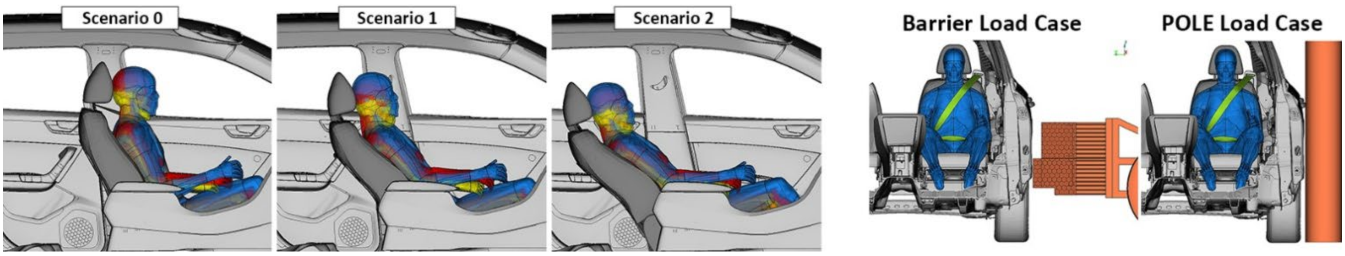

Fig. 1. *Left:* side-impact scenarios (left). *Right:* AE-MDB Barrier and Oblique Pole Load Case with THUMS AM50.

Several metrics were used to assess traumatic brain injury (TBI). Criteria based on linear head kinematics were considered, including the Head Injury Criterion calculated over a 15 ms time interval (HIC15) and the 3 ms resultant head acceleration (a3ms cumulative). In addition, metrics based on rotational head kinematics were used, including the Diffuse Axonal Multi-Axial General Evaluation (DAMAGE) [6] and the Universal Brain Injury Criterion (UBrIC) [7]. Brain tissue response was further evaluated using strain-based measures, including the 95th percentile Maximum Principal Strain (MPS-95) and the Cumulative Strain Damage Measure (CSDM). Furthermore, for the AF05 and AF50 female models, DAMAGE and UBrIC criteria were adapted following the approach proposed by Reynier *et al.* [4], resulting in the DAMAGE-AF05 and UBrIC-AF05 metrics.

III. INITIAL FINDINGS

Head injury metrics were evaluated using criteria based on linear head kinematics, rotational head kinematics and strain-based measures (Fig. 4). For linear head kinematics, HIC15 values ranged from 87.9 to 277.8 in barrier impacts and from 157.2 to 321.3 in pole impacts, while the 3 ms resultant head acceleration (acc3ms) ranged

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between 28.7 g and 50.2 g for barrier impacts and between 35.4 g and 65.1 g for pole impacts. Rotational head kinematic criteria showed DAMAGE values (including DAMAGE-AF05) between 0.162 and 0.291 in barrier impacts and between 0.190 and 0.553 in pole impacts, and UBrIC values (including UBrIC-AF05) between 0.186 and 0.269 in barrier impacts and between 0.244 and 0.461 in pole impacts. Strain-based measures showed MPS-95 values ranging from 0.936 to 1.369 in barrier impacts and from 1.076 to 1.702 in pole impacts, while CSDM values ranged from 0.781 to 0.876 and from 0.852 to 0.945 for barrier and pole impacts, respectively. Representative head trajectories for selected AM50 and AF05 configurations are shown for illustration purposes in Figs. 2 and 3.

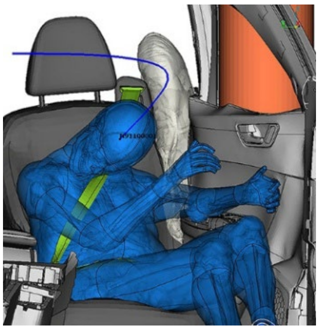

Fig. 2. Head trajectory of the AM50 model in Pole-Sc_0 (maximum DAMAGE/UBrIC values).

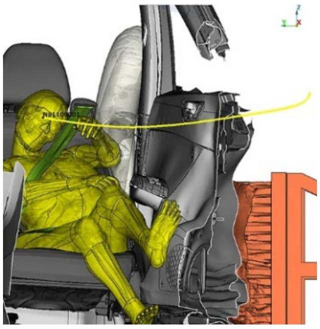

Fig. 3. Head trajectory of the AF05 model in Barrier-Sc_2 (maximum linear head acceleration in Barrier LC).

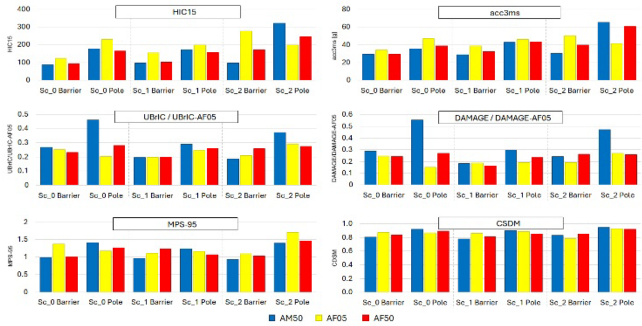

Fig. 4. Comparison of head injury metrics based on linear, rotational and strain-based criteria for all analysed configurations.

	HIC36	a3ms	UBrIC	DAMAGE	MPS-95	CSDM
HIC36	1.00					
a3ms	0.99	1.00				
UBrIC	-0.06	-0.05	1.00			
DAMAGE	-0.25	-0.25	0.80	1.00		
MPS-95	0.13	0.21	0.13	-0.27	1.00	
CSDM	-0.14	-0.03	0.32	0.34	0.42	1.00

	HIC36	a3ms	UBrIC	DAMAGE	MPS-95	CSDM
HIC36	1.00					
a3ms	0.89	1.00				
UBrIC	0.12	-0.08	1.00			
DAMAGE	0.23	0.03	0.99	1.00		
MPS-95	0.30	0.12	0.42	0.39	1.00	
CSDM	0.58	0.40	0.64	0.66	0.83	1.00

very strong
strong
moderate
weak
negligible
very poor
inconsistent

Fig. 5. Relationship between injury metric (based on Pearson correlation coefficients). *Left:* Barrier. *Right:* Pole.

IV. DISCUSSION

The results highlight the importance of considering multiple head injury assessment criteria when evaluating occupant protection in side impacts. Criteria based on linear head kinematics (HIC15 and acc3ms) showed consistent agreement across configurations and indicated responses compatible with acceptable protection levels; however, rotational and strain-based metrics showed additional differences related to loading condition, seating posture and occupant anthropometry. Correlations were strong within each metric family, while relationships between linear, rotational and strain-based approaches were less consistent. These relationships are summarised in Fig.5, which presents correlations at the metric-family level. In barrier impacts, similar levels of linear head acceleration were not always associated with comparable rotational responses or strain-based measures, indicating that different criteria did not consistently identify the same configurations as critical. Similar behaviour was observed in pole impacts, where increases in linear metrics were not systematically accompanied by proportional changes in rotational or strain-based measures. Differences between occupant models were also observed, with higher strain levels frequently identified for the AF05 model in several barrier configurations, while the highest rotational and strain responses for the AM50 model were observed in pole impacts. These observations suggest that a restraint system tuned to meet regulatory performance targets for an upright AM50 occupant may not produce equivalent biomechanical responses across different occupant sizes and seating postures when evaluated using rotational and strain-based criteria. Rather than indicating inadequate protection, the results emphasise that the use of linear acceleration-based metrics alone may not fully capture variations in head injury response across realistic occupant conditions, supporting the inclusion of complementary rotational and strain-based metrics [8] for a more comprehensive assessment of head injury mechanisms in side impacts.

V. REFERENCES

[1] Leledakis, A., *et al.*, *Accid Anal Prev*, 2021.
[2] Piqueras, A., *et al.*, *Front Bioeng Biotechnol*, 2023.
[3] Atwood, J., *et al.*, *Traffic Inj Prev*, 2023.
[4] Reynier, K. A., *et al.*, *IRCOBI*, 2022.
[5] Yoganandan, N., *et al.*, *Traffic Inj Prev*, 2015.
[6] Gabler, L. F., *et al.*, *Ann Biomed Eng*, 2019.
[7] Gabler, L. F., *et al.*, *Ann Biomed Eng*, 2018.
[8] Mueller, B. C., *et al.*, *IRCOBI*, 2025.