Experimental Assessment of Head Injury Mechanisms in Urban Falls of Vulnerable Road Users

Beatriz Juanes, Susana Escalante, Mónica Diez, Caroline Deck, Nicolas Bourdet

I. INTRODUCTION

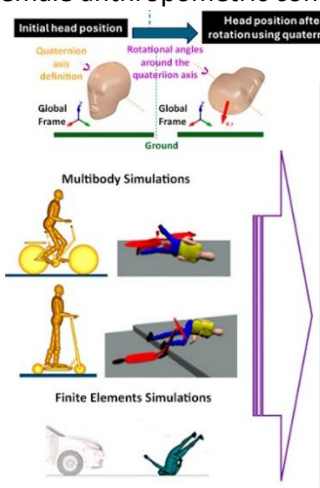
Head injuries remain a major challenge in road traffic safety, contributing substantially to mortality and long-term consequences (LTCs). Vulnerable road users (VRUs), such as pedestrians, cyclists and personal mobility device users, are particularly exposed due to the lack of structural protection [1-2]. Accident data indicate that head contact with the ground, often occurring as a secondary impact, plays a key role in injury outcome, especially in low-velocity urban scenarios commonly associated with LTCs [3-4].

Experimental data on head kinematics under realistic ground impact conditions are needed to achieve a more comprehensive representation of real-world impacts, where head response is driven by combinations of impact angle, velocity, and contact location.

Within this context, and as part of the EU-funded ProtAct-Us Project (Grant No. 101147445), this study presents an experimental methodology to reproduce head impact conditions derived from accident reconstructions of VRUs. Simulation-derived boundary conditions are used to define impact velocity and orientation, enabling controlled headform tests under realistic configurations. The resulting linear accelerations and angular velocities provide datasets to support the development of injury assessment methods and countermeasures for VRUs.

II. METHODS

Numerical simulations were performed to reproduce the most representative accident scenarios associated with LTCs, identified from prior accident data analysis [5, 6]. These included single-vehicle incidents (bicycles and micro-mobility users) due to loss of balance on straight roads, as well as car–pedestrian collisions with secondary head impacts against the ground. From these simulations, head kinematic boundary conditions immediately prior to ground impact were extracted and used as input for the experimental campaign (Fig. 1), for both male and female anthropometric configurations.



		Head orientation in the global frame				Head velocity in the global frame after repositioning			Head resultant velocity	Head normal velocity	Head tangential velocity	GENDER	Head impact area
		Rotation angle around the quaternion axis	Quaternion axis definition in the global frame			(m/s)			(m/s)	(m/s)			
	CASE_RESULTS	Q-angle (degrees)	Q-axis_x	Q-axis_y	Q-axis_z	V_x	V_y	V_z	V_r	V_n	V_t	GENRE	ZONES
Bicyclists	BkHole_ID001	123	0.70	0.68	0.20	2.1	-1.3	-4.4	5.0	4.3	2.6	MALE175-80	Lateral
	BkHole_ID002	130	0.88	0.36	0.31	-0.7	-2.2	-2.4	3.3	2.5	2.2	FEMALE162-65	Lateral
	BkHole_ID003	96	0.54	0.73	0.42	0.9	-1.0	-5.3	5.5	5.2	1.6	MALE175-80	Facial
	BkCurb_ID001	145	0.76	0.20	0.61	0.6	-2.7	-3.4	4.4	3.3	3.0	MALE175-80	Occipital
	BkCurb_ID002	105	0.78	0.46	0.43	0.4	-1.2	-4.0	4.2	4.0	1.4	FEMALE162-65	Lateral
	BkCurb_ID003	133	-0.18	0.85	0.49	1.7	-0.9	-1.4	2.4	1.4	1.9	MALE175-80	Frontal
	BkCurb_ID004	137	0.50	0.85	0.16	0.4	0.0	-1.3	1.4	1.3	0.5	FEMALE162-65	Vertex
	BkCurb_ID005	112	0.09	0.92	-0.38	1.0	0.2	-2.3	2.6	2.4	1.0	MALE175-80	Frontal
	BkCurb_ID006	111	0.99	-0.15	0.05	3.5	-0.3	-3.5	5.0	3.6	3.5	FEMALE162-65	Lateral
e-mobilities	ScPavement_ID002	114	0.09	0.90	0.42	1.5	0.5	-5.2	5.4	5.3	1.3	MALE175-80	Frontal
	ScPavement_ID003	146	-0.45	0.69	-0.57	1.4	-0.4	-4.4	4.6	4.1	2.2	MALE175-80	Lateral
	ScPavement_ID004	173	-0.70	0.25	-0.67	1.9	0.5	-5.0	5.4	5.0	1.9	FEMALE162-65	Occipital
	ScPavement_ID005	125	0.63	0.57	0.54	1.5	-0.3	-5.0	5.2	4.7	2.3	FEMALE162-65	Lateral
	ScPavement_ID006	150	-0.65	0.44	-0.62	2.3	-0.2	-5.2	5.7	5.2	2.3	FEMALE162-65	Lateral
	ScPavement_ID008	96	-0.04	0.87	0.49	2.2	1.3	-6.7	7.2	4.8	5.4	MALE175-80	Facial
	ScPavement_ID011	109	0.45	0.72	0.53	1.0	0.9	-6.1	6.2	4.6	4.1	FEMALE162-65	Facial
	ScPavement_ID012	164	-0.62	0.46	-0.64	2.3	-0.8	-5.9	6.4	5.4	3.4	FEMALE162-65	Occipital
	ScPavement_ID013	148	-0.40	0.89	-0.20	2.5	0.2	-5.0	5.6	4.3	3.5	MALE175-80	Lateral
	ScPavement_ID016	117	-0.12	0.98	-0.15	3.1	0.2	-5.4	6.2	6.0	1.8	FEMALE162-65	Vertex
Pedestrian	PdGround_ID004	110	-0.88	-0.28	0.39	4.5	0.9	-4.3	6.2	5.9	2.1	MALE	Occipital
	PdGround_ID005	133	-0.63	-0.77	-0.02	6.2	0.3	-3.3	7.0	5.1	4.8	FEMALE	Vertex
	PdGround_ID010	91	-0.10	0.98	0.19	3.3	0.2	-4.5	5.6	5.6	0.1	MALE	Lateral
	PdGround_ID019	117	0.44	-0.89	-0.13	4.3	-1.5	-5.3	7.0	6.2	3.2	MALE	Frontal
	PdGround_ID020	142	0.43	-0.90	-0.06	5.2	-1.8	-4.8	7.3	4.4	5.8	FEMALE	Vertex
	PdGround_ID025	119	-0.59	0.57	-0.57	6.1	-1.4	-3.9	7.4	6.5	3.5	MALE	Lateral
	PdGround_ID028	162	-0.63	0.70	-0.35	6.9	-1.2	-2.6	7.5	2.4	7.2	MALE	Vertex
	PdGround_ID029	130	-0.45	0.90	0.01	6.6	-1.1	-3.3	7.5	5.8	4.8	FEMALE	Vertex

Fig. 1. Simulation-derived boundary conditions for the experimental matrix.

Tests consisted of vertical drop impacts performed using instrumented Hybrid III 50th percentile male and 5th percentile female headforms onto a Stone Mastic Asphalt surface (SMA8, 6.5% bitumen). A highly controlled positioning of the headform and surface, together with a magnetic release system, ensured good test repeatability, evaluated across four identical tests with coefficients of variation (CV) below 4% for all assessed biomechanical metrics. The headform and impact surface were rotated to align the resultant impact velocity vector with the vertical axis, preserving the kinematic conditions derived from simulations (Fig. 2). This set-up simultaneously captures both the angular and linear motions of the head. The high repeatability of these tests enables the assessment of different impact surfaces and protective systems, to analyse various materials and strategies as potential countermeasures for head protection under this type of impact.

B. Juanes (e-mail: beajua@cidaut.es), S. Escalante and M. Diez are vehicle safety engineers in the Vehicle Safety department at CIDAUT Foundation (Investigación y Desarrollo en Transporte y Energía), Valladolid, Spain. C. Deck and N. Bourdet are researchers at the University of Strasbourg, France.

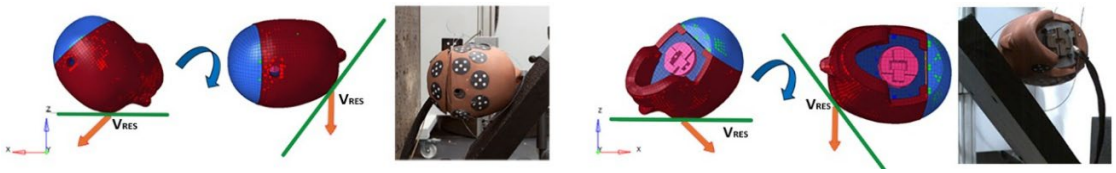
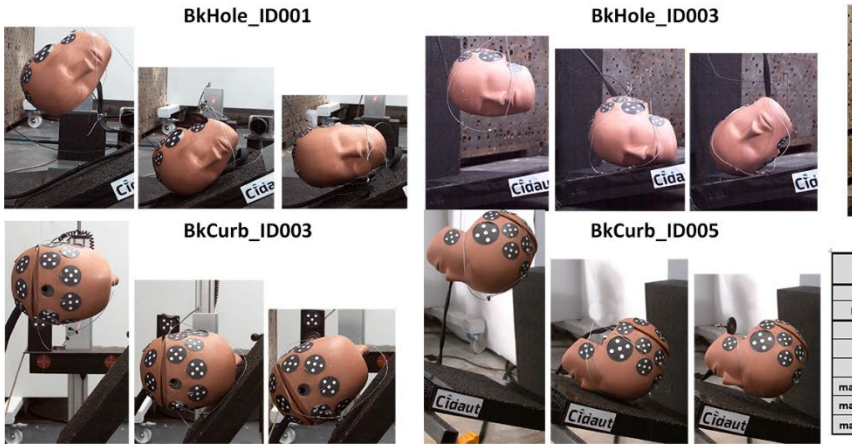


Fig. 2. Headform oblique impact test set-up definition.

Instrumentation included tri-axial accelerometers and angular rate sensors located at the head centre of gravity, with data acquired at 20 kHz. Laboratory temperature was controlled between 20 ºC ± 4 ºC. Signal processing followed SAE J211/1 [7] recommendations. Head response was assessed using four injury metrics: Peak Linear Acceleration; Peak Angular Velocity; Head Injury Criterion (HIC); and Diffuse Axonal Multi-Axis General Evaluation (DAMAGE).

III. INITIAL FINDINGS

Initially, impact tests for male bicyclist cases were conducted at CIDAUT facilities. Figure 3 illustrates the kinematics, including the initial head impact location, the instant of impact, and the subsequent head rebound. The corresponding linear and rotational head injury metrics measured on the headform, as well as the real test impact conditions for each case, are also presented.



CASE RESULTS	BkHole_ID001	BkHole_ID003	BkCurb_ID001	BkCurb_ID003	BkCurb_ID005
V (m/s)	5.3	5.6	4.4	2.3	2.8
Floor Angle	29.3	14.2	39.1	54	23.9
Acc3ms (g)	33.1	68.3	44.4	33.1	42.9
HIC15	2021.4	1210.1	1134.5	72.5	143.7
Damage	0.18	0.39	0.03	0.28	0.1
max AVX (rad/s)	19.9	39.3	4.1	14.4	4.1
max AVY (rad/s)	1.9	12.2	5.4	1.9	5.4
max AVZ (rad/s)	9.5	20.9	7.6	20.3	7.6

Fig. 3. Male bicyclist cases: kinematics and table, including impact conditions and head injury metrics.

IV. DISCUSSION

In this study, drop head impact tests were designed to reproduce both the angular and linear motions using a simple, repeatable set-up, which is critical for simulating impacts in VRU to ground impacts. Different impact locations, angles and velocities, were reproduced. Hybrid III 50th and 5th percentile headforms provide a standardized and widely used framework in automotive safety research, enabling consistent comparison of impact severity across conditions and population profiles. Although these surrogates do not fully reproduce human head response or global anthropometric variability, they represent a reasonable simplification for this initial study and establish a robust baseline for evaluating contact surfaces. Initial results indicate that rotational injury criteria are highly sensitive not only to impact angle but also to the initial head contact location, which directly influences rotational kinematics. Further testing will expand the experimental matrix, to systematically assess the influence of impact angle, head kinematics, and contact location on both linear and rotational injury metrics across male and female anthropometric configurations. This approach will enable a more comprehensive characterisation of head injury mechanisms in ground impact scenarios and the evaluation of potential countermeasures.

V. ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No. 101147445.

VI. REFERENCES

[1] WHO, 2023.
[2] EC, 2025.
[3] Sang, *et al*., *Accid Anal Prev*, 2018.
[4] ITF, 2024.
[5] Deliverable 1.2 of the ProtAct-Us project, 2025.
[6] Jänsch, et al., IRCOBI, 2025.
[7] SAE International, J211/1, 2022.

B. Juanes (e-mail: beajua@cidaut.es), S. Escalante and M. Diez are vehicle safety engineers in the Vehicle Safety department at CIDAUT Foundation (Investigación y Desarrollo en Transporte y Energía), Valladolid, Spain. C. Deck and N. Bourdet are researchers at the University of Strasbourg, France.