Can bicycle helmets mitigate severe head injuries in high-speed e-bike accidents?

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I. INTRODUCTION

Head injury remains a critical and growing public health concern. In Sweden, head injuries sustained by cyclists are disproportionately likely to result in permanent medical impairments compared to other trauma types [1]. On a broader scale, head trauma represents the leading cause of death among young adults in Europe, with a tragically rising incidence rate among the elderly demographic [2].

The rapid global adoption of electric bicycles (e-bikes) has altered head kinematics by introducing higher impact velocities. In Sweden, e-bikes operate at elevated sustained speeds, averaging 16.9 ± 2.9 km/h [3]. Despite this, biomechanical research evaluating available helmets for e-bike riders remains critically limited. Current standards (e.g., NTA 8776) rely on linear vertical drops up to 6.5 m/s, leaving a gap in evaluating oblique impacts representative of pedelec crashes. Furthermore, the Hybrid III headform used in current protocols exhibits biofidelity limitations due to unrepresentative moments of inertia and surface tribology [4]. To bridge this gap, this study investigates helmet performance under boundary conditions (6.0 and 7.6 m/s oblique impacts at four locations) that better reflect severe e-bike crash kinematics, utilising a headform with improved biofidelity.

II. METHODS

Headform: impacts utilised the EN 17950 headform (570 mm, Humanetics), which features human-representative geometry, moments of inertia, and surface friction to mitigate the rotational overestimate [5]. The coefficient of friction of the headform (0.30 ± 0.03) was verified before testing according to SS EN 17950:2024 strap-pull methodology. Kinematics were recorded at 20 kHz via an embedded 6DOF sensor along with a wireless acquisition system and were transformed to the headform's centre of gravity and filtered at CFC 180 (ISO 6487).

Helmets: a cohort of eight representative bicycle helmets, widely available in Sweden, was selected to maximise the translational impact of this research (Figure 1). Informed by recent literature review [6] and consultations with industry experts, the inclusion criteria prioritised high-sales-volume models across a wide price spectrum, systematically encompassing various advanced rotational protection technologies, alongside two expanded polystyrene (EPS)-only helmets acting as control references for the comparative analysis.

Figure 1. The eight bicycle helmets tested in this study, equipped: MIPS (1–4), KinetiCore (5–6), and EPS-only (7–8).

Impact set-up: a total of 128 impact tests were conducted at the KTH Royal Institute of Technology, using a guided free-fall drop rig. The inverted headform struck a 45° angled anvil, an established configuration for oblique impacts [7]. The test matrix evaluated the eight helmet models across four impact locations (side/pXR, front/pYR, rear/nYR, and front-side/pZR; Figure 2) at two initial velocities (6.0 m/s and 7.6 m/s). The four impact locations were divided between two helmet samples per model (pXR/pZR and pYR/nYR), with two repetitions per condition.

Data analysis: experimental kinematics were prescribed to the KTH head model [8] to analyse the brain response. A total of 64 simulations were executed in LS-DYNA, representing the full experimental matrix of eight helmets, four impact locations, and two initial velocities. All simulations lasted 30 ms. Head injury metrics (including Peak Linear Acceleration (PLA), Peak Angular Velocity (PAV), Head Injury Criterion (HIC), Brain Injury Criterion (BrIC), Diffuse Axonal Multi-Axis General Evaluation (DAMAGE) and Maximum Principal Strain (MPS)) were used to evaluate the brain response during oblique impacts [4].

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III. INITIAL FINDINGS

Figure 3 details the injury metrics across all tested configurations. While increased kinetic energy predictably escalated both kinematic and tissue-level trauma (e.g., overall mean PLA rose from 106 ± 16 g to 137 ± 21 g, PAV from 20.7 ± 5.1 rad/s to 25.7 ± 5.4 rad/s, and MPS from 0.17 ± 0.04 to 0.21 ± 0.05), the results indicate that helmet performance is sensitive to impact direction and velocity. Notably, protective efficacy scaled non-linearly with impact severity, driving dynamic shifts in the relative protective rankings among the evaluated models.

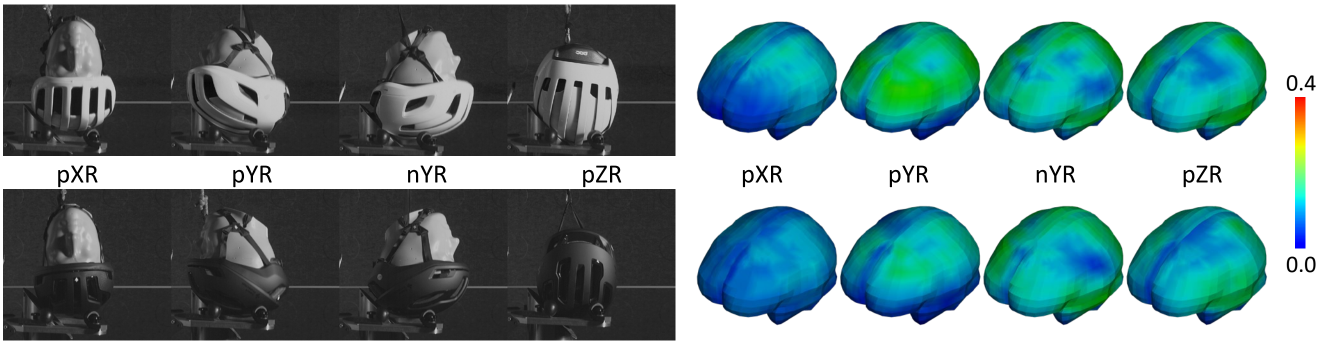

Figure 2. High-speed video frames (left) and corresponding brain maximum principal strain (MPS) distribution (right) across all four oblique impact locations. Representative case: Helmet 1 at 7.6 m/s (top) and Helmet 2 at 6.0 m/s (bottom).

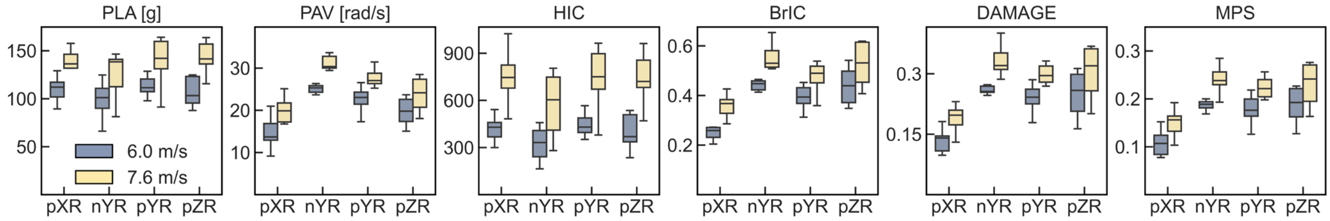

Figure 3. Comparison of head injury metrics in oblique impacts at four impact locations with velocities 6.0 m/s and 7.6 m/s.

IV. DISCUSSION

This study investigated bicycle helmet efficacy under high-speed oblique impacts representative of e-bike crashes using the biofidelic EN 17950 headform. The observed performance disparities under these high-energy boundary conditions highlight the inadequacy of current certification protocols.

Helmet performance is sensitive to both impact direction and velocity, with brain structures exhibiting morphology-dependent vulnerabilities. Although increased impact velocity elevated all injury criteria, no helmet model experienced liner densification. Helmet efficacy scaled non-linearly with velocity, resulting in dynamic shifts in relative protective rankings. Furthermore, helmets equipped with rotational management systems consistently reduced rotational responses. This study highlights the need to mitigate both linear and rotational injuries through the continued evolution of helmet designs and testing protocols, and underscores the necessity of advancing testing protocols to evaluate individual helmet performance under complex scenarios.

Limitations include the restricted cohort of eight helmets and the 7.6 m/s boundary condition, which may underestimate severe pedelec crashes. Future research should expand the helmet selection and evaluate elevated kinematic profiles to fully capture real-world e-bike accident severity.

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VI. REFERENCES

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