Slutrapport Skyltfonden

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An Oblique Impact Test Rig for Next-Generation European Bicycle Helmet Testing Standard

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Sammanfattning

Skallskador utgör fortsatt ett allvarligt och växande folkhälsoproblem. I Sverige indikerar traumadata att skallskador som drabbar cyklister i oproportionerligt hög grad leder till permanent medicinsk invaliditet jämfört med andra typer av trauman. Ur ett bredare perspektiv är skalltrauma den ledande dödsorsaken bland unga vuxna i Europa, med en oroväckande ökning av incidensen bland den äldre befolkningen. Även om cykelhjälmar ger ett grundläggande skydd, utvärderar nuvarande europeiska certifieringsstandarder skyddseffekten nästan uteslutande baserat på raka islag. Epidemiologisk och biomekanisk forskning visar dock att verkliga cykelolyckor till övervägande del involverar sneda islag. Dessa sneda islag inducerar komplex rotationskinematik, vilket är allmänt erkänt som den primära mekaniska drivkraften bakom allvarliga neurotrauman. Vidare förlitar sig traditionell provning på äldre fysiska provhuvuden, såsom Hybrid III. Dessa saknar människoliknande biofidelitet avseende tröghetsmoment och ytfriktionskoefficient, vilket försämrar noggrannheten i den registrerade islagskinematiken (särskilt för rotationssvaren). För att åtgärda dessa begränsningar utarbetar Europeiska standardiseringskommittén (CEN) nu en standard för provning av sneda islag. Denna förestående regulatoriska förändring blottlägger ett akut behov av nationell infrastruktur i Sverige, och ställer nya krav på nuvarande hjälmkonstruktioners förmåga att skydda vid sneda islag.

För att möta detta behov har projektet utvecklat en testrigg för sneda islag med hög repeterbarhet, fullt anpassad till de kommande europeiska standarderna. Infrastrukturen integrerar det nya provhuvudet EN 17950. Jämfört med Hybrid III besitter detta provhuvud en hög biofidelitet (avseende ytfriktionskoefficient och tröghetsmoment), vilket säkerställer en realistisk fysisk interaktion mellan det mänskliga huvudet och hjälmens stötupptagande liner under ett islag. För att garantera ett korrekt tribologiskt beteende kalibrerades och verifierades provhuvudets ytfriktionskoefficient rigoröst med hjälp av en standardiserad Capstan-baserad metod. Via denna plattform genomfördes en empirisk utvärdering av åtta representativa cykelhjälmar på den svenska marknaden. Det valda urvalet täckte medvetet in olika prisklasser och integrerade teknologier för rotationsskydd. Testmatrisen utsatte hjälmarna för sneda islag mot ett 45-gradigt vinklat städ på fyra specifika islagspunkter på hjässan (benämnda pXR, pYR, nYR och pZR) vid två initiala hastigheter (6,0 m/s och 7,6 m/s). Islagskinematiken registrerades med ett inbyggt trådlöst sensorsystem med sex frihetsgrader.

För att koppla den externa kinematiken till den interna skaderisken användes avancerad finita element-analys. Detta för att utvärdera responsen på vävnadsnivå under islagen, specifikt genom att kvantifiera den maximala första huvudtöjningen i hjärnan. De elva experimentella, kinematikbaserade skadekriterierna samt hjärnans beräknade MPS visade sig vara i hög grad beroende av den initiala islagshastigheten och islagspunkten. Som förväntat ledde en ökning av islagshastigheten från 6,0 m/s till 7,6 m/s till konsekvent högre värden för samtliga linjära, rotationella och kombinerade skadekriterier. Simuleringarna påvisade tydliga skillnader i skyddsprestanda: hjälmar utrustade med rotationsskyddssystem dämpade genomgående den maximala töjningen mer effektivt än konventionella hjälmkonstruktioner i samtliga testkonfigurationer. Detta projekt åtgärdar inte bara en nationell brist på infrastruktur för säkerhetsprovning, utan etablerar även ett robust empiriskt ramverk för att vägleda konsumentval, informera framtida europeisk standardisering och driva hjälmindustrin mot kontinuerlig teknisk utveckling. Därmed stärks Sveriges ledande position inom förebyggande av trafikskador.

Summary

Head injury remains a critical and growing public health concern. In Sweden, trauma data indicates that head injuries sustained by cyclists are disproportionately likely to result in permanent medical impairments compared to other trauma types. 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. While helmets provide essential protection, current European certification standards evaluate protective efficacy based almost exclusively on radial impacts. However, epidemiological and biomechanical research demonstrates that real-world cycling accidents predominantly involve oblique collisions. These oblique impacts induce complex rotational kinematics, which are recognized as the primary mechanical catalyst for severe neurotrauma. Furthermore, traditional testing relies on physical dummy headform, such as the Hybrid III, which lack human-like biofidelity regarding moments of inertia and surface coefficient of friction, thereby compromising the accuracy of the recorded impact kinematics (especially rotational responses). To address these limitations, the European Committee for Standardization is crafting an oblique impact testing standard. This imminent regulatory shift exposes an urgent national infrastructure need in Sweden and challenges the current helmet design in terms of their protection performance in oblique impact conditions.

To address this critical gap, this project developed a highly repeatable oblique impact test rig aligned with the forthcoming European standards. The infrastructure incorporates the new EN 17950 headform, which, in comparison to the Hybrid III counterparts, possesses high biofidelity (in terms of friction of coefficient and moment of inertia) to ensure an accurate physical interaction between the human head and the helmet liner during an impact. To guarantee realistic tribological behaviour, the headform's surface coefficient of friction was rigorously calibrated and verified using a standardized Capstan-based methodology. Utilizing this advanced platform, an empirical evaluation of eight representative bicycle helmets available on the Swedish market was conducted. The selected cohort deliberately encompassed diverse price points and integrated rotational protection technologies. The testing matrix subjected the helmets to oblique impacts against a 45° angled anvil at four specific cranial locations (termed as pXR, pYR, nYR, and pZR) and two initial velocities (6.0 m/s and 7.6 m/s). Impact kinematics were recorded using an embedded 6-degree-of-freedom wireless sensor system.

To bridge the gap between external kinematics and internal injury risk, high-fidelity finite element analysis was employed to evaluate tissue-level responses during helmeted impacts, specifically quantifying the maximum principal strain within the brain. The eleven experimental kinematics-based injury metrics and maximum principal strain of the brain are highly dependent on the initial impact velocity and the specific impact location. As anticipated, increasing the impact velocity from 6.0 m/s to 7.6 m/s consistently increased the values of all linear, rotational, and combined injury metrics. The simulations revealed a distinct stratification in protective performance: helmets equipped with rotational protection systems consistently attenuated peak maximum principal strain more effectively than conventional designs across all tested configurations. This project not only resolves a national deficit in safety testing infrastructure but also establishes a robust empirical framework to guide consumer choices, inform future European standardization, and incentivize the helmet industry toward continuous technical advancement, thereby reinforcing Sweden's leading position in traffic injury prevention.

Innehåll

1. Traffic safety benefit obtained

This project has established an oblique impact test rig for the next generation European bicycle helmet testing standard, providing a critical infrastructure upgrade for national traffic safety and helmet performance evaluation. Unlike traditional radial impact testing, this advanced system better replicates the complex linear and rotational kinematics inherent in real-world cycling accidents. To ensure maximum data fidelity and procedural consistency, the rig integrates the anatomically representative EN 17950 headform alongside advanced measurement technologies. The system features a dual-axis inclinometer for precise angular positioning, comprehensive tribological measurement capabilities, high-speed cinematography, and a sophisticated 6-degree-of-freedom wireless data transmission system. Together, these technological integrations substantially enhance the accuracy and repeatability of oblique impact data. Ultimately, this infrastructure directly advances traffic safety by enabling a highly reliable assessment of a helmet's capacity to mitigate rotational accelerations and prevent tissue-level neurotrauma, thereby catalysing the development of biomechanically optimized protective gear.

2. Background

Head injury remains a critical and growing public health concern. In Sweden, trauma data indicates that head injuries sustained by cyclists are disproportionately likely to result in permanent medical impairments compared to other trauma types. Longitudinal data reveals a dramatic and continuous upward trend in the incidence rate of concussions among Swedish hockey players over recent decades (Pauelsen et al., 2017). 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 (Maas et al., 2017).

While helmets serve as the primary protective countermeasure, current homologation standards present significant biomechanical limitations. Present European test protocols evaluate helmet performance by dropping a helmeted physical dummy headform onto a flat surface to simulate a radial impact. The pass/fail criterion relies strictly on ensuring the resultant peak linear acceleration remains below specific thresholds, such as 250 g for bicycle helmets under the EN1078 standard. Currently, several Swedish institutions, including our research group, operate test rigs exclusively designed for these radial impacts. However, this conventional standard fails to account for the biomechanical reality that oblique impacts—characterized by combined linear and angular motions—are significantly more prevalent in real-world accidents. Modern biomechanical research has conclusively demonstrated that angular loading is the predominant mechanism behind severe brain trauma and must therefore be actively integrated into helmet safety evaluations.

To better capture the real-life brain trauma condition, the European Committee for Standardization is crafting a next-generation helmet testing program centred on oblique impacts. This forthcoming protocol mandates dropping the helmeted headform against a 45° angled surface at four specific impact locations, requiring the simultaneous recording of both linear and angular accelerations. European regulatory bodies intend to integrate this comprehensive program into official testing standards by 2026. This imminent regulatory transition exposes an urgent national infrastructure deficit in Sweden, where currently only one commercial entity (Mips AB, Täby) possesses an oblique impact test rig, which is restricted to internal commercial use. Consequently, three critical technical challenges emerge: establishing reliable methodologies to measure angular kinematics during oblique impacts, ensuring repeatable control over initial impact locations, and determining how existing helmets will perform under these more stringent testing conditions.

3. Purpose

To address these infrastructural and scientific needs, this project aims to develop a state-of-the-art oblique impact test rig capable of meeting the forthcoming European regulatory requirements. By systematically upgrading our existing direct impact test rig, we will achieve highly reliable and repeatable test results to accurately evaluate helmet efficacy. The project's framework is structured around three complementary aims: measuring linear and angular accelerations via an instrumented headform, pinpointing precise impact locations through real-time visualization of helmet orientation, and ranking the protective performance of helmets based on the new standards. Ultimately, the delivery of this test rig will resolve the national infrastructure deficit, reinforce Sweden's position at the forefront of safety evaluation, and push the frontiers of head injury prevention by incorporating advanced in silico computational biomechanics into the evaluation pipeline.

4. Method and material

4.1 Experiment Setup

To accurately evaluate helmet performance under realistic crash conditions, this study utilizes the EN17950 headform manufactured by Humanetics. Developed in alignment with the directives of the European Committee for Standardization Working Group 11 (CEN/TC158/WG11), this specific headform is designed to address the biomechanical limitations of legacy models such as the Hybrid III and the standard EN960. The advantage of the EN17950 headform lies in its optimized physical properties, specifically its moments of inertia (MoI) and the coefficient of friction (CoF) of its surface. Previous comparative studies have demonstrated that legacy surrogates, such as the Hybrid III, tend to overestimate peak rotational kinematics due to unrepresentative surface friction and inertial properties (Yu et al., 2022). Furthermore, the head and face geometry are derived from extensive 3D anthropometric data of the human population, providing a more representative fit. The headform was equipped with a 6DOF sensor package along with a wireless acquisition system. It enabled the measurement of the linear X-, Y- and Z-accelerations and the rotational velocities around the three headform axis. All the kinematics were filtered at CFC180 according to ISO 6487.

To verify its realistic tribological properties, the headform's CoF was calibrated following the EN 17950 protocol (**Figure 1**). A structured polyester strap, simulating standard comfort padding, was wrapped over the headform at a 90° angle of coverage with a 2 kg mass. A force gauge pulled the strap horizontally at a constant speed across five test cycles to confirm compliance with the required CoF of 0.3.

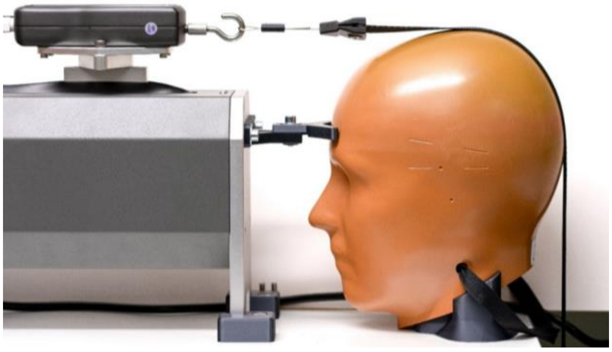


Figure 1. Experimental setup for EN17950 headform friction measurement.

To ensure the translational relevance of the experimental findings, the selection of bicycle helmets was meticulously curated to reflect the current consumer landscape. The initial candidate pool was established by reviewing existing literature across various helmet testing programs (Baker et al., 2024; Bland et al., 2020; Deck et al., 2019; Stigson et al., 2017) and conducting consultations with two industry specialists, alongside input from insurance sector researchers. From this process, a representative cohort of helmets widely available on the Swedish market was identified. To guarantee a comprehensive comparative analysis, the inclusion criteria strictly prioritized high-sales-volume models while deliberately spanning a broad retail price spectrum. The selection was designed to encompass a diverse array of contemporary rotational energy management technologies, specifically including Mips and KinetiCore systems. Finally, an initial set of eight helmets were selected, and the detailed of the selected helmets are provided in **Table 1** and **Figure 2**.

Table 1. List of the bicycle's helmet models tested in this project.

ID	Brand	Model	Type	Tech	Size (cm)	Mass (g)	Price (~sek)
1	POC	Cytal	Road	MIPS	M 54-59	266	3500
2	Sweet Protection	Falconer 2Vi	Road	MIPS	M 56-59	300	3000
3	Scott	Argo Plus Mips	MTB	MIPS	SM 54-58	320	950
4	ABUS	Urban-I 3.0 Mips	Road	MIPS	L 56-61	320	1350
5	Lazer	Verde	Urban	KinetiCore	ML 55-61	350	1000
6	Lazer	Codax	Urban	KinetiCore	ML 54-58	269	600
7	ABUS	Urban-I 3.0 ACE	Urban	None	L 56-61	300	1000
8	Scott	ARX	MTB	None	M 55-59	230	1000

The impact tests were conducted at the KTH Royal Institute of Technology. The experimental apparatus comprises a vertical aluminium guide column anchored to a rigid concrete foundation, a 45° angled anvil, and the EN 17950 headform. During the pre-impact free-fall phase, a cantilevered release arm maintained the headform's precise spatial orientation, automatically retracting immediately prior to the collision. The inverted headform was mounted to a U-shaped free-falling carriage designed to strike the angled anvil (Halldin and Kleiven, 2013). This specific 45-degree anvil configuration is a well-established testing paradigm in contemporary oblique head impact biomechanics (Arnesen et al., 2024; Fahlstedt et al., 2021; Aare et al., 2003).

Figure 2. Eight bicycle's helmets tested in this study.

The experimental testing matrix encompassed four specific oblique impact locations to simulate diverse crash kinematics: side impact (pXR), front impact (pYR), rear impact (nYR), and front-side impact (pZR), as illustrated in **Figure 3**. To evaluate the consistency of the dynamic response, each specific impact condition was repeated twice. In total, eight types of helmets were tested across four impact locations with two initial velocities. Furthermore, the impact duration was captured via high-speed cinematography at 10,000 frames per second. This footage was systematically reviewed post-test to verify the initial kinematic boundary conditions and to confirm that the mechanical interaction between the helmet, headform, and anvil proceeded exactly as intended (Fahlstedt et al., 2016).

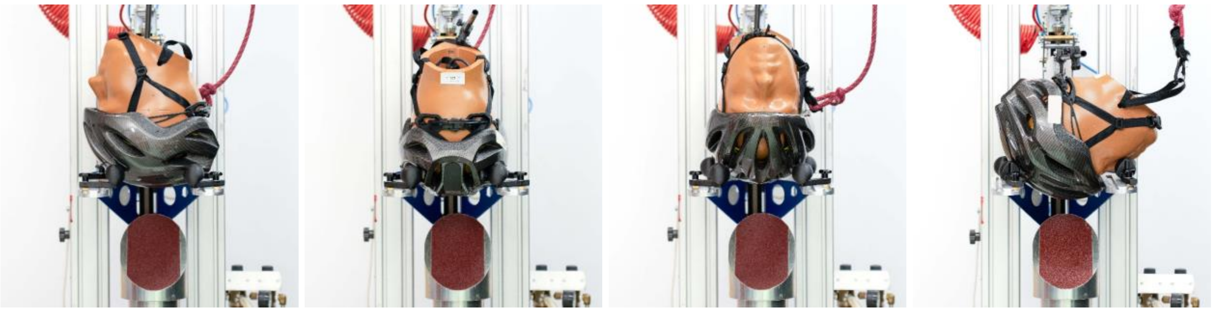

pXR pYR nYR pZR

Figure 3. Four impact locations: side impact, front impact, rear impact, and front-side impact.

4.2 Data analysis

Various brain injury criteria have been employed in traumatic brain injury research, typically based on translational and/or rotational parameters of head kinematics, derived from experimental data fitting or reduced-order mechanical models (Zhan et al., 2021; Zhou et al., 2022).

In this study, we selected eleven kinematics-based head injury metrics to quantify head dynamic responses and helmet protective performance during oblique impacts. These metrics include two linear motion-based indices: peak linear acceleration (PLA) and the head injury criterion (HIC) (Versace, 1971); six rotational motion-based indices: peak angular acceleration (PAA), peak angular velocity (PAV) (Halldin et al., 2003), Brain Injury Criterion (BrIC) (Takhounts et al., 2013), Universal Brain Injury Criterion (UBrIC) (Gabler et al., 2018), Rotational Injury Criterion (RIC) (Kimpara and Iwamoto, 2012), and Diffuse Axonal, Multi-Axis, General Evaluation (DAMAGE) (Gabler et al., 2019); and three metrics that combine both linear and angular motion: Head Impact Power (HIP) (Newman et al., 2000), Kleiven Linear Combination (KLC) (Kleiven, 2007), and the Generalized Acceleration Model for Brain Injury Threshold (GAMBIT) (Newman, 1986).

Equations and detailed explanations for these metrics are provided in **Table 1.** For example, PLA is used to predict the risk of skull fractures and focal brain injuries (Allsop et al., 1988; Gurdjian et al., 1966), while PAA has been proposed as a predictor for subdural hematoma (Depreitere et al., 2006; Gennarelli et al., 1982). Given that these pathologies are commonly observed in vulnerable road user casualties, these metrics were employed to evaluate protection performance and were post-processed using Python (v 3.12).

Table 2. Head injury metrics used in this study. The coordinate system (XYZ) used to compute the kinematic-based metrics is the same as the laboratory tests.

Metrics	Description
PLA	$\max\big(a(t)\big)$
PAV	$\max\big(\omega(t)\big)$
PAA	$\max\big(\alpha(t)\big)$
HIC	$\max\left\{(t_2 - t_1)\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right)^{2.5}\right\}$
BrIC	$\sqrt{\left(\frac{\omega_x}{\omega_{xc}}\right)^2 + \left(\frac{\omega_y}{\omega_{yc}}\right)^2 + \left(\frac{\omega_z}{\omega_{zc}}\right)^2}$
UBrIC	$\left\{\sum_i \left[\omega_i^* + (\alpha_i^* - \omega_i^*)\, \mathrm{e}^{-\frac{\alpha_i^*}{\omega_i^*}}\right]^r\right\}^{\frac{1}{r}}$
RIC	$\max\left\{(t_2 - t_1)\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \alpha(t)dt\right)^{2.5}\right\}$
HIP	$\max\left\{m \sum a_i(t) \int a_i(t)dt + \sum I_{ii}\alpha_i(t) \int \alpha_i(t)dt\right\}$
KLC	$\mathrm{k}_1 \max\lvert\omega(\mathrm{t})\rvert + \mathrm{k}_2\mathrm{HIC}_{36}$
GAMBIT	$\max\left\{\left[\left(\frac{\lvert a(t)\rvert}{a_c}\right)^2 + \left(\frac{\lvert\alpha(t)\rvert}{\alpha_c}\right)^2\right]^{1/2}\right\}$
DAMAGE	$\beta \max\{\lvert\bar{\delta}(\mathrm{t})\rvert\}$
MPS	The maximum value of the 1st principal Green-Lagrange strain in the brain

4.3 Finite element simulation

To estimate the dynamic intracranial response during oblique impacts, the experimentally acquired kinematics were applied to the KTH finite element (FE) head model (Kleiven, 2007). This model incorporates the scalp, skull, brain, meninges (dura mater and pia mater), falx, tentorium, cerebrospinal fluid, eleven pairs of parasagittal bridging veins, and a simplified neck incorporating the spinal cord. The brain is modelled as a homogeneous, isotropic structure; its hyperplastic non-linear behaviour is defined by a second-order Ogden constitutive model, while its viscoelasticity is captured via a six-term Prony series (Kleiven, 2007). Comprehensive details regarding geometric discretization, material properties, and structural interfaces are documented in previous studies (Kleiven and Hardy, 2002; Zhou et al., 2021). The model's predictive capability is extensively validated against experimental data for brain-skull relative motion (Giordano and Kleiven, 2016), intracranial pressure (Kleiven, 2006) and brain strain (Zhou et al., 2018).

A total of 64 simulations were executed, representing the full experimental matrix of eight helmets, four impact locations, and two initial velocities. For each condition, the input kinematic boundary conditions were derived from the mean responses of the two repeated physical tests. Specifically, the six-degree-of-freedom impulses directly from the headform's internal accelerometer array were applied to the centre of gravity of the FE model and constrained to the rigid skull (Zhou et al., 2020). Each simulation computed a 30 ms impact duration, matching the experimental data window. The explicit dynamic simulations were solved using LS-DYNA (revision 13.0.0, double precision) on an HPE Cray EX high-performance computing system equipped with AMD EPYC processors (Huang and Kleiven, 2023; Huang et al., 2024; Makoundou et al., 2025).

5. Results

5.1 Overview of the oblique impacts

Figure 4 presents snapshots from the high-speed camera, capturing the dynamic sequence immediately following the initial contact between the helmet, headform, and the angled anvil. The visual data is organized into four rows, corresponding to the oblique impact configurations from top to bottom: pXR, pYR, nYR, and pZR. Each helmet model is depicted undergoing the impact process at two initial velocities: (a) 6.0 m/s and (b) 7.6 m/s, respectively.

(a) Helmet 1, at 7.6 m/s

(b) Helmet 2, at 6.0 m/s

Figure 4. Snapshots from the high-speed camera of the helmeted headform oblique impacts at four impact locations (pXR, pYR, nYR, and pZR, from top to bottom) with two velocities.

The measured head kinematic time-histories for all impact configurations are presented in **Figure 5**. This visualization synthesizes 64 impacts derived from the eight helmets, four standardized impact locations (pXR, pYR, nYR, pZR), and two initial impact velocities (6.0 m/s and 7.6 m/s). Each subfigure displays six filtered kinematic channels including triaxial linear acceleration (Lin. Acc.) and triaxial rotational velocity (Rot. Vel.), which were acquired directly via the wireless sensor system embedded within the headform. The black curve in each plot represents the calculated resultant value. The data is shown over a critical 30 ms duration starting 5 ms before the initial helmet-anvil contact. The figure illustrates direction-dependent variation in kinematic signatures across the different impact locations. Certain helmets exhibit substantially reduced peak rotational velocities compared to others in specific configurations, suggesting varying degrees of efficacy for the integrated rotational protection technologies.

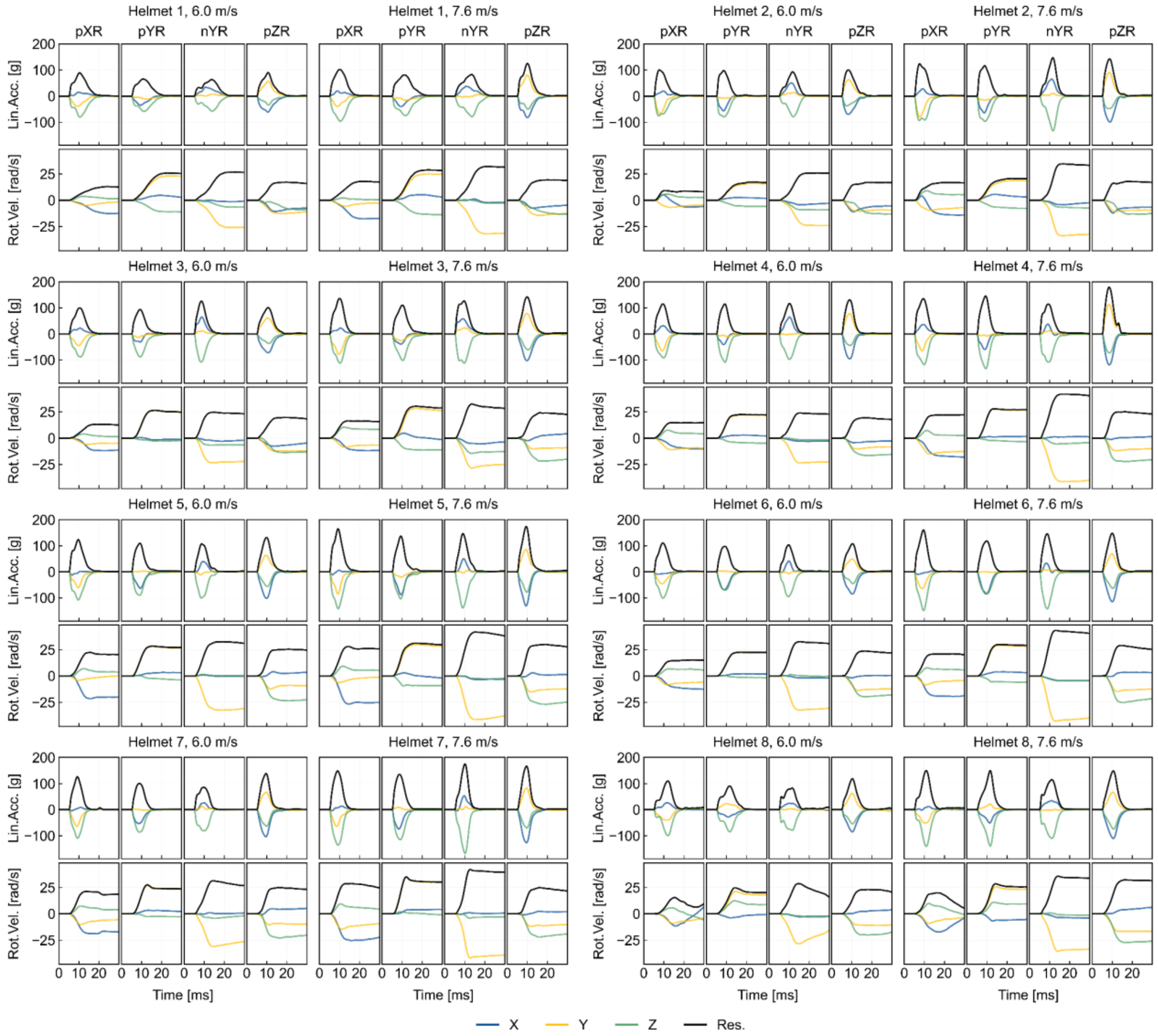


Figure 5. Kinematics including linear acceleration (Lin.Acc.) and angular velocity (Ang.Vel.) of 64 oblique impacts extracted from the headform. Eight helmets under four impact locations (pXR, pYR, nYR, and pZR) with two velocities (6.0 m/s and 7.6 m/s). The black curve represents the resultant value.

5.2 Injury metrics and analysis

Maximum principal strain (MPS) was employed to evaluate how the helmets influence the brain injury pattern. The 95th MPS was extracted for all brain tissue elements ($N = 4{,}124$) and directly output from the simulation. These elements encompass major anatomical regions such as the cerebral cortex, brain stem, white matter, thalamus, cerebellum, and corpus callosum. **Figure 6** illustrates the distributions of the MPS within the brain tissues across the eight evaluated helmets. As anticipated, an elevation in the initial impact velocity from 6.0 m/s to 7.6 m/s systematically amplifies both the absolute magnitude and the spatial distribution of the MPS across all helmet models.

Moreover, the strain distribution pronounced direction-dependent injury vulnerabilities. The structural interaction between the helmet and the headform varies significantly with the impact location. Generally, the nYR impact configuration induces the highest MPS across the tested helmets. These substantial variations in brain tissue deformation under identical initial conditions underscore the complex interplay between a helmet's specific energy-absorbing architecture and the resultant biomechanical loading transmitted to the brain. A comparative evaluation of the spatial strain distributions reveals a stratification in protective efficacy intrinsically linked to helmet design. Helmets 1-4, which incorporate rotational protection technologies, consistently exhibit attenuated peak MPS when compared to Helmets 5-8. This enhanced mitigation of brain tissue deformation remains evident across all configurations.

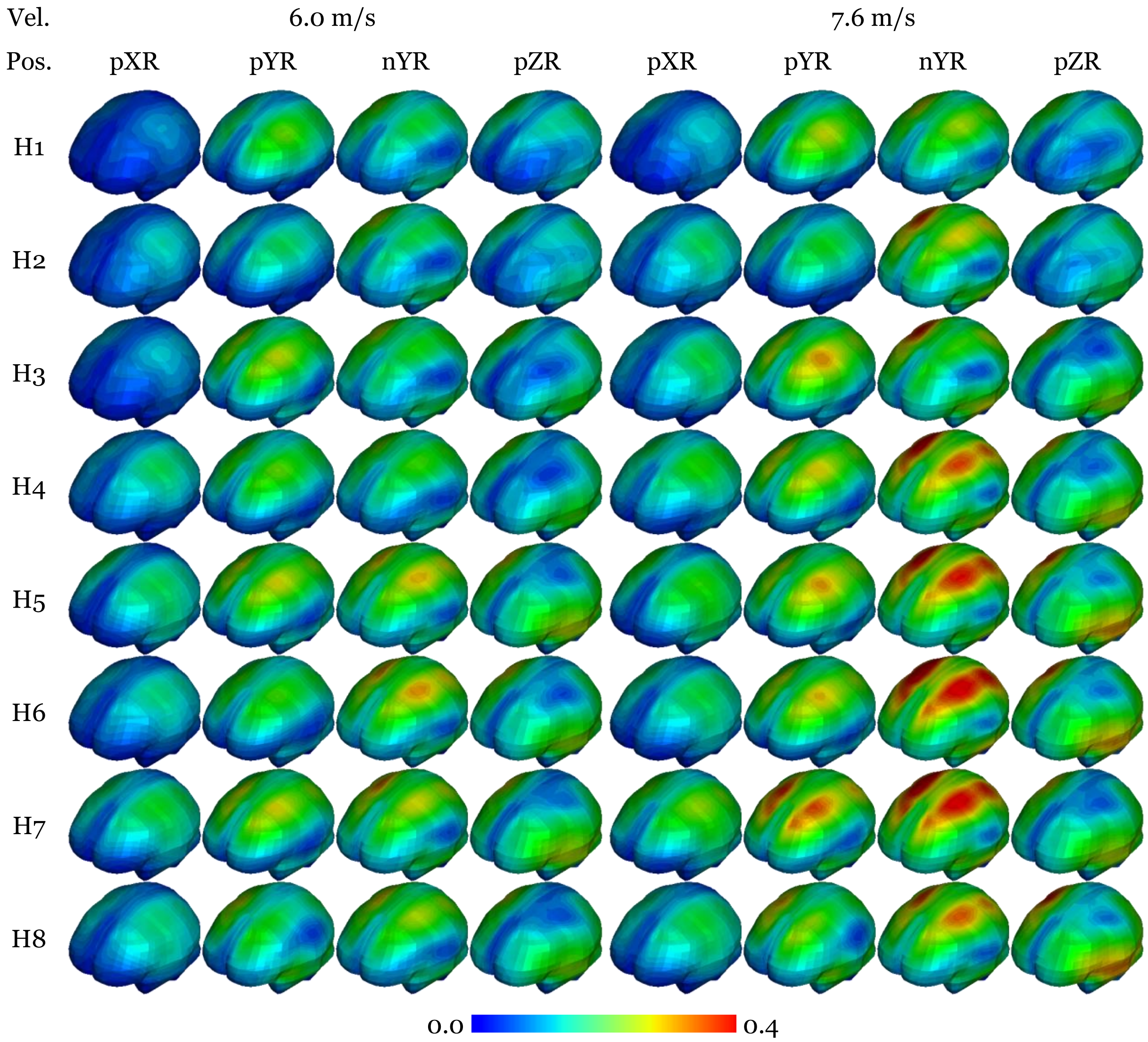
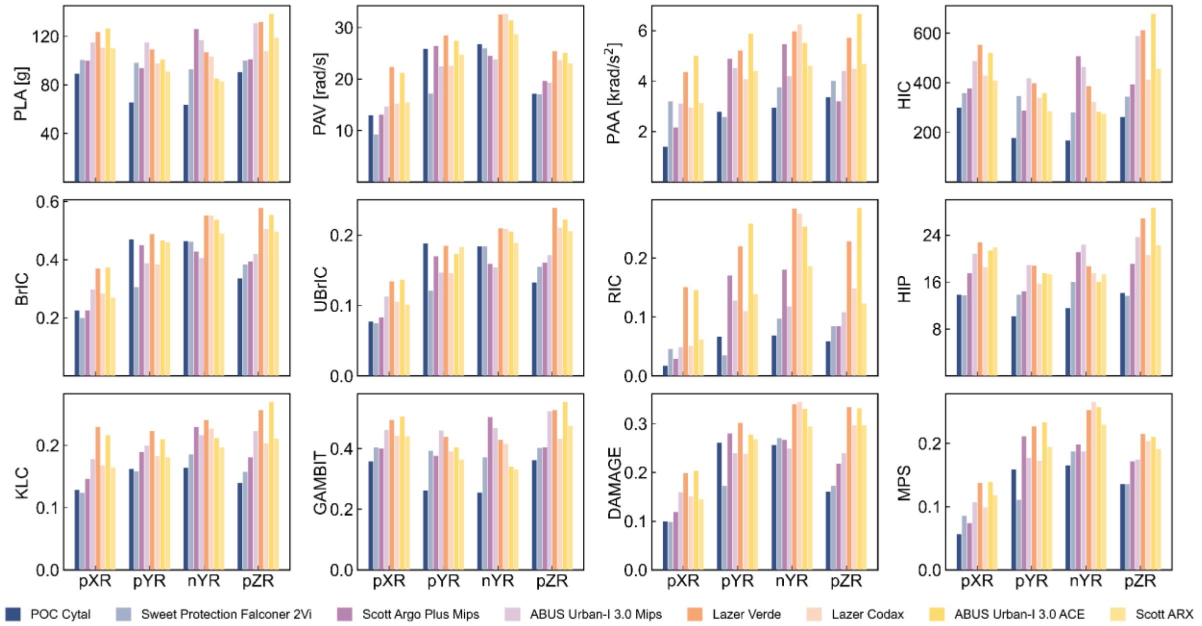
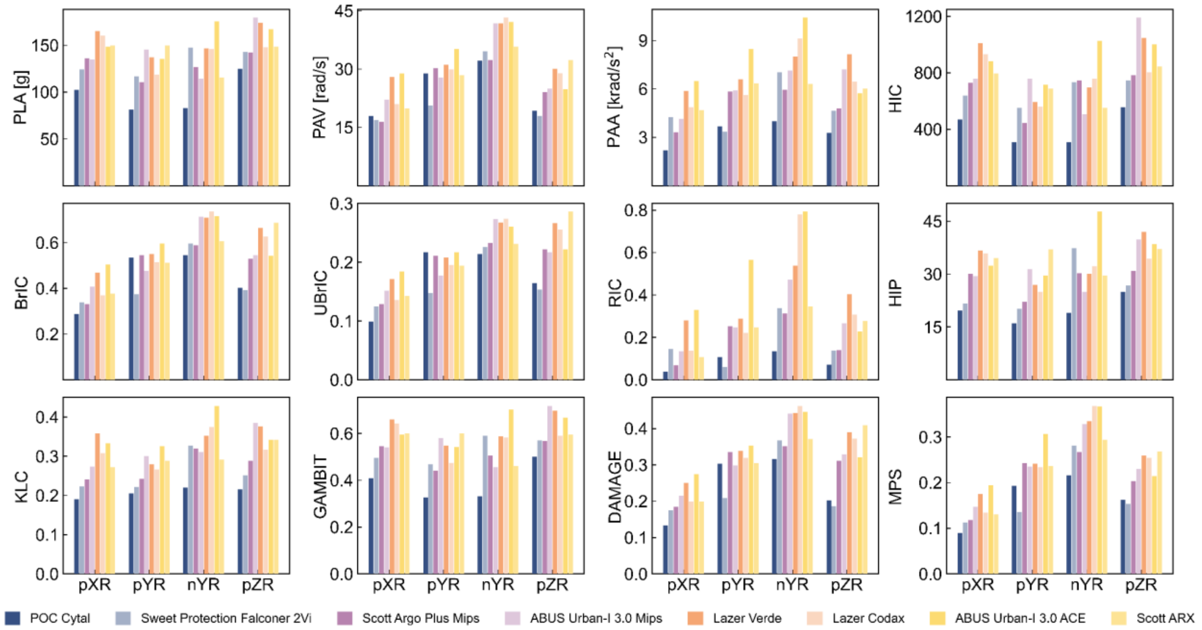


Figure 6. Maximum principal strain (MPS) distribution of brain tissues during oblique impact with eight helmets (H1-8) at four impact locations (pXR, pYR, nYR, and pZR) with two velocities (6.0 m/s and 7.6 m/s). The color bar indicates strain from 0 to 0.4.

Figure 7 presents the eleven kinematics-based and one strain-based head injury metrics evaluated for the eight helmets across four impact locations (pXR, pYR, nYR, and pZR) at two initial impact velocities (6.0 m/s and 7.6 m/s). The responses of the individual helmet models are distinguished by color. Regarding the primarily linear-related metrics (PLA and HIC), the recorded values exhibited an upward trend with increased kinetic energy input. Using the pXR as an example, the mean PLA across the eight helmets increased from 95 g (SD = 25 g) at 6.0 m/s to 125 g (SD = 30 g) at 7.6 m/s. The HIC values at the same location rose from 350 (SD = 150) at the lower velocity to 650 (SD = 250) at the higher velocity.



(a) head injury metrics at 6.0 m/s



(b) head injury metrics at 7.6 m/s

Figure 7. Eleven kinematics-based and one strain-based head injury metrics of eight helmets at four impact locations (pXR, pYR, nYR, and pZR) with two velocities (6.0 m/s and 7.6 m/s).

For the rotational-related metrics (PAV, PAA, BrIC, UBrIC, and RIC), velocity-dependent scaling was similarly observed. At the pXR location, the mean PAV and PAA increased from 15 rad/s (SD = 5 rad/s) and 3.2 krad/s^2 (SD = 1.2 krad/s^2) at 6.0 m/s to 22 rad/s (SD = 5 rad/s) and 4.5 krad/s^2 (SD = 1.5 krad/s^2) at 7.6 m/s, respectively. BrIC at pXR increased from 0.28 (SD = 0.06) to 0.38 (SD = 0.08), while UBrIC and RIC shifted from 0.11 and 0.08 to 0.14 and 0.16, respectively.

Metrics incorporating coupled linear and rotational dynamics (HIP, KLC, and GAMBIT) also responded to the altered initial conditions. The mean HIP at pXR increased from 15 kW to 25 kW. KLC and GAMBIT shifted from means of 0.16 and 0.42 at 6.0 m/s to 0.26 and 0.53 at 7.6 m/s. DAMAGE similarly increased from a mean of 0.14 to 0.20 at this specific location. MPS averaged 0.10 (SD = 0.03) at 6.0 m/s under the pXR condition and increased to 0.14 (SD = 0.04) at 7.6 m/s.

6. Conclusions

This project established a state-of-the-art oblique impact testing infrastructure, proactively addressing a critical national capability gap in anticipation of the upcoming European standardization mandates. The comprehensive experimental and computational evaluation of eight representative bicycle helmets yields the following primary conclusions:

- The integration of the high biofidelic headform featuring calibrated inertial and tribological properties, provides a highly repeatable, biomechanically accurate platform for evaluating rotational kinematics during complex oblique impacts.
- Both head kinematics and the brain tissue deformations dependent on the initial impact velocity and the impact location. As anticipated, increased kinetic energy systematically escalates the magnitudes across all evaluated linear and rotational injury metrics.
- Finite element analysis revealed a distinct stratification in helmet protective performance. Helmets equipped with rotational protection technologies consistently attenuated peak strain more effectively than conventional helmet architectures across all tested conditions.
- The established testing paradigm provides a robust empirical baseline to guide consumer decision-making (e.g., consumer rating programs). Furthermore, it equips Sweden with the necessary technical infrastructure to actively influence future CEN regulatory frameworks, directly supporting the national Vision Zero initiative.

7. Dissemination and implementation

The dissemination of results has been strategically planned to ensure that the scientific community, regulatory bodies, and relevant industry stakeholders can effectively access, review, and utilize the project's outcomes. In all communications and publications, Skyltfonden has been explicitly acknowledged as the funding agency. A primary output of this work will be the generation of empirical data and novel methodologies intended for publication in high-impact, peer-reviewed scientific journals. These publications will be made available via Open Access, ensuring that the insights are immediately accessible to all stakeholders without subscription barriers. The publications will provide a transparent description of the testing workflow, validation processes, and data-driven insights that can directly support future guidelines for safety standardization. Furthermore, key findings will be presented at premier international forums, such as the International Research Council on Biomechanics of Injury (IRCOBI) conference.

The newly developed oblique impact rig functions not merely as an academic instrument, but as a crucial national asset. To maximize societal benefit, the rig will be made accessible to external parties upon regulated request. This open-access approach fosters direct synergies with other Swedish traffic safety initiatives, strengthening collaborative efforts in structural safety evaluation.

The project generates actionable knowledge to rank the protective performance of bicycle helmets currently available on the Swedish market. This transparent ranking empowers cyclists to make informed purchasing decisions based on verified rotational protection metrics. Simultaneously, the rigorous testing methodologies provide empirical feedback that incentivizes the helmet industry to refine their designs and integrate advanced energy-absorbing technologies.

A central next step is to expand the utility of the test rig beyond bicycle helmets. The established architecture is highly versatile, and planning is underway to adapt the system for testing other types of protective headgear. By transferring these technical insights across various headgear, the project actively contributes to the long-term goal of implementing comprehensive, injury-mitigating safety standards across all modes of transport.

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