Influence of Headform on Assessments and Ratings of the Protective Performance of Bicycle Helmets

Natalia Lindgren, Peter Halldin, Madelen Fahlstedt

Abstract Numerous helmet rating methods have been proposed to assess the safety and effectiveness of bicycle helmets. The methods usually involve a series of experimental impact tests using an Anthropomorphic Test Device (ATD) headform. There are several headforms available for the purpose and this study sought to assess how the choice of headform influences the safety assessment and ratings of bicycle helmets by following four proposed rating programs using three commonly used headforms. 19 head impact cases were evaluated computationally using the National Operating Committee on Standards for Athletic Equipment (NOCSAE) headform, Hybrid III (HIII) headform, and standard EN960 headform. The results show that for most oblique impact cases, EN960 produced considerably lower Peak Angular Acceleration (PAA), Peak Angular Velocity (PAV) and head injury risk compared to HIII and NOCSAE. This implies that the safety performance of bicycle helmets could be rated higher when using uncoated metal headforms compared to rubber-coated ones. The different headforms' tendency to produce varying rotational motion in oblique impacts raises questions about which of the headforms are suitable for such impact tests. The results presented in this study emphasize the occasional contradictions in helmet ratings presented by helmet rating programs.

Keywords Head impact testing, Head injury risk, Oblique impacts, Bicycle helmet, Headform.

I. INTRODUCTION

Bicycle helmets serve as a vital form of safety protection for the most unprotected road user groups by reducing mortality rates and risk of head injury [1-2]. The vast majority of helmets on the market conform to specific national standards that specify the criteria that helmets must meet when performing helmeted headform impact tests in a laboratory environment. The key requirements in the standards are often specified in terms of maximum allowed Peak Linear Acceleration (PLA) during impacts against flat, hemispherical or kerbstone anvils [3-5].

Meanwhile, it has long been argued that some brain injuries are more sensitive to angular motion than linear motion [6–9]. Despite this, the inclusion of angular motion in helmet testing has not yet been implemented in standards. The standards do not include oblique impact tests against angled surfaces, which would mimic a real impact situation better than impacts to a flat surface [10]. The biofidelity of the standard tests can be further disputed, as many of the standards often use uncoated ATD headforms made of metal [3][11], favouring repeatability, instead of using the available rubber-coated headforms, such as the commonly used National Operating Committee on Standards for Athletic Equipment (NOCSAE) or Hybrid III (HIII) headforms. The standard metal headforms have also been argued to be particularly unsuitable for oblique impacts, which has partially been explained by its less biofidelic inertial properties [12]. In headform impact tests, the mentioned headforms have shown a tendency of producing varying kinematic responses, where EN960 has been reported to produce lower magnitudes in rotational kinematics compared to both HIII and NOCSAE [12], while HIII has been observed to produce greater head acceleration and rotation compared to NOCSAE [13]. The HIII headform was originally designed for crash tests for automotive safety testing [14], while NOCSAE was developed for drop tower tests for football helmets [15], which needless to say plays a part in their impact response.

Given the state of knowledge of head injury mechanisms and injury epidemiology of cyclists, helmet rating methods have been developed to assess the protective performance of helmets as a complement to the standard evaluations. The proposed rating programs often include oblique helmeted headform impacts, where the helmet

N. Lindgren (+4687904876, nalindgr@kth.se) is a Ph.D student in Biomechanics of Head and Neck Injuries, P. Halldin is a researcher in Biomechanics of Head and Neck Injuries and Helmets and M. Fahlstedt is a researcher in Biomechanics of Head and Neck injuries, all at the Department of Neuronic Engineering, School of Technology and Health, KTH Royal Institute of Technology, Stockholm, Sweden. P. Halldin is also the CSO of MIPS AB.

performance is evaluated based on certain kinematic risk metrics and/or metrics derived from Finite Element (FE) simulations using FE head models [16–18].

Due to the plenitude of rating methodologies, the accessible helmet ratings recurrently result in contradictory and confusing recommendations for end-consumers. An example is how the Bontrager Charge Wavecel was ranked as “Best available” (5/5 stars) by one rating program [19] and “Average” (2/4 stars) by another [20]. Little is known about how these ratings are influenced by the headform used for the underlying impact tests. Several studies have pointed out the differences in biomechanical impact response in oblique impacts between different headforms [10][14-15]. Also, between the commonly used HIII and NOCSAE headforms there are considerable differences in shape [22], mass and inertial properties [23]. Despite these recognized differences, the influence of the headform choice in bicycle helmet rating has not previously been quantified.

In this present study, the objective was to evaluate the influence of headform on bicycle helmet safety assessments and ratings. This was done by following a selection of helmet rating programs to obtain the rating of a single conventional helmet model, using a selection of commonly used headforms. To obtain the ratings and investigate the effect of the headforms on the kinematic response, 19 different impact cases, 15 of them oblique, were evaluated using FE simulation. 19 helmeted HIII headform impacts and three helmeted EN960 headform impacts were performed experimentally, repeated twice, for model validation.

II. METHODS

Four helmet rating programs were evaluated in this study, hereby referred to as Folksam (F) [17], Certimoov (CM) [18], Virginia Tech STAR (STAR) [16] and Länsförsäkringar (LF) [24]. The four programs involved a set of helmeted headform drop impact tests, which were all performed using FE simulation. The impact tests were computed once using HIII headform (Fig. 1A), once using NOCSAE headform (Fig. 1B), and once using a standard EN960:2006 size J magnesium headform (EN960) (Fig. 1C). The helmet model (Fig. 1D) was evaluated against a set of drop tower experiments using a conventional helmet model (Fig. 1E). Based on simulation output, ratings of the helmet were calculated following respective rating programs based on respective headforms.

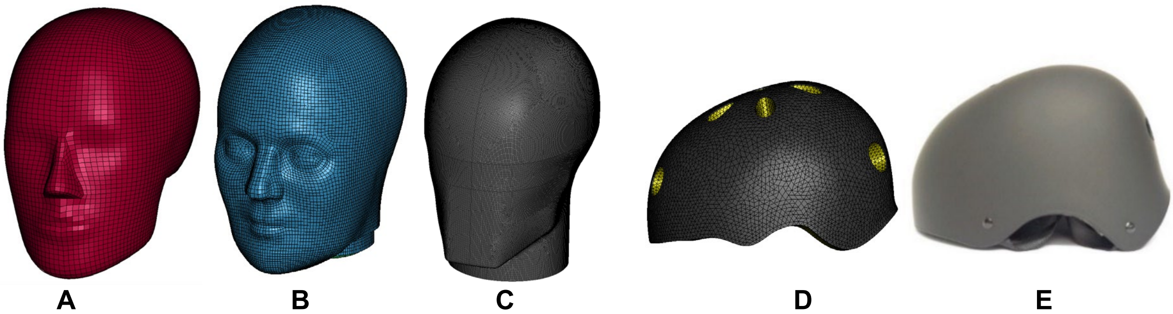

Fig. 1. FE model of the (A) HIII headform, (B) NOCSAE headform and (C) EN960 headform, together with (D) the helmet used in the simulations and (E) the physical helmet model used for experimental validation drop impact tests.

Head Impact Cases

The sets of drop impact tests associated with each rating program are presented in Fig. 2. The impact tests are referred to as ‘oblique’ or ‘straight’. An oblique impact involves both normal and tangential incident velocities, while a straight impact involves only a normal velocity component. A flat anvil is used to obtain a straight impact test, while an 45°-angled anvil is used for the oblique tests. Folksam rating program included one straight impact and three oblique impacts [17], while Certimoov included three straight and three oblique impact cases [18]. STAR rating program included a total of 6 impact configurations in two different impact velocities [16]. Länsförsäkringar included the same impact cases as Folksam, but without the straight impact case. Originally, Certimoov rating program was based on head impacts using HIII headform [18], while STAR rating program involved the NOCSAE headform [16]. Folksam and Länsförsäkringar use HIII for oblique impacts and Folksam use EN960 for the single straight impact. More details of the impact configurations can be found in the Appendix.

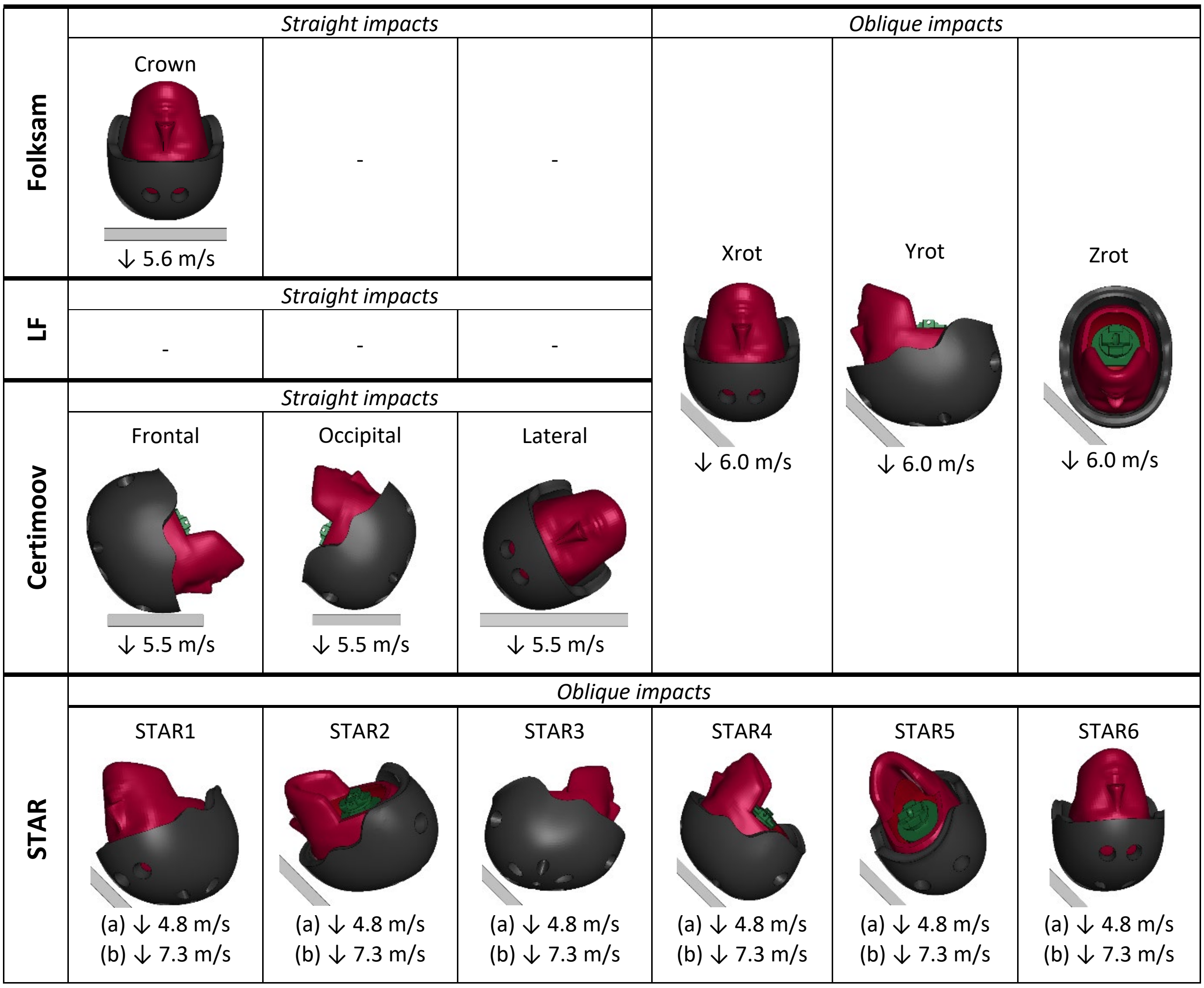

Fig. 2. Head impact cases and drop velocities considered by respective helmet evaluation programs. Note that the oblique tests were the same for Folksam, Länsförsäkringar and Certimoov. Länsförsäkringar did not include any straight impact cases. The denomination of each impact case is presented jointly with respective impact. For instance, the second STAR impact case tested with a drop velocity of 7.3 m/s is referred to as STAR2b.

Modelling and Validation of Helmet Model

The simulated impact tests were conducted using a conventional helmet model with an expanded polystyrene (EPS) liner (Fig. 1D), modelled without comfort liner or a chinstrap. The EPS liner was modelled with a Fu-Chang foam material model (*MAT_FU_CHANG_FOAM, material model number 83 in LS DYNA [25]). The compressive stress-strain curves describing the EPS were based on the static and dynamic compression tests conducted by [26], for a foam density of 80 kg/m^3. Tension curves were added based on in-house data and the stress-strain curves were optimized to increase the correlation with performed experiments. For detailed geometry and material parameters of the outer helmet shell, see [27].

The FE helmet model (Fig. 1E) was evaluated against experimental tests using a helmet available on the market. Two tests per impact case, meaning a total of 38 experimental tests, were conducted using a 50th percentile HIII headform without attached neck. The headform were instrumented with nine accelerometers in a 3-2-2-2 array at the centre of gravity (COG). The angular accelerations were calculated from the 9-accelerometer system according to [28]. The angular velocity was calculated based on the angular acceleration.

Impacts Xrot, Yrot and Zrot were also tested twice experimentally using the EN960 headform. The headform was instrumented with 3 accelerometers and 3 angular rate sensors. The angular acceleration was calculated based on the angular velocity. The data were sampled at a frequency of 25 kHz and the linear acceleration was filtered with a CFC 1000 filter and angular velocity with CFC 180.

For oblique impacts using HIII, the average COrrelation and Analysis (CORA) score was 0.83 for linear acceleration, 0.62 for angular acceleration and 0.70 for angular velocity, suggesting a reasonable correlation between experiments and simulations. For EN960 tests in Xrot, Yrot and Zrot, the average CORA score was 0.89 for linear acceleration, 0.73 for angular acceleration and 0.82 for angular velocity. Further details on the experimental setup, calculated CORA scores and resulting time-histories can be found in the Appendix.

FE Simulations

A total of 57 impact tests (three headforms per impact case) were conducted computationally using LS DYNA (version 7.1.2, LSTC, Livermore, CA, US) with multiple CPUs. The HIII and the NOCSAE FE headforms were developed by [23]. The EN960 FE model was developed in-house and is constructed of 143,734 rigid 4-node shell elements. The coefficient of friction (COF) used for the three headforms are presented in Table I, while the masses and inertias are specified in Table II. The simulations of the drop impacts had a duration of 30 ms. All processing and data analysis was done using MATLAB (version 2021a, The 251 MathWorks, Inc., Natick, Massachusetts, United States).

TABLE I

FRICTION COEFFICIENTS USED FOR SIMULATED IMPACT TESTS

	Coefficient of Friction
Ground against helmet outer shell	0.80
Helmet against HIII headform	0.70
Helmet against NOCSAE headform	0.70
Helmet against EN960 headform	0.30

TABLE II

MASS AND INERTIAL PROPERTIES OF THE THREE FE MODEL HEADFORMS

Headform	Mass [kg]	I_{xx} [kg·cm^2]	I_{yy} [kg·cm^2]	I_{zz} [kg·cm^2]
HIII [23]	4.54	153	210	181
NOCSAE [23]	4.41	188	240	162
EN960*	4.70	264	318	193

* *Measured in-house*.

Ratings

Respective ratings were derived according to the approaches illustrated in Fig. 3.

To obtain the Folksam helmet rating [17], the linear and angular accelerations obtained from the simulated oblique impacts were applied to the KTH Royal Institute of Technology FE brain model [8] to extract the maximum first principal Green–Lagrange strain of the brain tissue. A strain above 26% was assumed to correspond to a 50% risk for concussion. The risk curve was obtained by Kleiven [8] and is based on FE analyses of collected kinematics of 58 concussive and sub-concussive impacts in American football. The Folksam risk of concussion was governed by:

$$R_F\,(\varepsilon_{max}) = \frac{e^{-3.6194 + 13.5513\,\cdot\,\varepsilon_{max}}}{1 + e^{-3.6194 + 13.5513\,\cdot\,\varepsilon_{max}}} \tag{1}$$

where ε_{max} (-) denotes the peak value of the strain in the brain per element of an impact case. The Folksam rating score incorporated the relative risks of each oblique impact, as well as the relative PLA of the single straight impact case. The relative metrics were calculated by dividing the obtained risks and Crown PLA with the average of a set of helmets. The reference helmet set consisted of 18 different helmet models, tested using HIII headform in Xrot, Yrot and Zrot impact cases, and EN960 headform in the Crown impact case. For more details on the 18 models and their corresponding reference values, see [14].

Similarly, Länsförsäkringar rating method [20] used the KTH FE brain model to extract the peak brain tissue strain for the three oblique head impact cases. The Länsförsäkringar rating method was based on the average of the obtained risks for the three impacts. The same risk function as Folksam was used, see Equation (1).

The Certimoov rating [18] was calculated by taking the average of the calculated Certimoov risk R_{CM} of all six oblique impact cases. The risk R_{CM} is based on risk curves obtained from 109 FE-reconstructed head trauma cases, collected from documented motorcycle accidents, football accidents, pedestrian accidents and Formula One accidents [26-28]. The intracerebral von Mises stress σ and the risk of injury R_{CM} in terms of moderate Diffuse Axonal Injuries (mDAI) were obtained using the software SUFEHM Box (version 3.20200619, Humanetics Group, Farmington Hills, MI, US). The linear and rotational head accelerations were used as inputs to run the Strasbourg University Finite Element Head Model (SUFEHM) [32] internally by the software, which assumed that a maximum stress of 36 kPa corresponded to a 50% risk of mDAI.

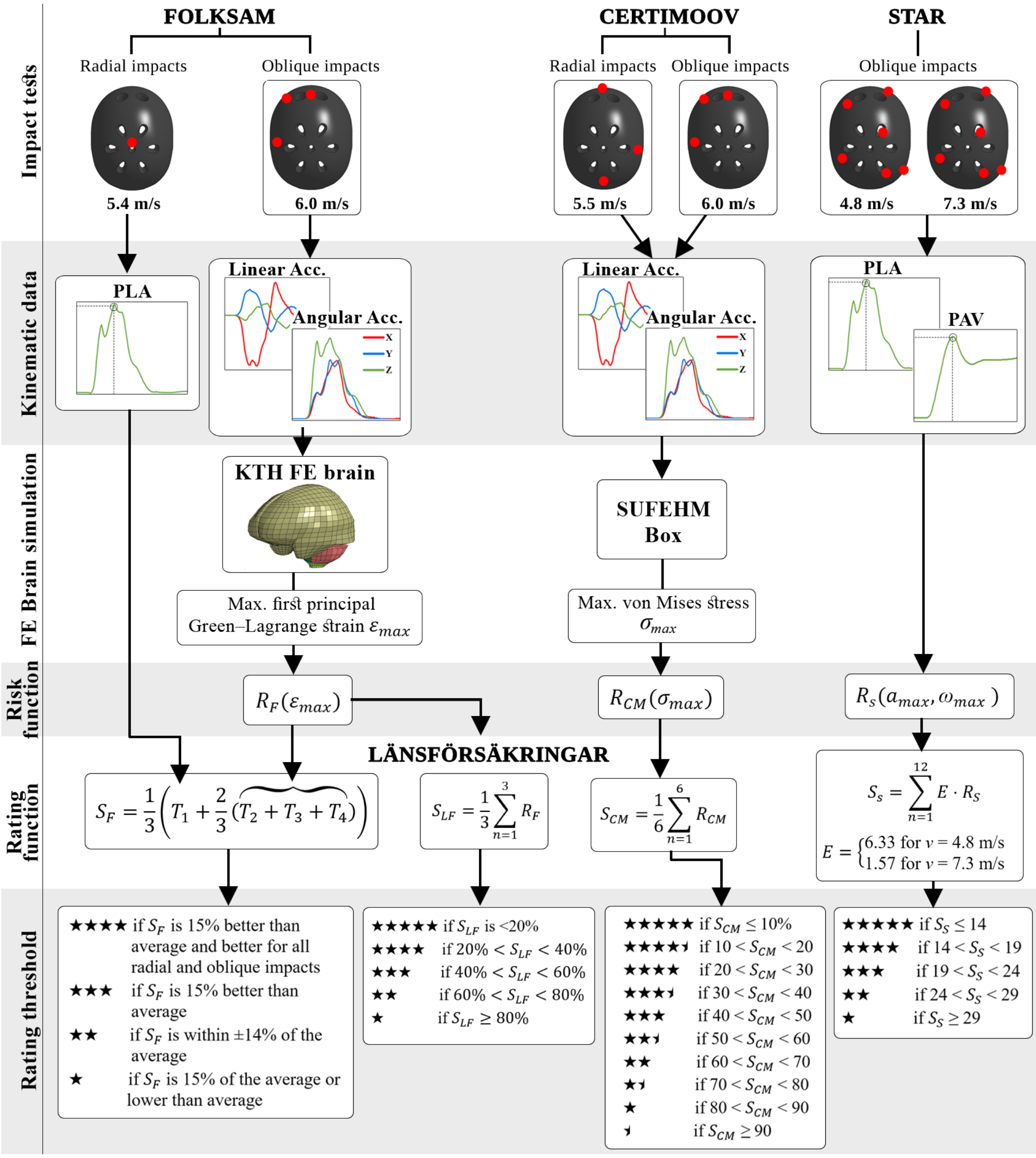

Fig. 3. Steps to obtain the Folksam, the Länsförsäkringar, the Certimoov and the STAR helmet rating. Note that T_1 denotes the PLA of the Crown impact case divided by the average of PLA including all reference helmets. T_2 to T_4 are the calculated risks for each Folksam oblique impact case divided by the average risk including all reference helmets.

The STAR rating [16] was calculated by using the resultant PLA and PAV to estimate the STAR risk of concussion R_S for each impact case. The rating was calculated based on the risk weighted by a so-called exposure term E (-) assumed to reflect the impact case frequency in real-world impact scenarios (see Fig. 3). The risk was calculated as:

$$R_s(a,\omega) = \left(1 + e^{-(10.2 + 0.0433 \cdot a + 0.19686 \cdot \omega - 2.075 \cdot 10^{-4} \cdot a\omega)}\right)^{-1} \quad (2)$$

where a (g) denotes the resultant PLA and ω (krad/s^2) denotes the resultant PAV of an impact. The risk equation was generated using logistic regression of head impact data from concussive and non-concussive head impact cases of American football players [33].

III. RESULTS

A visual comparison of the peak kinematic response for all impact cases is shown in Fig. 4. In the majority of impacts, EN960 headform produced lower PLA, PAA and PAV compared to HIII and NOCSAE headforms. In oblique impacts, HIII generally produced the highest PLA, PAA and PAV of the three headforms.

EN960 produced higher PLA compared to HIII in 2 out of 19 cases (Frontal and STAR2b), and 4 out of 19 instances compared to NOCSAE (Frontal, Yrot, Zrot and STAR2b). HIII produced lower PLA compared to NOCSAE in 3 out of 19 cases (STAR2a, STAR3a and STAR 3b).

EN960 produced higher PAA compared to HIII in 2 out of 19 cases (STAR2a and STAR2b), and 2 out of 19 instances compared to NOCSAE (Frontal, STAR2b). HIII produced lower PAA compared to NOCSAE in 1 out of 19 cases (Zrot).

For oblique impact cases, EN960 produced lower PAV compared to HIII in all cases. EN960 produced higher PAV compared to NOCSAE in two impact cases (STAR5a and STAR5b). In all straight impacts, NOCSAE produced higher PAV compared to HIII and EN960. In Frontal, Occipital and Lateral impact cases, EN960 demonstrated PAV similar to NOCSAE.

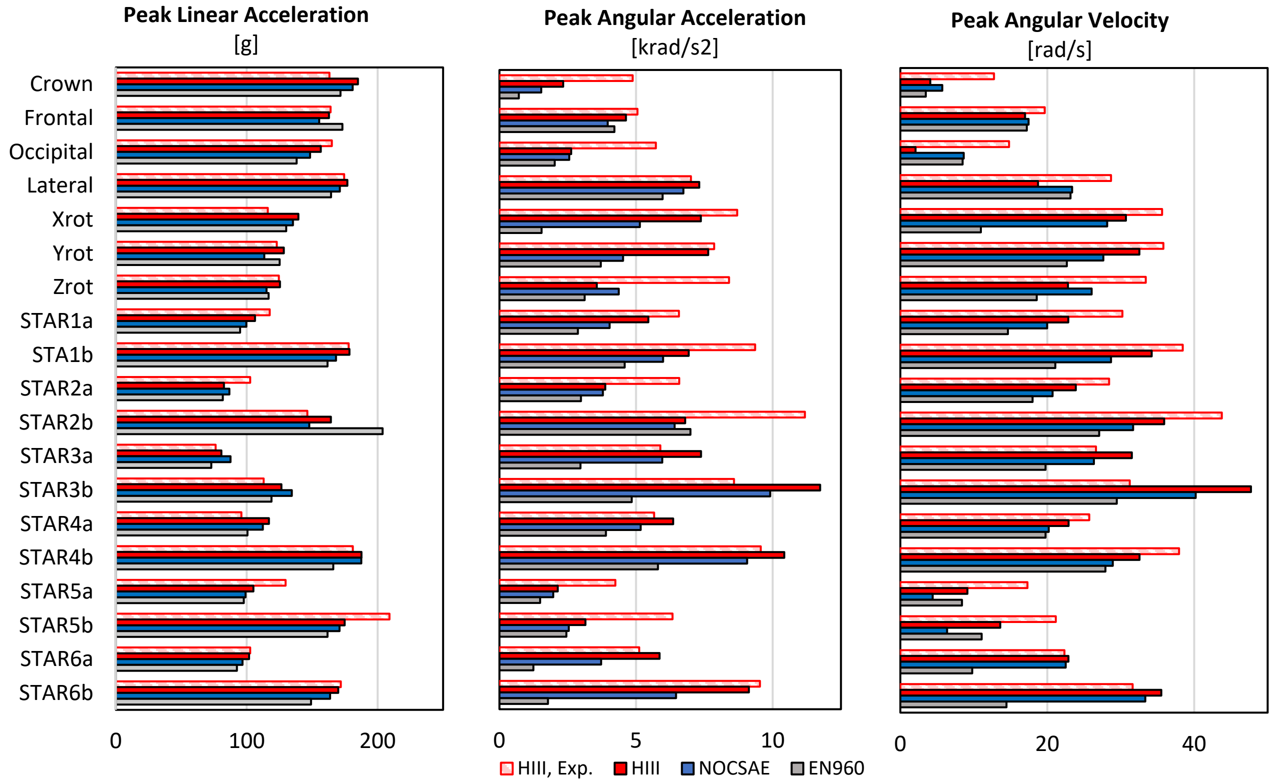

Fig. 4. Comparison of global kinematic peak values for each impact case simulated using HIII headform (red), NOCSAE headform (blue) and EN960 headform (grey). PLA data are shown to the left, PAA in the middle and, PAV to the right. Experimentally derived peak data using HIII headform is also included in the figure (striped red).

In general, the headform choice had more influence on the PAA and PAV than it had on the PLA. In oblique impacts, HIII and NOCSAE headform did not produce more than 7.1% higher PLA compared to EN960 on average, and more than 79% higher PAA and 38% higher PAV on average.

The largest differences in kinematics among the headforms were between HIII and EN960 headform. On average for oblique impacts, HIII produced 7.1% (±8.4) higher PLA, 130% (±140) higher PAA and 60% (± 52) higher PAV compared to EN960. The largest difference in peak value ratios between the two was for impact case STAR2b in PLA, STAR6b in PAA and Xrot in PAV.

Comparing the two rubber-coated headforms in oblique impacts, HIII produced 3.5% (±6) higher PLA, 24% (±22) PAA and 25% (±36) higher PAV compared to NOCSAE headform. The largest difference in peak value ratios between the two was for impact case STAR2b in PLA, Yrot in PAA and STAR5b in PAV.

The calculated risk values for Folksam/Länsförsäkringar and STAR rating methods are shown in Fig. 5. Using EN960 resulted in injury risks noticeably lower than both HIII and NOCSAE in most impacts, except impact cases STAR2b and STAR5. All STAR impact cases yielded higher risk of concussion (according to STAR risk metric) when using HIII instead of NOCSAE. Regarding Folksam/Länsförsäkringar risk metric, the risk of concussion was significantly higher when using HIII in Xrot and Yrot impacts compared to using NOCSAE. The Folksam/Länsförsäkringar risk R_F for impact cases Xrot, Yrot and Zrot were, on average, 82% (±9.4%) using HIII, 61% (±20%) using NOCSAE and 24% (±9.9%) using EN960. The STAR risk R_S for all STAR impact cases was, on average, 51% (±41%) using HIII, 43% (±41%) using NOCSAE and 24% (±31%) using EN960.

The risk of AIS2+ brain injury R_{CM} according to the Certimoov injury risk metric is not presented due to limitations in the license agreement of the SUFEHM box software.

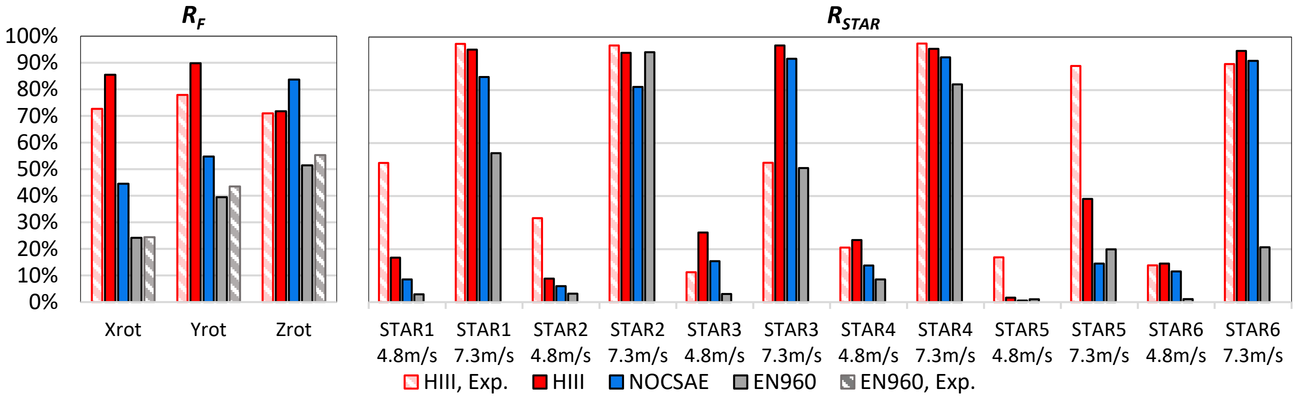

Fig. 5. Risk values for Folksam/Länsförsäkringar injury risk metric (left) and STAR (right). R_F denotes the risk of concussion according to Folksam injury risk metric. R_{STAR} refers to the risk of concussion according to STAR injury risk metric.

The calculated scores and corresponding ratings for each rating method are presented in Table IV. The Folksam score was calculated to be 1.94 using HIII headform, 1.42 using NOCSAE and 1.01 using EN960.

The influence of the headform choice was dependent on the rating method. The helmet was rated higher by Folksam rating program using EN960 headform compared to using HIII or NOCSAE headform. For Länsförsäkringar, all three headforms resulted in a different number of stars. For Certimoov and STAR rating programs, the helmet model received the same end-rating by using HIII headform as using NOCSAE headform or EN960. The STAR and Folksam final scores were the highest using HIII headform, but did not result in a lower final rating compared to using NOCSAE.

TABLE IV
FINAL CALCULATED SCORES AND RATINGS

	HIII		**NOCSAE**		**EN960**	
	Score	Rating	Score	Rating	Score	Rating
Folksam	98% > avg.	★	44% > avg.	★	2.4% > avg.	★★
Certimoov	27%	★★★★	27%	★★★★	28%	★★★★
STAR	13.9	★★★★★	10.7	★★★★★	6.35	★★★★★
LF	82%	★	61%	★★	38%	★★★★

IV. DISCUSSION

In this study, the influence of ATD headform on the safety performance evaluation of bicycle helmets was investigated. The results show that the choice of headform has an evident effect on the kinematic response of helmeted head impact tests considered by proposed rating methods. For drop tests against a flat and an angled surface, the use of EN960 instead of NOCSAE or HIII tended to reduce the PLA, PAA and PAV notably. Using HIII instead of NOCSAE headform in oblique impacts generally produced higher PLA, PAA and PAV. The proposed risk functions of concussion predicted lower injury risks when EN960 headform was used for head impact tests instead of NOCSAE or HIII. The results imply that the safety performance of helmets could potentially be rated differently dependent on the choice of headform, which could confuse the end-user. For example, in the rating method presented by LF the helmet received four stars when the EN960 headform was used, two stars for NOCSAE headform and one star for the HIII headform. The results presented in this study highlight how the choice of headform might influence the results in helmet impact tests and emphasizes the occasional contradictions in helmet ratings presented by helmet rating programs. The demonstrated differences in peak kinematics is a valuable contribution to the ongoing discussions and efforts in developing new biofidelic headforms and future standard safety assessment strategies for helmets.

Kinematic Response

For the vast majority of the straight and oblique impact cases evaluated in this study, NOCSAE headform resulted in lower PLA compared to HIII. For all oblique impact cases, HIII resulted in a higher PAA compared to NOCSAE. This trend has varying levels of agreement with other studies comparing the two headforms. Reference [13] conducted experimental helmeted drop impact tests on a road bicycle helmet using both HIII and NOCSAE, testing impact cases that were similar to impact cases we refer to here as Xrot and Yrot. In accordance with the results presented in Fig. 4, [13] showed that the PLA, PAA and PAV were 17–35% greater using HIII headform compared to NOCSAE. It should be mentioned that in [13], a dissimilar helmet model was used and the results were based on physical experiments.

Reference [12] conducted helmeted impacts under comparable conditions as the Folksam and LF method presented in this study. It was also concluded in the study that a similar EN960 headform produced lower PAA and PAV compared to HIII in Xrot and Yrot impact cases. However, it was also found that their EN960 headform produced slightly lower PLA compared to HIII, which is not in line with the findings of this study. The discrepancy could be partly explained by the slight inertial differences between the EN960J headform used in this study and stated by [12], as well as the differences in helmet models. It has previously been established that there is a close relationship between impact response and headform inertia in helmeted oblique impacts [12].

The inertial properties associated with each of the three headforms can explain some of the differences seen in kinematic response demonstrated by the three headforms, particularly when it comes to the oblique impact cases. The inertia about the X- and Y-axis for the NOCSAE headform is 18% and 13% larger than for the HIII headform, while the inertia about the Z-axis is 11% larger for HIII than NOCSAE. The differences in headform inertia did not greatly affect the linear acceleration of the impact, but might yet be manifested in the rotational kinematic response of the helmeted head during impacts that induce head rotation. For instance, Xrot, Yrot and Zrot impact cases are designed to produce rotations mainly around one axis, hence the names Xrot, Yrot and Zrot. For Xrot, Yrot and Zrot impact cases, the PAA was affected by the choice of headform of a magnitude not comparative to the straight impacts. In accordance, [12] reported that the headform inertia has apparent effect on the PAA of helmeted impacts, while the PLA is more influenced by the mass distribution about the impact location. The moment of inertia and the mass of the human head vary considerably across the population, so it is possible that the headforms presented in this study fall within a biofidelic range. However, the differences in the responses between these headforms emphasize the need for a new biofidelic headform, developed with accurate inertia, mass distribution and COG – a necessity that has also been stressed by other researchers [12].

A major difference between the HIII, NOCSAE and EN960 headforms is their helmet-liner frictional properties. Both HIII and NOCSAE have a rubber coating, while the EN960 headform has an exterior metal surface. As a result, these headforms show varying sliding properties, which can influence the response in helmeted impact tests. In this study, the EN960 headform was defined with a rather low COF compared to the HIII and NOCSAE headforms, in accordance with previous findings. In study [34], a COF of 0.75 was reported for the helmet internal liner and rubber coating of HIII. In the same study, a notably lower headform-to-helmet COF of 0.16 for a magnesium EN960 headform was observed. Reference [35] derived COFs for headforms against a woven cotton fabric, where a COF of 0.20 for uncoated headforms and 0.78 for rubber-coated headforms was observed. Efforts have also been made to investigate the actual COF of human scalp against helmet liner, where coefficients of 0.29 [34] ranging up to 0.68 [36] has been suggested. There are ongoing discussions about whether or not the sliding properties of the head are accurately represented in the ATD headforms [34]. Consensus has not been reached regarding a viable COF for the head-liner interface, therefore studies are needed to validate the frictional properties of the headforms. In the current study, a friction coefficient of 0.70 was used for the rubber-coated headforms, supported by the findings by [34] and [35]. A COF of 1.0 was also tested, but with negligible effect, see Appendix for details. For the EN960 headform, a friction factor of 0.30 was chosen based on its agreement with the experimental impact tests, see Appendix for details.

Helmet Rating

The risks calculated for the Folksam/Länsförsäkringar and STAR head impact cases highlight the influence that the choice of headform can have on helmet assessments. The EN960 headform produced Folksam/Länsförsäkringar and STAR injury risks far below the risks produced by helmeted oblique impacts using HIII or NOCSAE in most cases. The risk of concussion derived by the STAR method was the highest for all impact cases when using HIII headform.

Helmet ratings have previously been recognized to be affected by the choice of FE brain model and risk metric [37], but to the authors' knowledge no studies have evaluated the influence of the ATD headform on the output of FE brain simulations nor the risk metrics. In this study, the KTH head model produced varying risk levels of concussion for Xrot, Yrot and Zrot among the headforms. The KTH head model has previously been shown to be sensitive to rotations [37], which might explain why the high differences in PAA and PAV for the three impact cases are translated into high differences in injury risks. The SUFEHM model, which is used for the Certimoov rating, might be more sensitive to linear accelerations. Reference [38] show higher correlation to PLA than to PAV for the SUFEHM model, while [37] show higher correlation to PAV than to PLA for the KTH model.

Likewise, the different FE headforms were also shown to be more or less sensitive to rotations. EN960 showed significantly less response to induced rotation compared to HIII and NOCSAE, as clearly shown in Fig. 4, which is a somewhat expected outcome [12][35]. This could partially be explained by the observed poor biofidelity of the standard EN960 headforms in regard to mass and inertial properties [12], but also by the differing COF at the interface between the headform and the interior of a helmet, as observed in [35]. In [35], helmeted head impacts using a 'bare' headform was compared to using a rubber-coated headform. By having the same inertial and mass properties of the two headforms, it could be observed that the frictional properties alone had considerable influence on the impact kinematics, and was also dependent on the magnitude of the tangential velocity.

It can be hypothesized, that the impact response of HIII and NOCSAE headform would be more similar to EN960 headform if the COF between the headform outer surface and the helmet liner was the same. This was briefly investigated in this study, where HIII headform was simulated with the same COF as EN960 (0.3) in Xrot, Yrot and Zrot. The PAA and PAV was indeed decreased by reducing the COF to 0.3 from 0.7, moving towards more similar-looking curves compared to EN960 simulated time-histories. However, a more extensive study might be needed to draw any reliable conclusions in this matter. See Appendix for details on the comparison.

Reference [37] had demonstrated how helmet ratings are influenced by the choice of assessment metric and how kinematic-based metrics can differ depending on the choice of FE head model. In the mentioned study, eight different brain FE models were used to rank and rate 17 different bicycle helmets subjected to oblique impacts, using multiple outputs. Even though a generally good correlation between FE models was observed, there were noteworthy exceptions. For instance, one particular helmet model was rated with two stars using one brain model and four stars using another, illustrating the sometimes contradictory recommendations for end-consumers that have been discussed in the current study. Supported by the conclusions made in [37], there is a clear need for further evaluation of the performance of injury metrics and standardized validation procedures for FE head models.

The calculated scores for the helmet were all influenced by the choice of headform. The final rating was affected differently depending on the rating method. Following the Folksam rating program resulted in two different ratings of the helmet. The Folksam rating based on helmeted impacts using EN960 resulted in a higher rating of the helmet compared to using HIII or NOCSAE. The choice of headform had a significant influence on the Länsförsäkringar rating of the helmet, resulting in three different ratings from 1-star to 4-star.

The final STAR rating was not affected by the headform. However, the rating scores showed observable sensitivity to the different headforms. The helmet was rewarded the highest possible scores by the STAR rating program. Judging by the CORA scores and kinematic time-histories comparing the simulations with the experiments, the FE model showed a tendency to underestimate the rotational kinematics. This might in particular influence the STAR rating, since the STAR function is related to the PAV in a more direct sense than Folksam and Certimoov rating functions. If the PAV is underestimated by the simulation model, it might also lead to overestimated STAR ratings. It could be that the experimental test configuration did not perfectly match the impact configurations suggested by the STAR rating program [16] due to the complexity of the impact configurations. The STAR impact cases required an initial positioning of the helmeted head specified by three specified angles (an angle relative to the head X-, Y- and Z-axis, whereas Folksam and Certimoov impact cases mostly involved one axis of rotation to consider when positioning the helmeted head, facilitating the reproducibility of the drop tests.

When examining the rating for similar helmet models performed by Virginia Tech [39], few of them were rated high. A helmet of similar type and geometry received similar score to the experimental values in this study (17.5 compared to S1 Lifer 17.83). This suggests that the scores calculated based on the simulations might be too low and could raise the rating. Irrespectively, the aim of this study was to bring attention to the difference between headforms. This difference is still clearly reflected in the calculated scores of 6.35-13.9. For the Certimoov rating program, all headforms resulted in four stars.

The varying differences in peak kinematics between the headforms are not to be overlooked. In numerous suggested ratings methods, peak kinematic values are often used as pass/fail thresholds or incorporated into rating functions. Hence, if the choice of headform has an increasing/decreasing effect on the input values, it can cause the rating methods and standard tests to fail in excluding unsafe helmets from the consumer market. The difference among headforms and their effect on safety assessments should be addressed, especially since efforts are currently being made to develop a new test method for helmet standard in Europe [40].

Models

The models used in the FE simulations of this study were evaluated against a series of experimental tests. Some simulated impact cases demonstrated particularly low similarity with experiments, such as the Occipital and Crown impact cases, which obtained an overall CORA score of 0.45 and 0.49, respectively. This might suggest that we may obtain different ratings using the experimental impact data. This of course serves as one of the major limitations of this study. More validation of the material model for the helmet foam liner is needed. Adding complexity to the material model, such as viscoelastic behaviour in shear, and amending the helmet geometry to better match the physical model would also play a key role in the fidelity of the model.

Some of the variances between experimental and numerical data may be explained by the geometric differences between the physical helmet model and the FE helmet model. The two helmet models showed some difference of shape and geometry, especially in the occipital and parietal part the helmet, which may become extra evident during head impacts impacting those regions. Furthermore, the FE helmet model was designed without restraint system or chinstrap, which might also influence the reported impact kinematics to some extent, even though no particular relative movement between the headform and helmet was observed. Example images of the helmet position relative to the helmet at the end of head impact are found in the Appendix. It has previously been shown that for motorcycle helmets, the comfort foam has little effect on the PLA and PAV [41]. Note that the comfort foam in motorcycle helmets are much thicker compared to the thin comfort foam in the physical helmet model used in this study. Even though the restraint system was not tightly secured, the restraint system could of course influence the experimental results. But it should be emphasised, that the helmet model in this study has been evaluated against an extensive set of validation data, covering more impact tests than often seen in other helmeted impact simulation studies. It is not uncommon to only validate simulated helmet impacts against peak kinematics, whereas in this study CORA scores have been calculated for three kinematic metrics, analysing all of its components and not only resultants.

During the experiments, in some cases the helmet was fractured due to the impact. The material model implemented in the FE simulation neglected such behaviour, adding a plausible explanation for some of the low CORA scores and sometimes seen discrepancies between two sets of experimental impact time-histories.

No physical head impact tests were performed using the NOCSAE headform, which is a limitation of this study. The validity of the NOCSAE FE model has, however, been asserted in previous studies. Reference [42] validated the FE models against 20 commonly used load cases for helmet evaluation, including drop tests, pendulum impactor tests and linear impactor tests. Furthermore, in the process of validating a FE model of a football helmet, 19 helmeted headform impact cases were simulated using the NOCSAE FE headform, showing overall high CORA scores comparing the FE simulation and physical experiments [43]. Similarly, [44] and [42] found a good correlation between simulations and physical experiments in their studies using the NOCSAE FE model to validate FE football helmet models.

V. CONCLUSIONS

The choice of headform has an effect on the kinematics of simulated helmeted head impact tests considered by helmet rating programs. For drop tests against a flat or an angled surface, the use of EN960 headform instead of NOCSAE or HIII might decrease the PLA, the PAA and the PAV. The proposed risks of concussion were comparatively low for oblique impacts using EN960 headform. The tendency of different headforms to produce varying rotational motion in oblique impacts raises questions about which of the metal headforms are suitable for such impact tests. The results imply that the safety performance of bicycle helmets might be rated higher when using standard uncoated metal headforms. The test series presented in this study contributes to a wide-ranging comparison of helmeted kinematic response for HIII, NOCSAE and EN960 headforms.

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VIII. Appendix

Time-histories for Impact Cases

The results from the simulations were verified against 38 experimental helmeted drop impact tests. In Fig. A.1 – A.4, the experimental kinematic time-histories using the HIII headform are compared to the results from the simulations. In Fig. A.5, the experimental kinematic time-histories using the EN960 headform is shown compared to the simulated time-histories. The data have been filtered with a CFC 1000 filter before analysis.

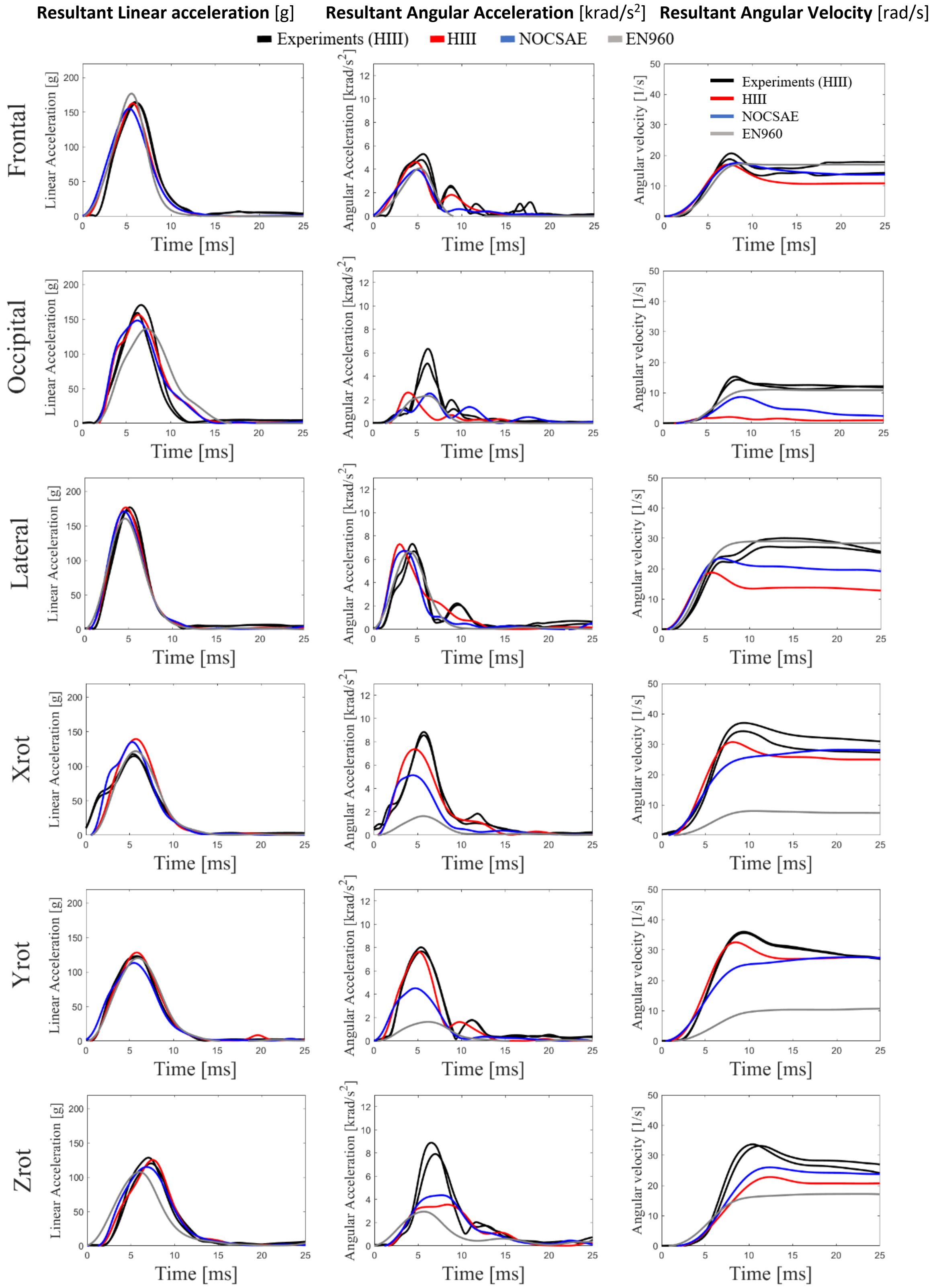

Fig. A.1. The kinematic time-histories for impact tests Frontal, Occipital, Lateral, Xrot, Yrot and Zrot. The experimental results are shown in black, and the simulation results are shown in red (HIII) and blue (NOCSAE).

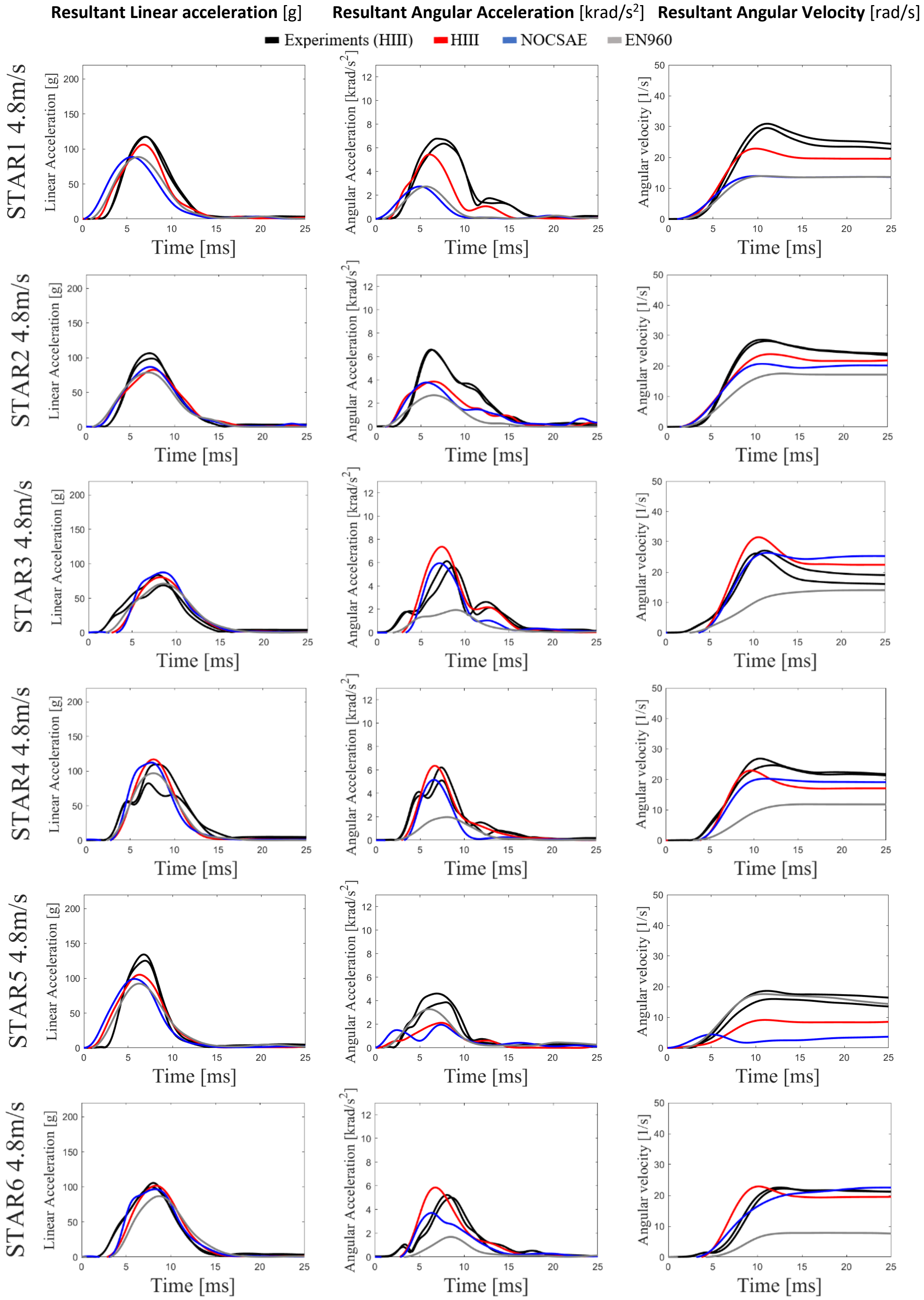

Fig. A.2. The kinematic time-histories for impact tests STAR1-STAR6 for drop velocity of 4.8m/s. The experimental results are shown in black and the simulation results are shown in red (HIII) and blue (NOCSAE).

Resultant Linear acceleration [g] **Resultant Angular Acceleration** [krad/s^2] **Resultant Angular Velocity** [rad/s]

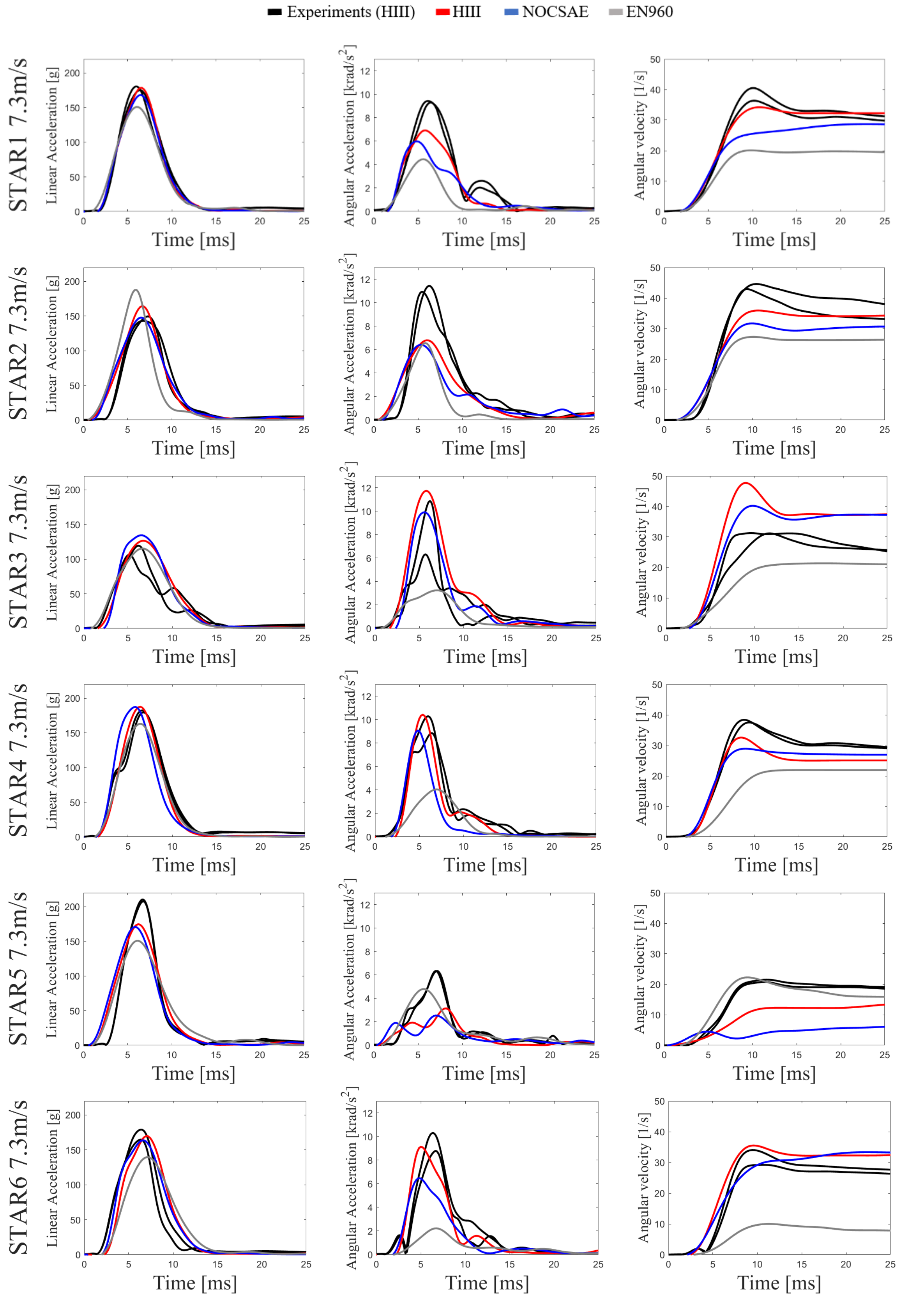

Fig. A.3. The kinematic time-histories for impact tests STAR1-STAR6 for drop velocity of 7.3m/s. The experimental results are shown in black and the simulation results are shown in red (HIII) and blue (NOCSAE).

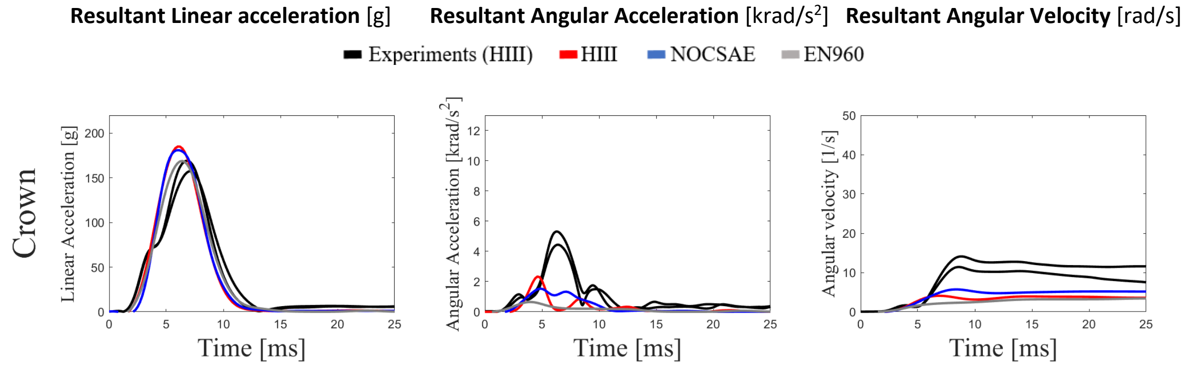

Fig. A.4. The kinematic time-histories for Folksam straight impact. The experimental results are shown in black and the simulation results are shown in red (HIII) and blue (NOCSAE).

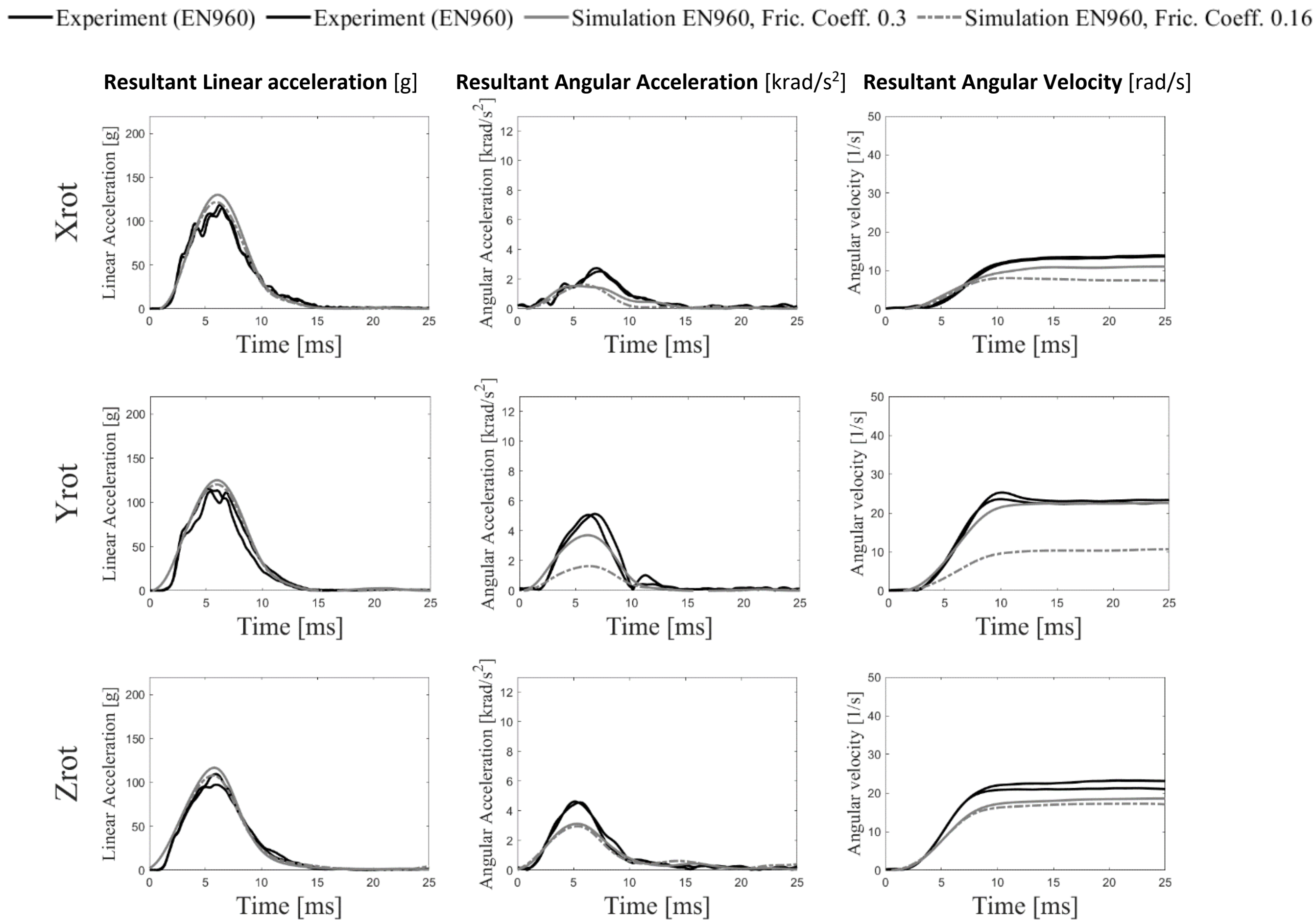

Fig. A.5. The kinematic time-histories for Xrot, Yrot and Zrot using EN960 headform. The experimental results are shown in black and the simulation results are shown in grey. Two friction coefficients were tested in the simulations: 0.16 (dotted line) and 0.3 (solid line).

A higher friction factor was tested for NOCSAE and HIII impacts. In Fig. A.6 below, the difference between the impact cases using a COF of 0.70 compared to 1.0 is presented. Less than 1% difference was shown in PLA, less than 4% for PAA and less than 1% for PAV.

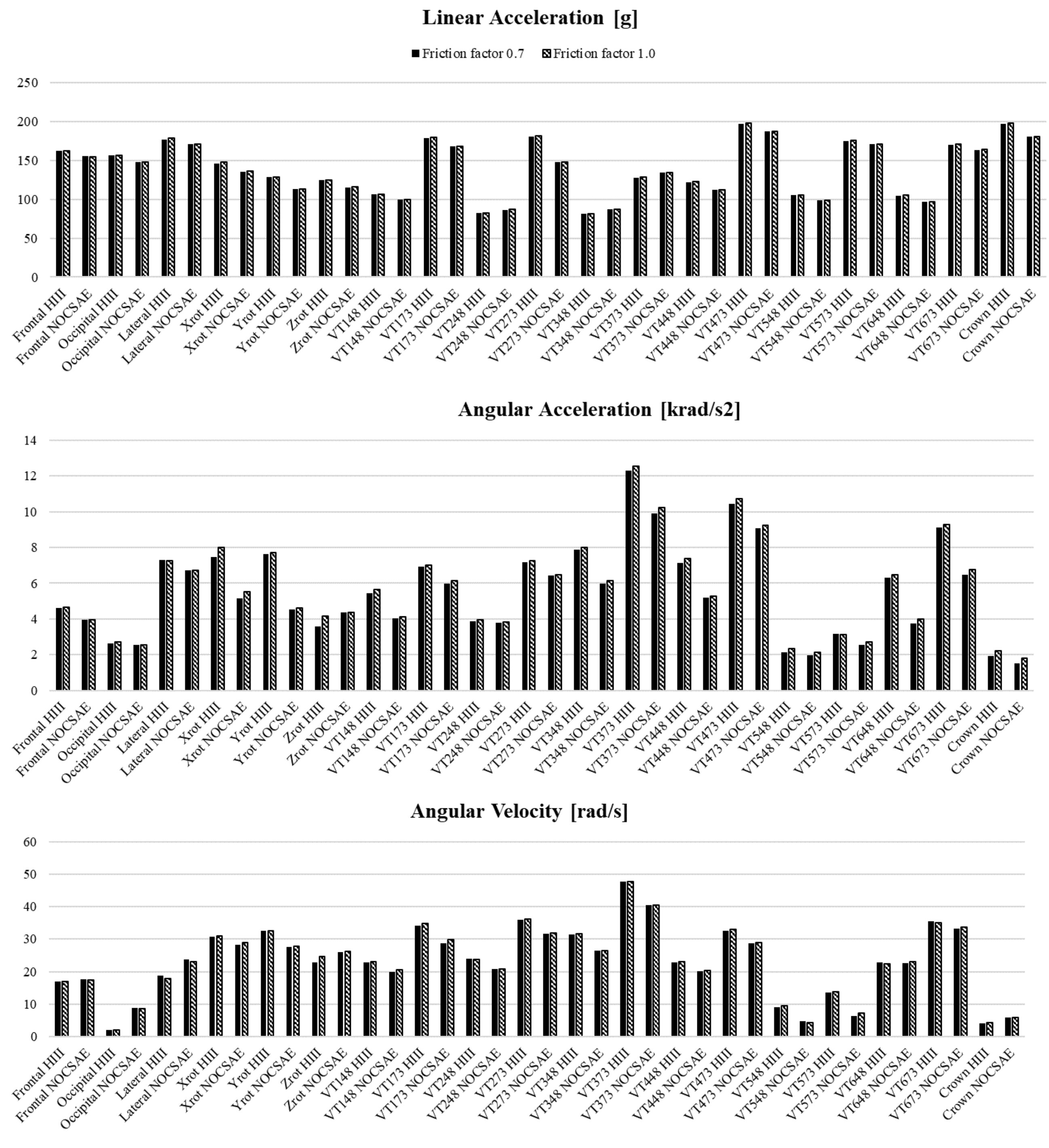

Fig. A.6. PLA, PAA and PAV for NOCSAE and HIII using two different friction factors.

Experiment Setup and CORA Scores

The helmet was positioned on the headform with a distance between the nose tip and the helmet rim of 65 mm and aligned with the centreline of the helmet and headform. The neck retention system was tightened so that the head and retention had contact, and the chinstrap was secured. The helmet was positioned in a cradle with the angles specified for the different impact tests [13-15]. The position of the headform was controlled with an inclinometer mounted to the bottom plate of the HIII headform with a margin of ±2.0° of the described values. The same drop velocities as presented in Fig. 2 were used. The experimental impact tests are presented in Fig. A.7.

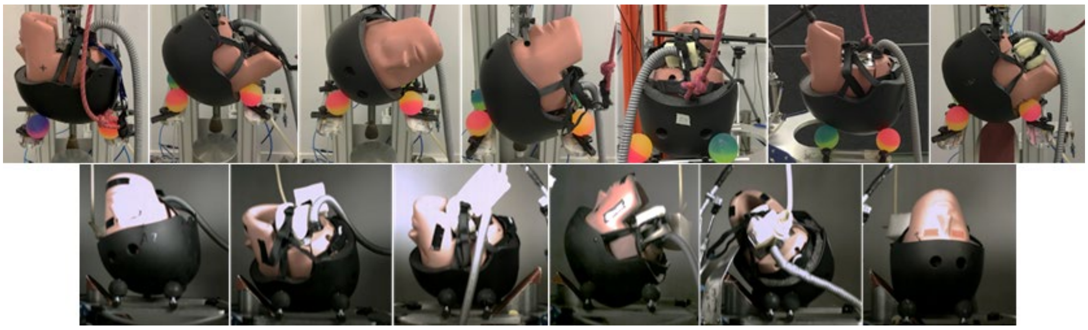

Fig. A.7. The different experimental tests: first row Crown, Frontal, Occipital, Lateral, Xrot, Yrot and Zrot; second row STAR 1-6.

Two experimental tests were made per impact case and the presented score is the average score between the two. The scores were calculated for X-, Y- and Z-components of the kinematic responses and averaged. The CORA score is a rating indicating how well two time-histories correlate and ranges between 0 and 1, where 1 indicates a perfect correlation and 0 a poor correlation. The components of the CORA score were weighted using the method described by Davis *et al.* [4]. For the parameters used in the CORA calculations, the default parameters presented in the CORA manual [5] were used, except for the time interval of evaluation which was set to start when head impact was initiated and to end after 20 ms. The resulting CORA scores are presented in Table A.I and A.II.

TABLE A.I
AVERAGE CORA SCORES FOR HIII HEADFORM IMPACT TESTS

	Linear Acceleration	**Angular Acceleration**	**Angular Velocity**
Frontal	0.91	0.67	0.73
Occipital	0.84	0.21	0.30
Lateral	0.95	0.52	0.56
Xrot	0.80	0.66	0.71
Yrot	0.90	0.74	0.74
Zrot	0.93	0.50	0.78
STAR1 4.8m/s	0.84	0.81	0.86
STAR1 7.3m/s	0.90	0.72	0.86
STAR2 4.8m/s	0.85	0.64	0.79
STAR2 7.3m/s	0.87	0.67	0.79
STAR3 4.8m/s	0.86	0.68	0.76
STAR3 7.3m/s	0.82	0.47	0.70
STAR4 4.8m/s	0.72	0.59	0.72
STAR4 7.3m/s	0.90	0.72	0.82
STAR5 4.8m/s	0.72	0.37	0.38
STAR5 7.3m/s	0.71	0.33	0.36
STAR6 4.8m/s	0.82	0.72	0.61
STAR6 7.3m/s	0.80	0.66	0.60
Crown	0.60	0.42	0.44

TABLE A.II
AVERAGE CORA SCORES FOR EN960 HEADFORM IMPACT TESTS

	Linear Acceleration	**Angular Acceleration**	**Angular Velocity**
Xrot	0.93	0.59	0.79
Yrot	0.88	0.73	0.84
Zrot	0.86	0.88	0.83

In Fig. A.8, a cross section of the NOCSAE headform and helmet during impact Yrot and Xrot is shown to illustrate any potential relative motion between headform and helmet.

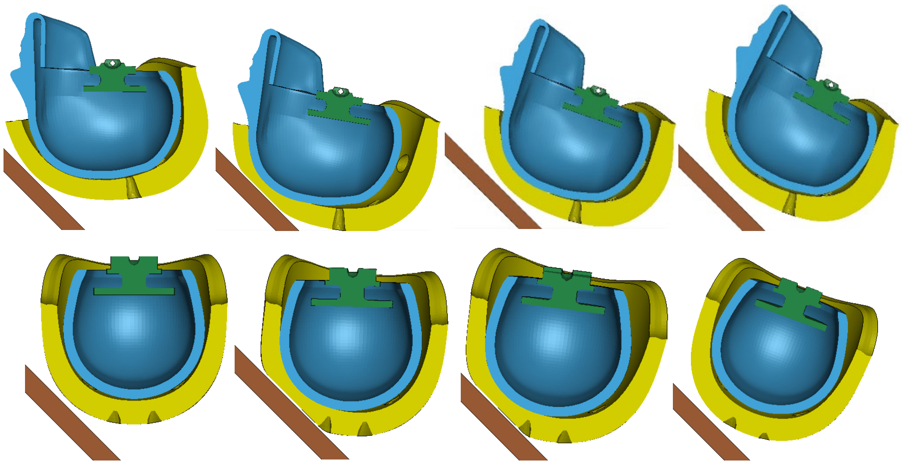

Fig. A.8. Cross section of NOCSAE headform during impact: Yrot (top row) and Xrot (bottom row).

In Fig. A.9., a comparison of the kinematic time-histories for simulated impact cases Xrot, Yrot and Zrot using EN960 and HIII with two different COF is shown.

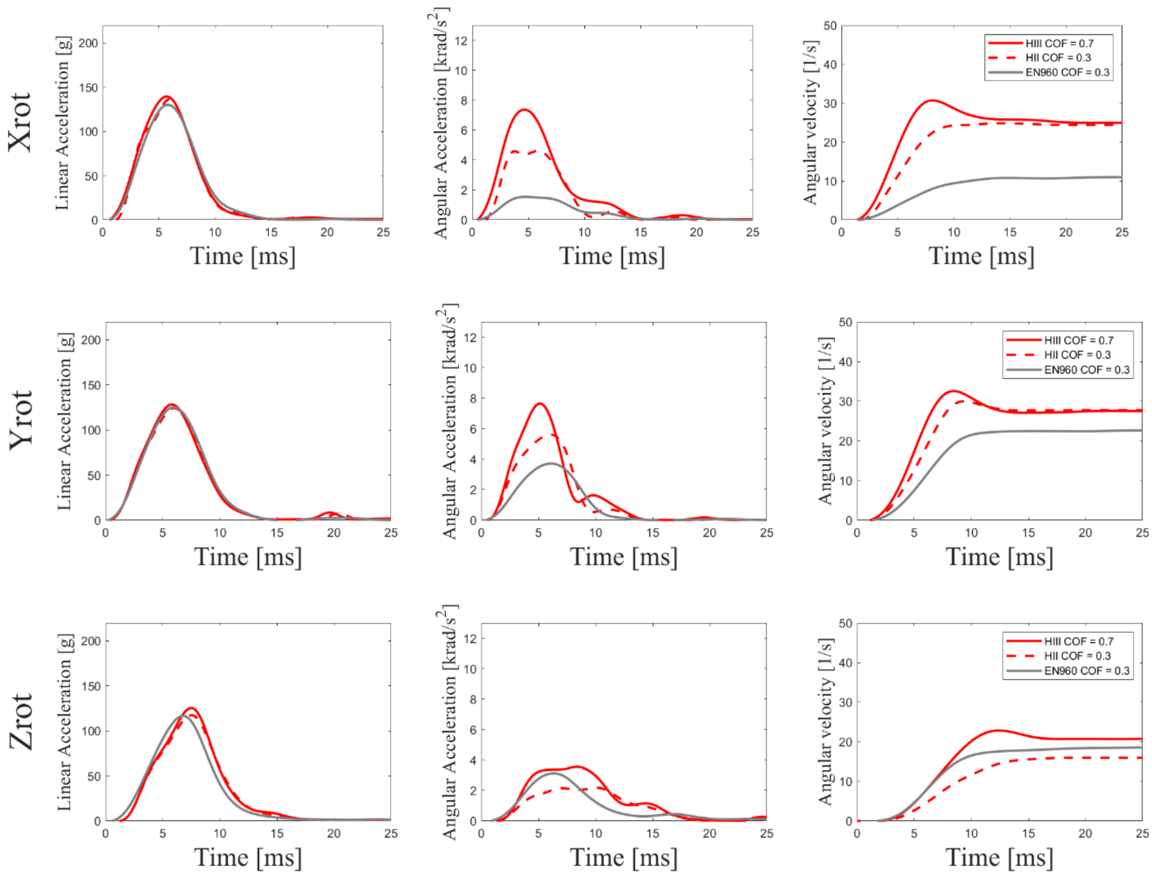

Fig. A.9. The simulated kinematic time-histories for Xrot, Yrot and Zrot using HIII (red) and EN960 headform (grey). For HIII, two different COF was tested and presented in the plots: 0.30 (dotted line) and 0.7 (solid line).

Head Impact Configurations

In Fig. A.10, the positioning of the helmeted headform is specified for each impact case. The positioning applies to the EN960 headform as well.

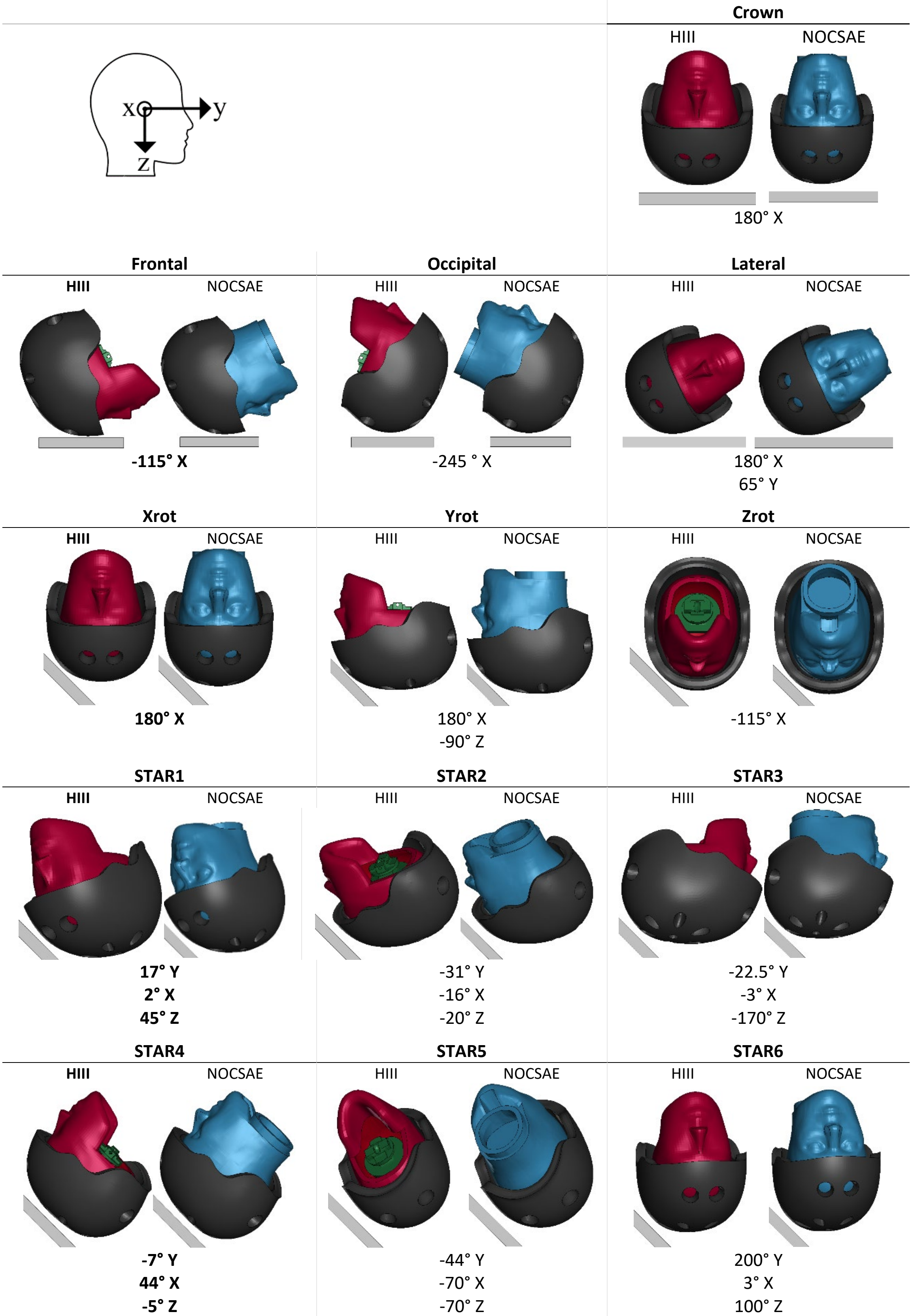

Fig. A.10. Positioning of helmeted head in simulations, for HIII and NOCSAE, with specified rotations. The default position of the head together with the coordinate system used is illustrated as well. This also applies to the EN960 headform.