How Efficient are the Rotational Impact Tests in ECE R22.06 Motorcycle Helmet Test Standard to Decrease the Rotational-Induced Brain Injuries?

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Abstract Head injuries are among the most common injuries in motorcycle accidents, where the helmet is the main protection. Until recently, the test standards have only evaluated protection against linear impacts. Evaluating protection against rotational impacts has been recently introduced. The objective of this study was to evaluate how current motorcycle helmets perform in ECE R22.06 rotational impact tests.

The rotational impact tests were performed on three helmet models and the linear impact tests were performed on one helmet model. All the helmets passed the rotational impact tests. The maximum value for the experimental tests was 4.5 krad/s^2 for PRA and 0.48 for BrIC compared to the threshold values of 10.4 krad/s^2 and 0.78. In the linear impact tests five out of twenty-two impact tests failed the threshold for peak linear acceleration or head injury criterion.

The results from this study suggest that motorcycle helmets will be more optimised towards reducing linear-induced injuries and not rotational-induced injuries in the newly introduced test standard ECE R22.06. This is not responding to the protection requirements when evaluating the accident statistics, which shows that rotational-induced injuries are as common or even more common than linear-induced injuries in helmeted motorcycle accidents.

Keywords Brain injury, head injury, helmet, motorcycle, test standard.

I. INTRODUCTION

Approximately 1.35 million people are killed every year in road traffic accidents and among them 28% are caused by powered 2- or 3-wheeler modes of transport [1]. The European project Pioneer has showed that motorcycling had the lowest decrease in fatalities between 2006 and 2015 in the European Union [2]. The same project also showed that head injuries are among the most common injuries seen in motorcycle accidents where data from fatal and non-fatal accidents were included from different European countries. Another study showed that the second most common injured body part for injuries with more severe long-term consequences (permanent medical impairment (PMI) 10+)) was the head [3].

Today, helmets are the primary source of head protection for motorcyclists. Many studies have shown a protective effect against head injuries when wearing a motorcycle helmet. Reference [4] showed in a Cochrane review comprising 18 different studies, that the unadjusted odds ratio between wearing and not wearing a motorcycle helmet was lower than 1.0 for all studies, meaning a protective effect against head injuries. These results were supported by another review article [5]. These reviews have focused on the protective effect against head injuries, grouping different types of head injuries together. Previous research has also shown different injury mechanisms for different types of head injuries [6–9]. So, to understand how test methods and helmet test standards can be improved it is essential to understand how the test methods can be designed to further reduce injuries. For example, skull vault fractures have shown a good correlation to linear acceleration [10], whereas some brain injuries such as concussion and diffuse axonal injury (DAI) have shown better correlation to angular kinematics [11].

Epidemiological studies have indicated that helmets protect more against skull vault fractures, compared to more diffuse injuries such as concussion and DAI [12–14]. This could be because helmets have only been evaluated for linear kinematics in straight impacts against flat, kerbstone, or hemisphere anvils in the test

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standards [15-16]. This could lead to a helmet optimisation against skull vault fractures and other injuries associated with linear kinematics. Recently, rotational impact tests have been introduced into different test standards such as the racing homologated programme by Federation Internationale de Motocyclisme (FIM) [17] and United Nation's ECE R22.06 [18]. These test standards are similar but have some important differences. The test standards are summarised in Appendix I. The oblique tests in both FIM and ECE R22.06 are performed by dropping the helmeted headform against a 45 degrees angled surface covered with abrasive paper. In the FIM test standard the linear and angular kinematics are evaluated, measuring the peak linear acceleration (PLA), head injury criterion (HIC) [19], peak rotational acceleration (PRA), and brain injury criterion (BrIC) [20]. Meanwhile in ECE R22.06 only the angular kinematics are evaluated by PRA and BrIC.

Prior studies have evaluated the rotational performance of motorcycle helmets with the new test standards. Reference [21] evaluated the influence of helmet/headform friction, which differs from the FIM-RHR programme and ECE R22.06, where FIM-RHR use the metal headform covered with a silicone layer (higher friction) and ECE R22.06 has just the metal headform (lower friction). They found that a combination of low friction and low tangential velocities could underestimate the rotation of the headform. To the authors' knowledge there is no study that has evaluated how current motorcycle helmets perform during the rotational impact tests in the new ECE R22.06 test standard. The objective of this study was to evaluate how current motorcycle helmets perform in ECE R22.06 rotational tests.

II. METHODS

Tested Helmets

Experimental tests as described in the ECE R22.06 standard for the rotational impact tests were performed on three helmets that represent the market (Helmets A, B, C). One of the helmets (Helmet C) was also evaluated in the linear impact tests as described in the ECE R22.06 standard to be able to compare the performance in the rotational and linear impacts when it comes to exceed the pass/fail criteria for the different impact configurations.

The helmet models are summarised in Table I. Helmet A and B have been certified according to the previous revision of ECE (ECE R22.05). Helmet C is developed for research purposes and not certified according to ECE R22.05. In total five helmets per helmet model were used for the oblique impacts and seventeen helmets for the linear impacts. Every impact configuration was tested twice with separate helmets.

TABLE I
HELMETS TESTED

	Helmet A	Helmet B	Helmet C
Mass (without visor) [kg]	1.38	1.49	1.15
Foam material	EPS	EPS	EPS
Shell material	Polycarbonate	Fiber composite	Glass-fiber composite
Rotational Protection System	No	No	No

Rotational Impact Tests

The oblique impact tests were performed according to the protocol specified in ECE R22.06 [18]. The impact configurations are shown in Fig. 1. The bottom of the EN960 headform was kept horizontal with the laboratory ground.

The EN960 headform (size J) was equipped with 3 linear accelerometer and 3 angular rate sensors. The accelerometer data were sampled at a frequency of 25 kHz and filtered with CFC 1000 for the linear accelerations and with CFC 180 for the angular velocities. The angular acceleration was calculated by differentiating the angular velocity with difference quotient.

The impact surface was angled 45 degrees and covered with 80 grit abrasive paper. The impact velocity was 8.1±0.06 m/s. All the tests were performed in ambient condition.

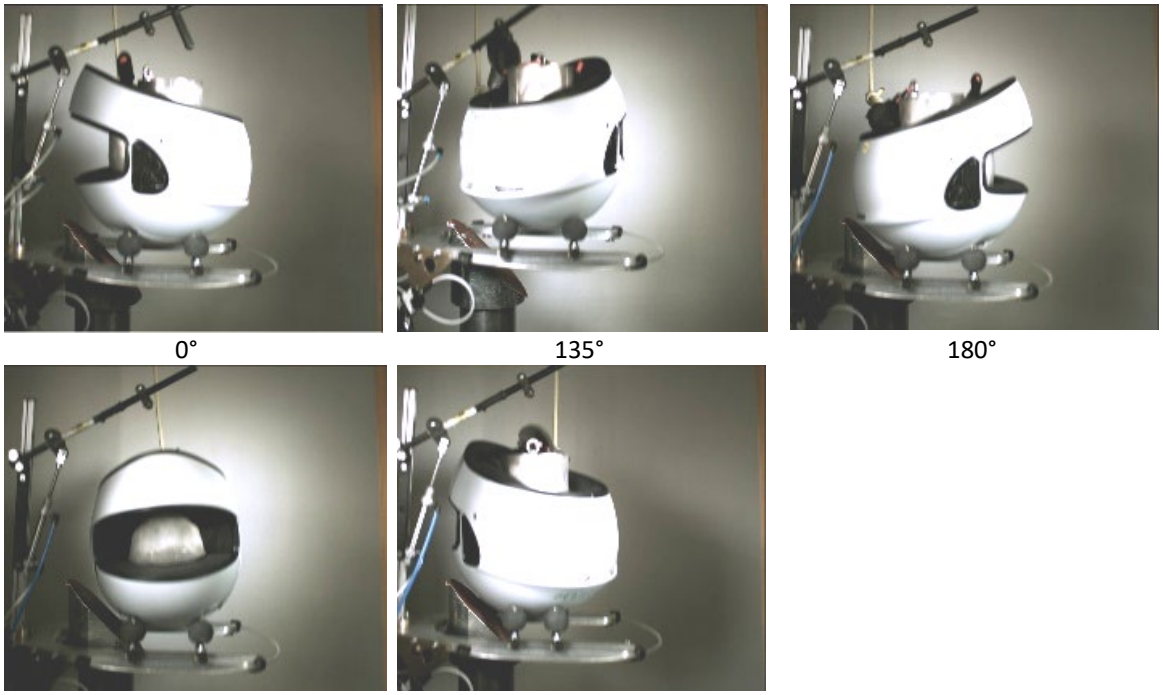

Fig. 1. The impact points for the oblique impact tests.

Linear Impact Tests

In addition to the oblique impacts, linear impact tests in ambient condition were performed for Helmet C. The helmet impact point located at the chin bar was not tested and evaluated in this study. The EN960 headform (size J) with the same accelerometer and rate sensor system used in the rotational tests was utilised. The impact was either against a flat surface or a kerbstone, and both were made of steel. Impacts were performed in three different velocities according to the standard in ambient condition [18]. The velocity was 6.0±0.02 m/s, 7.5±0.04 m/s, and 8.2±0.04 m/s.

In the standard the impact areas are defined, then the test lab decides the positioning of the headform and helmet to get the worst impact situation at the impact areas. The impacts that were evaluated for Helmet C is presented in Fig. 2 for the impacts against the flat surface and Fig. 3 for the impacts against the kerbstone.

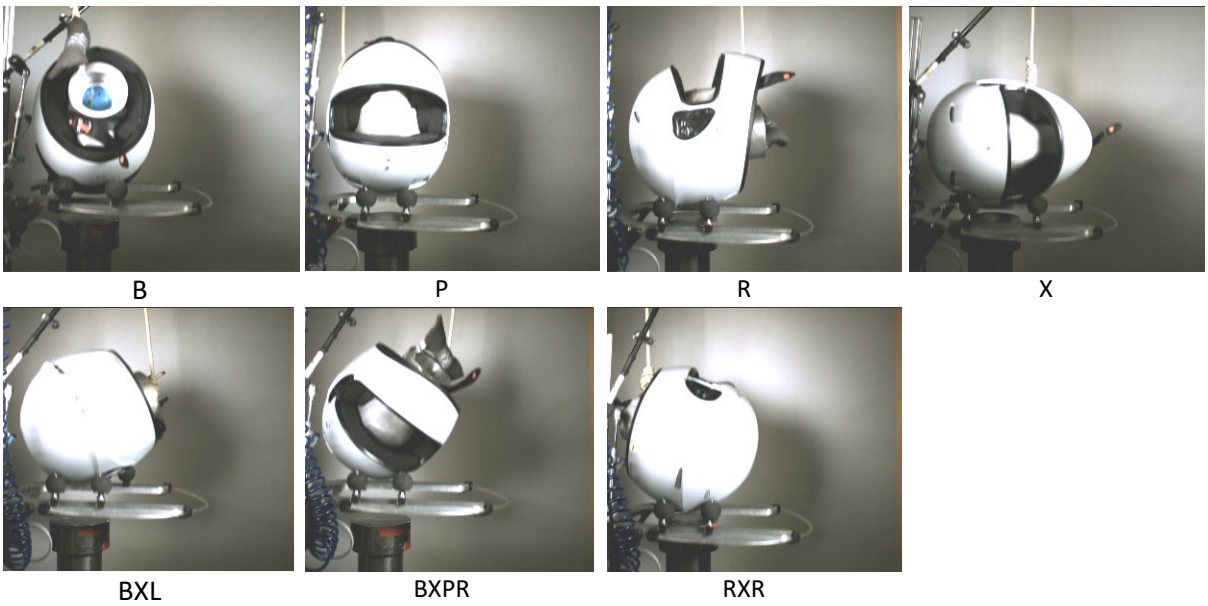

Fig. 2. The impact points for the linear impact tests against the flat surface.

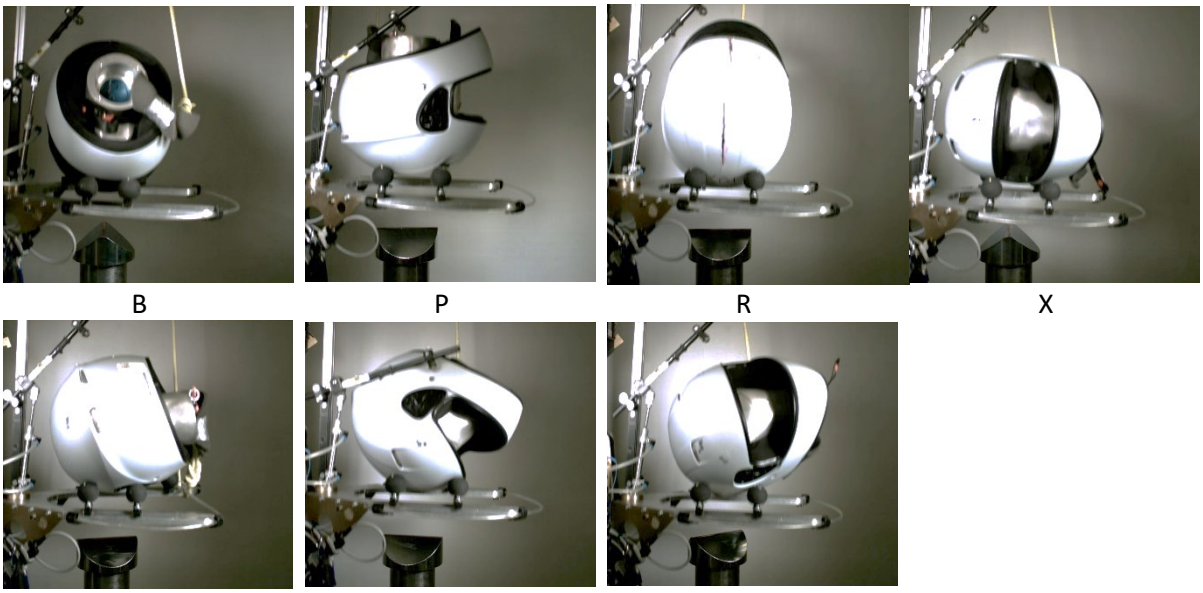

Fig. 3. The impact points for the linear impact tests against the kerbstone.

Data Analysis

The peak linear acceleration (PLA), head injury criterion (HIC) [19], peak rotational acceleration (PRA), and brain injury criterion (BrIC) [20] were calculated for all tests. The average value from the two replicated tests were used to analyse the results. These metrics were then compared to the thresholds proposed by ECE R22.06 [18]. The PRA should not exceed 10.4 krad/s^2 and the BrIC should not exceed 0.78 in the rotational impact tests. In the linear impact test the PLA and HIC were evaluated. The PLA should not exceed 180g in 6.0 m/s, 275g in 7.5 m/s and 8.2 m/s. The HIC should not exceed 1300 in 6.0 m/s, 2400 in 7.5 m/s, and 2880 in 8.2 m/s. To compare the results from the experimental tests and the threshold values, the ratio between the experiments and the threshold values were calculated. A ratio greater than one indicates that the test exceeded the threshold value.

III. RESULTS

Rotational Impact Tests

All three helmets, evaluated in this study for the rotational impact tests were below the threshold value for PRA, which mean that they had acceptable performance for the rotational tests. The peak value varied between 2.3 to 4.5 krad/s^2 for all three helmets and impact locations (Fig. 4). The highest PRA depended on both the impact location and helmet model. For example, Helmet B had similar values for all five impact locations (3.0-4.1 krad/s^2) whereas Helmet A had larger range (2.3-4.5 krad/s^2) with the lowest PRA being for 270 degrees.

In all the rotational impacts, the measured BrIC value had a value lower than the threshold of 0.78 (Fig. 4). Helmet A had a BrIC value ranging from 0.36 to 0.48, Helmet B 0.35-0.48, and Helmet C 0.27-0.41. Helmet C showed the lowest BrIC value for 180 degrees closely followed by 270 degrees. While Helmet A and Helmet B showed the lowest BrIC value for 270 degrees.

The PLA and HIC are not evaluated for the rotational impact tests in the ECE R22.06 standard, but the results are presented in Fig. 4. The PLA varied between 119g and 212g. The HIC value varied between 679 and 1847.

Linear Impact Tests

For Helmet C, the threshold for PLA and HIC were exceeded in five out of the twenty-two impact configurations (Fig. 5). For PLA the threshold was exceeded for impact point P against the flat surface in all three impact velocities (6.0, 7.5, and 8.2 m/s) and impact points R and X for the impact velocity 6.0 m/s. For HIC, the threshold was also exceeded in all three impact velocities for impact point P and for impact point R in 6.0 m/s and 7.5 m/s.

There is no evaluation of PRA and BrIC in the linear impact tests, but the results are presented in Fig. 5. A large variation for the PRA was seen between 2.9 to 12.1 krad/s^2. The BrIC value varied between 0.06 and 0.64.

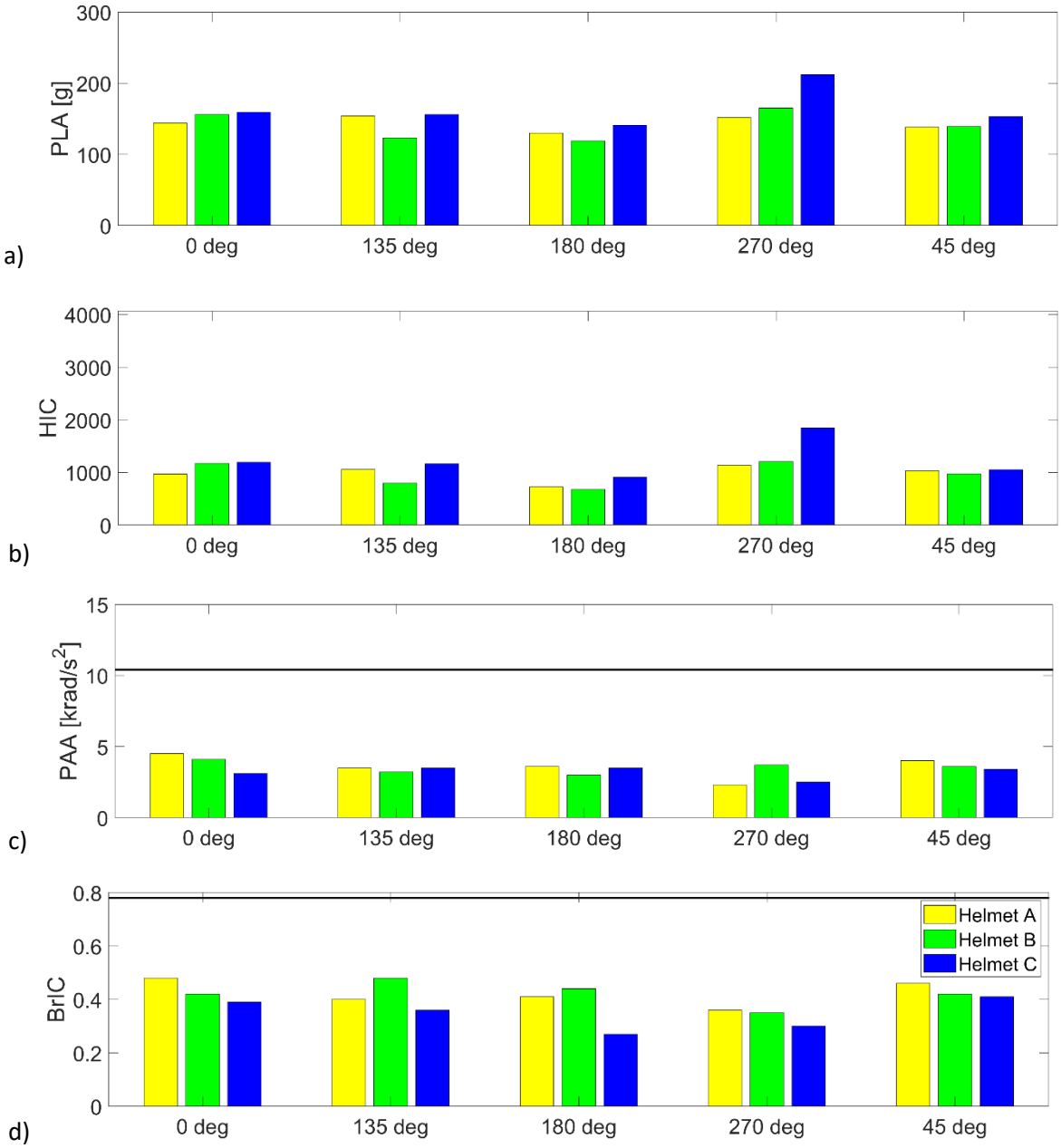

Fig. 4. Rotational impact tests a) PLA; b) HIC; c) PRA; d) BrIC. The black horizontal line shows the threshold for pass/fail according to ECE R22.06 for PRA and BrIC.

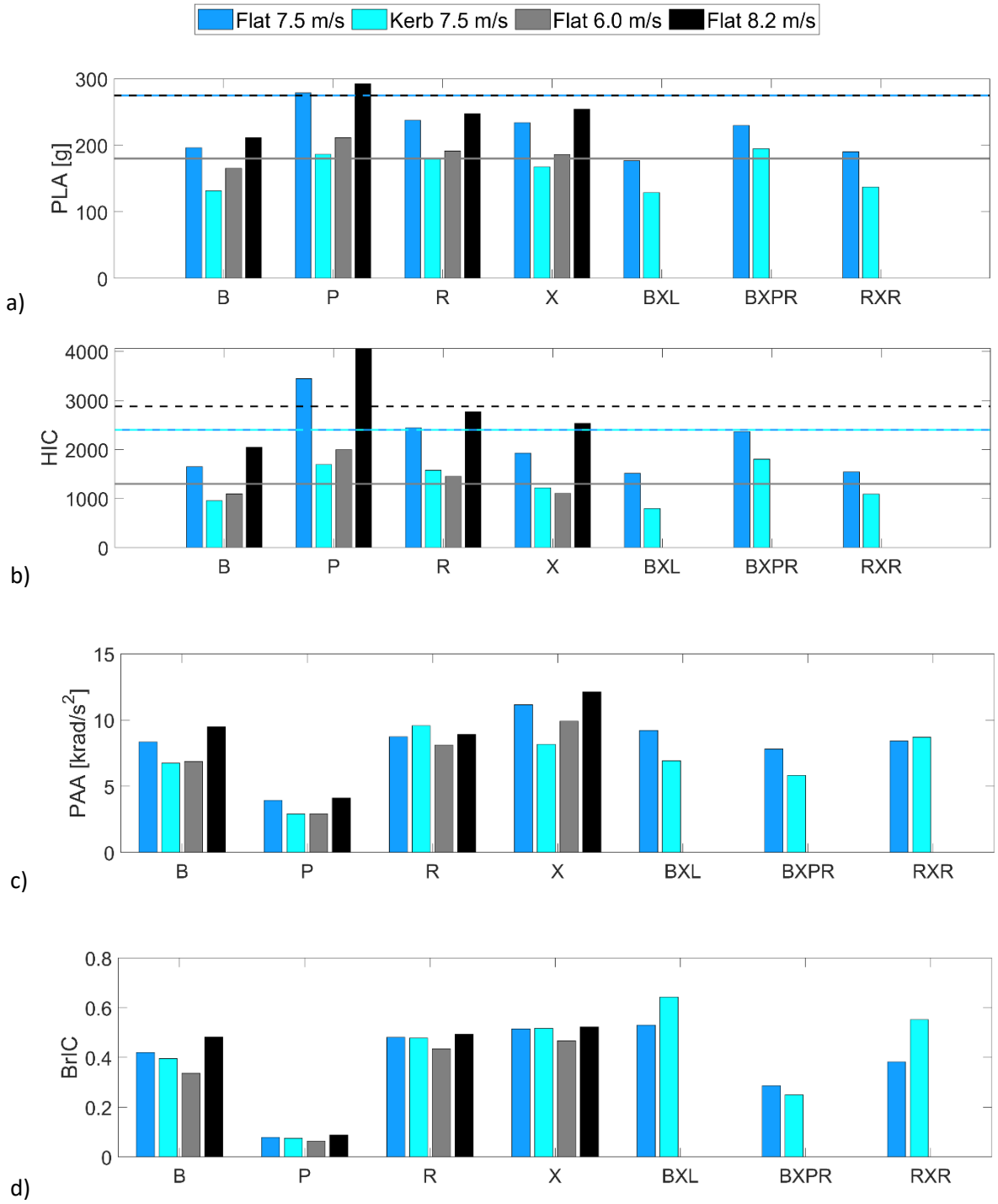

Fig. 5. Linear impact tests for Helmet C a) PLA; b) HIC; c) PRA; d) BrIC. The horizontal lines show the threshold for pass/fail criteria for ECE R22.06 with the color corresponding to the bar with the same color.

IV. Discussion

In this study the newly updated motorcycle helmet test standard ECE R22.06 was evaluated. The focus was on the newly implemented rotational tests and the helmets tested were representative of helmets currently available on the market. The results showed that there was not a problem for current helmets to pass the rotational impacts tests. All impact configurations for all three helmets had PRA and BrIC values below the pass and fail threshold for the rotational impacts. But for Helmet C, which also were evaluated in the linear impacts, five of the 22 linear impact tests did not pass.

The purpose of the rotational tests in ECE R22.06 is to measure the rotational kinematics in oblique impacts and thereby potentially improve helmet design. It could be questioned if this potential is realised based on the

results from this study and the head injury statistics in real accident scenarios. The results from this study, and the thresholds proposed by ECE R22.06 suggest that today's helmets protect better against rotational-induced injuries than linear-induced injuries. This is suggested as the helmets clearly pass the threshold for the rotational test but are closer to the threshold or over the threshold for the linear tests. Several studies have shown that PLA and HIC correlate to skull vault fractures, whereas some types of brain injuries correlate better to rotational kinematics [10-11], [22-23]. There are several studies that have evaluated different types of head injuries when a helmet was worn or when no helmet was worn, which is an indicator of how well the helmet protects against head injuries in real accidents. Reference [12] evaluated different types of head injuries in Kentucky, U.S between 2008 and 2012 for 4314 helmeted riders and 3637 unhelmeted riders. They found a higher odds ratio for concussions (0.80), which is related to rotational kinematics, compared to skull fractures with an odds ratio of 0.31. Two other studies [24-25] from the U.S also showed a smaller decrease of intracranial injuries compared to skull fractures when evaluating with and without helmet. There are also other studies that have shown a higher decrease of skull fractures compared to some intracranial injuries whereas some other intracranial injuries have had the same decrease as skull fractures [26-27]. This could be influenced by the injury mechanisms of different types of head injuries. When evaluating epidemiological studies where a helmet was worn, the number of skull fractures varies, e.g., [28] showed data of accidents where 11.6% of the victims of AIS4+ injuries had skull fractures compared to 34% that had intracerebral hematomas. Reference [29] showed in their study that 5% had skull fractures and 14% had intracranial injuries.

The epidemiological studies do not show a more superior performance against rotational-induced injuries as suggested when evaluating the helmets according to ECE R22.06. The epidemiological studies show more results towards better protection are required for rotational-induced brain injuries. There are different aspects that influence the performance of the helmet in ECE R22.06: the choice of threshold values and the choice of headform. To encourage helmet manufactures to improve the protection against rotational-induced injuries, the standard requires changes, such as a changing to the threshold value for the rotational metrics or a changing the properties of the headform. Within CEN Working Group 11 there is ongoing work to develop a headform for oblique impacts. The headform has been developed based on data from medical images and post mortem human subjects to get a good match in geometry, mass and inertia properties that represent the European population. A focus has also been to create a skin surface that should represent a realistic coefficient of friction.

Threshold Values

In the ECE R22.06 test standard the threshold values are different dependent on impact velocity for PLA and HIC (thresholds for PLA are 180g, 275g, 275g for the respectively impact velocities 6.0 m/s, 7.5 m/s, 8.2 m/s and for HIC the values are 1300, 2400, 2880 for respectively velocities 6.0 m/s, 7.5 m/s, 8.2 m/s). The rotational impacts are just evaluated in one velocity and the thresholds are 10.4 krad/s^2 for PRA, and 0.78 for BrIC. The background to these threshold values is not specified in the standard. In the ideal case, there should be a direct link between the threshold value in the standard and the injuries seen in the real-life accidents. There are some challenges to overcome before the standard can be developed in this way. In the literature we can see a larger variety of threshold values or injury risk functions. For example, [20] showed a 25% risk for a AIS4+ traumatic brain injury (TBI) and 88% risk for a AIS2+ TBI, compared to [30] who presented a 3% risk for a severe TBI, and 50% risk for a mild TBI (mTBI) for BrIC value of 0.78. Since it is a large variety in risk within, e.g., brain injuries, it will be difficult to relate different types of head injuries, such as TBI and skull fractures. Reference [31] presented risk curves for skull fracture based on PLA or HIC. With the threshold values used in ECE R22.06, the risk for a skull fracture would be 65% for a PLA of 275g and above 95% for a HIC value of 2400. The risk curves presented for brain injuries and skull fractures suggest combined with the results presented in the current study that the risk of sustaining a fracture is higher compared to sustaining a brain injury. However, the risk curves can be discussed. For example, the risk curve developed for skull fracture by [31] is based on unhelmeted impacts.

As mentioned above the higher risk of skull fracture is not supported by the statistics from real accident scenarios. Several studies have shown the opposite. For example, [12] showed a higher odds ratio, between wearing a motorcycle helmet and not wearing a motorcycle helmet, for concussions (0.80) compared to skull fractures (0.31). Reference [24] showed a larger decrease in skull fractures compared to intracranial injuries when comparing with and without a helmet. The data show that helmets on the market protect the skull against fractures better than they protect the brain. Also, some intracranial injuries could be more related to linear kinematics, but several brain injuries such as concussions or mTBI and DAI have shown a better correlation to rotational kinematics than linear kinematics.

The choice of injury metrics in ECE R22.06 has not been motivated by, but takes into account, different injury metrics. PLA and HIC have shown a relatively good correlation to skull fracture [10]. BrIC has shown good correlation to TBIs when comparing the strain response in FE models with BrIC [32]. In the same study [32], less correlation was found between PRA and peak strain, but [33] proposed a threshold of subdural hematoma based on PRA (10 krad/s^2), which was developed from only impacts to the occipital part of the head causing rotation in the sagittal plane.

FIM [17] has also introduced rotational impact tests in their test protocol. They have initially proposed the same threshold values used by ECE R22.06, but they have also proposed a second stage where everything is the same as in the first stage except that the threshold values for PLA, HIC, PRA, and BrIC are decreased. With the lower threshold values in the second stage in the FIM standard (PRA = 8.0 krad/s^2 and BrIC = 0.60), all tests in this study would pass the lower threshold also for both PRA and BrIC for rotational impact tests. However, one difference between FIM and ECE R22.06 is that in FIM, the EN960 headform is coated with a thin layer of silicone rubber whereas, in ECE R22.06 the original EN960 headform with a metal surface is used, which will affect the coefficient of friction. This in turn can lead to higher rotational kinematics.

Another difference in addition to the different coating of the headforms between FIM and ECE R22.06 is that ECE22.06 is only evaluating the PRA and BrIC in the rotational impact tests meanwhile FIM evaluates PLA, HIC, PRA and BrIC. FIM has also introduce two stages of threshold, where the first stage was first introduced and then later on the thresholds will be decreased in stage 2. The results in this study pass the PLA threshold from stage 1 (208g) in all impact tests except Helmet C in impact configuration 270 degrees. For stage 2, Helmet B fails the threshold of 160g at 270 degrees. For HIC more impact configurations and helmets fail the threshold from stage 2 (1000), where nine out of 15 tests fail. However, FIM is using an EN960 headform coated with silicone, which can influence the PLA and HIC.

Headform Surface

Another factor is the coefficient of friction. The coefficient of friction for a EN960 headform has been measured at 0.16 compared to between 0.20 and 0.32 for a human scalp with or without hair [34]. Another study has proposed that the coefficient of friction between the helmet and scalp should be higher, up to 0.7 [35]. Both [35] and [21] have evaluated the influence of coefficient of friction in oblique impacts by evaluating the original EN960 headform with a metal surface and an EN960 headform coated with silicone rubber. Both studies found lower rotational kinematics when the original EN960 headform was used compared to the coated headform. Reference [21] proposed that the coefficient of friction between the helmet and headform should be high enough to guarantee the motion between the helmet and headform without sliding of the headform. They recommended a higher headform coefficient of friction to better evaluate a worst-case scenario, which may be higher than the friction between the human scalp and helmets. There will need to be a balance between headform's coefficient of friction, the threshold values and other aspects that will influence rotational kinematics.

Other Aspects

A standard is designed to consistently evaluate helmets and acceleration limits are set so that poor performing helmets are not allowed to be sold on the market, but standards set the minimum level of protection not the maximum. Another way to distinguish helmets that have passed the standard is to use rating methods. There are several rating methods available for motorcycle helmets, such as [36-37]. Reference [37] is a rating method that uses both linear impacts and oblique impacts. The evaluation of the performance is based on the stress of the brain tissue in the Strasbourg University finite element head model. None of the helmets included in the current study are yet evaluated in the Certimoov rating programme. The SHARP rating programme consists mainly of linear impacts where the PLA and HIC are evaluated. Thirty linear impacts are conducted in addition to 2 oblique tests to evaluate the surface frictional properties of the helmet. In the current SHARP rating with a top scoring of 5 stars, Helmet A got 3 stars and Helmet B got 4 stars. Helmet A and Helmet B are both available to buy on the European market, from relatively large brands and are in the price range 120 to 400 Euros.

All the impact points in the ECE R22.06 rotational tests result in rotation mainly in the transverse plane and little rotation around the z-axis (superior-inferior axis). The brain has shown to be more vulnerable to injury when the rotation is around the z-axis [38-39]. If an impact configuration that caused rotation around the z-axis was added, the PRA and BrIC value could increase compared to the current impact configurations. Reference [21] evaluated one impact configuration that had primary rotation around the z-axis, and this impact configuration gave the highest peak values compared to the other impact configurations that had primary rotation in the

transverse plane. However, the threshold values for PRA and BrIC were not exceeded when the original EN960 headform without any coating was used.

Limitations

The focus of this study was to evaluate three helmets that represent the current market in the newly implemented rotational tests for the ECE R22.06 standard. The results are influenced by the helmet design so there could be a wider range of results if different helmet models had been included in the study. Also, in this study, results from linear impacts according to ECE R22.06 were presented but limited to one helmet. This helmet is developed for research purposes. Its design is based on the helmets in the current market; however it has not been certified.

The linear impacts in the ECE22.06 standard should also be performed at hot and cold temperature. In the current study, only the ambient condition where evaluated. The hot and cold condition can result in higher peak values compared to the ambient temperature, but this was not evaluated in this study.

V. CONCLUSIONS

The helmets evaluated in this study clearly pass the threshold for the ECE R22.06 rotational tests. The ratio between measured value and threshold value was 0.23-0.43 for PRA and 0.35-0.62 for BrIC. Meanwhile, the linear impact tests for one of the helmets did not pass five out of 22 impact configurations. The ratio between measured value and threshold value was 0.40-1.16 for PLA and 0.25-1.51 for HIC.

The results from this study suggest that motorcycle helmets will be more optimised towards linear-induced injuries and not rotational-induced injuries when considering the newly introduced ECE R22.06 test standard. Since the impacts for the oblique impact are clearly below the threshold whereas for the linear impact, the thresholds are exceeded for some of the impacts and more time is required to improve the helmets for these impacts. This is not responding to the requirement when evaluating the real-life accident statistics, which show that rotational-induced injuries are as common or even more common than linear-induced injuries in helmeted motorcycle accidents. The data from real-life accidents suggest that more effort should be put on improving the rotational protection.

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VII. APPENDIX

Table A1 and Table A2 specify the shock absorptions tests according to Federation Internationale de Motocyclisme (FIM) and ECE R22.06. FIM has decided to have a two-step process for the thresholds for the FIM racing homologation programme for helmets (FRHPhe). The first step (FRHPhe-1) has one set of thresholds for PLA, HIC, PRA and BrIC. The second step is going to be implemented in the future, where the thresholds are decreased.

Table A1
THE SHOCK ABSORPTIONS TESTS ACCORDING TO FIM. FRHPE-01 IS THE FIRST STAGE AND FRHPE-02 IS THE SECOND PHASE

	Anvil	Conditioning	Headform	Resultant Impact Velocity	Impact points	Thresholds FRHPhe-01	Thresholds FRHPhe-02
Linear Impacts	Flat(steel)	Ambient	EN960	8.2 m/s 8.2 m/s 6.0 m/s	B,X,P,R Extra points P	PLA≤275g HIC≤2880	PLA≤275g HIC≤2400
				5.0 m/s	B,X,P,R,S	PLA≤208g HIC≤1300	PLA≤160g HIC≤1000
Rotational Impacts	45° angled (abrasive paper 80-grit)	Ambient	Coated EN960	8.0 m/s	Frontal-Lateral (45°) Rear (180°) Left-Lateral (270°) Frontal (0°) Rear-lateral (135°)	PLA≤208g HIC≤1300 PRA≤10.4 krad/s^2 BrIC≤0.78	PLA≤160g HIC≤1000 PRA≤8.0 krad/s^2 BrIC≤0.60

TABLE A2
THE SHOCK ABSORPTIONS TESTS ACCORDING TO ECE R22.06

	Anvil	Conditioning	Headform	Resultant Impact Velocity	Impact points	Thresholds
Linear Impacts	Flat (steel)	Ambient	EN960	6.0 m/s	B,P,R,X S	PLA≤180g HIC≤1300
		Ambient Hot Cold UV rad. & moisture		7.5 m/s	B,P,R,X, 3 additional impact points	PLA≤275g HIC≤2400
	Kerbstone (steel)			7.5 m/s	B,P,R,X, 3 additional impact points	
	Flat (steel)			8.2 m/s	B, P, R, X	PLA≤275g HIC≤2880
Rotational Tests	45° angled (abrasive paper 80-grit)	Ambient		8.0 m/s	Frontal-Lateral (45°) Rear (180°) Left-Lateral (270°) Frontal (0°) Rear-lateral (135°)	PRA≤10.4 krad/s2 BrIC≤0.78