Comparative Evaluation of Motorcycle Helmets Complying to R22-06 with Helmets Complying to R22-05 based on Certimoov methodology.

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Abstract Since 2022, the new ECE R22-06 motorcycle helmets standard has been put into effect. The authors suggested to investigate the contribution of this new standard to the evolution of th protective performance of helmets. The present paper proposes a comparative evaluation of helmets complying to the 06 and 05 version of the ECE R22 regulation in terms of global head injury metrics as well as model-based brain injury risk under both, linear and oblique impact conditions based on the certimoov method.

With 47 helmet models complying to R22-05 and 16 helmet models fulfilling R22-06, the 63 helmets models were evaluated according to the Certimoov testing methodology consisting in 18 impact tests on 6 samples. A total of 1,134 experimental impacts were conducted. Results indicate marginal decreases in kinematics parameters with R22-06 conforming helmets. Considering the mean brain injury risk, the results show very little improvement. The larger improvement can be observed under ZROT impacts which however are not considered in this new standard. All the results are marred by a large disparity and a significant standard deviation. Thus, the authors conclude that the ECE R22-05 helmets do not look significantly different from R22-06 helmets in terms of head protection.

This research provides insight into the effect of the new standard on head protection, highlighting almost no improvement in performance, particularly under oblique impacts introduced by R22-06.

Keywords Standard ECE R22-06, Brain Injury Risk, oblique impacts, helmet performance.

I. INTRODUCTION

There are several motorcycle helmet standards around the world, and this paper focusses on UN-ECE R22 under effect in Europe. Since 2022, the new ECE R22-06 motorcycle helmets standard has been introduced with a key evolution focusing on oblique impacts.

The significance of head rotational acceleration in causing brain injury has been recognised since the mid-20th century. Early studies by Holbourn in 1943 [1] and Ommaya *et al.* [2] in 1967 highlighted the role of rotational acceleration in generating cerebral concussion. Subsequent research, including studies by Gennarelli *et al.* [3], Deck *et al.* [4], Kleiven *et al*. [5], Zhang *et al.* [6], and Takhounts *et al.* [7], further emphasised the critical impact of rotational acceleration on intra-cerebral loading and brain-skull relative motion, leading to neurological injuries such as subdural hematoma.

Additionally, investigations by Mills *et al.* [8] and Bourdet *et al.* [9] demonstrated that tangential loading of the head, particularly under oblique impacts common in motorcycle accidents, contributes significantly to head rotational acceleration. Studies by Otte *et al.* [10] and Harrison *et al.* [11] corroborated these findings, highlighting the prevalence of oblique impacts and their impact angles in case of motorcycle accidents.

Real-world accident analyses, including those from the COST 327 European project [12], have revealed that rotational motion plays a predominant role in causing head injuries, with over 60% of injuries attributed to rotational motion and about 30% to linear motion. Median speeds associated with concussion and brain injury have also been documented, along with the distribution of impact angles, further illustrating the importance of considering rotational dynamics in understanding head injury mechanisms.

Despite this widely recognised understanding of head rotational loading and the effect of the induced rotational acceleration to the brain for decades, helmet standard has only recently considered this phenomenon. The UN-ECE R22-05 motorcycle helmet standard considered a tangential impact, but the evaluation of helmets was restricted to the recorded tangential force [13]. This limitation was partly due to the fact that there was no

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consensus on the injury criteria and and pass/fail value for assessing helmet performance under oblique impact.

A number of studies focusing on helmet response under oblique impacts [14][15][16] considered maximum head rotational accelerations, but omitted to consider the time evolution as well as the rotation direction. The present authors concluded that to account for the complexity of brain geometry and material properties under diverse head impact conditions, progression towards tissue-level brain injury criteria, as seen in existing Finite Element [FE] model-based criteria, is necessary. Deck *et al.* 2004 [17] highlighted the strong dependence of helmet optimisation on the chosen head substitute and injury criteria. Recent efforts aimed to optimise helmets using biomechanical criteria by coupling human head FE models with helmet FE models [5][6][18][19].
Several attempts have been made to address head protection against tangential impacts. Aldman *et al.* [14] conducted tests with a helmeted headform against a rotating steel disc, while Halldin *et al.* [15] designed a new oblique impact test based on a sliding anvil for motorcycle helmets. In the context of bicycle helmet evaluation, Milne *et al.* [20] and Deck *et al.* [21] suggested a new assessment method using model-based head injury criteria under both linear and tangential impact conditions, similar to Hansen *et al.* approach [22]. Similarly, Post *et al.* [23] suggested hockey helmet evaluation based on impacts against a helmeted Hybrid III head–neck system and integrating linear and rotational accelerations into existing head FE models for injury risk assessment. Pang *et al.* [16] introduced a novel laboratory test for investigating head and neck responses under oblique motorcycle helmet impacts. In hockey helmet research, Gerberich *et al.* [24] and Flick *et al.* [25] studied hockey head trauma by recreating typical impact conditions on the Hybrid III head–neck system. Rousseau *et al.* [26] developed a hockey helmet impact test on which they recorded linear and rotational head accelerations during frontal and lateral impacts. Walsh *et al.* [27] further investigated helmeted Hybrid III head kinematics and demonstrated the importance of recording both linear and rotational accelerations during testing, as they showed a correlation between the two injury parameters.

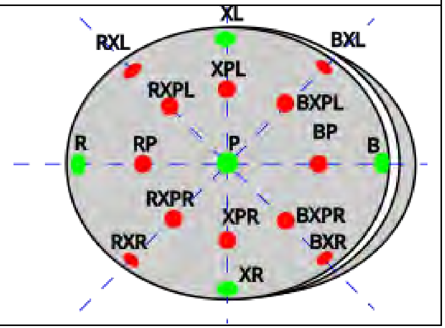
Directive ECE 22 05 was the standard in all countries of the European Union until 2022. The absorption capacity of the helmet during an impact was assessed by recording the headform acceleration when the free fall helmeted headform impacted at a specific speed against a rigid anvil. The impact speeds required by this Directive are 7.5 m/s for points B (frontal), P (vertex), R (occipital), X (lateral) [BPRX] and 5.5 m/s for the point S (chin bar). The headform used during the tests must be instrumented with a triaxial linear accelerometer. Helmets are impacted against two anvils: flat horizontal and kerbstone. The absorption efficiency is considered to be sufficient when the resultant acceleration measured at the CG of the headform at no time exceeds 275 G, and when the Head Injury Criterion (Eq. 1) does not exceed 2 400 for the five impact points.

$$Eq.1.\ HIC = max_{(t_1,t_2)}\left\{(t_2 - t_1).\left(\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a(t)dt\right)^{2.5}\right\} \quad (1)$$

Until 2022, no improvement in standard tests had been proposed. Recently, the new R22-06 standard has been proposed and includes oblique impacts with consideration of rotational velocity and acceleration. This new version of the ECE R22 regulation makes some changes to the absorption capacity assessment, adding higher and lower impact speeds as well as oblique impacts. In the linear impact test configurations, the impact speeds used for both anvils, similar to those specified in the R22-05 standard, are set at 7.5 m/s for the BPRX points. Furthermore, assessments involving high and low energy impacts with the flat anvil are required. For the high-energy assessment, the velocity is adjusted to 8.2 m/s for the BPRX points, whereas for low-energy impacts, also using the flat horizontal anvil, the speed is reduced to 6.0 m/s for the same impact points. The pass/fail criteria for these linear impacts focused on the peak linear acceleration and the Head Injury Criterion [HIC] values. Additionally, it is mandated to include at least three supplementary test points from a pool of 12 options, thereby ensuring a more thorough assessment of helmet performance under varying conditions. Table 1 summarises R22-06 standard linear impact configurations in terms of velocity and pass/fail criteria.

TABLE I. Linear Impacts configurations for R22-06 standard. Points in greens are same as for R22-05

Type of test	Impact Velocity [m/s]	PLA [g]	HIC
Linear Impact Std - points in green	7.5	≤ 275 g	≤ 2400
Linear Extra Point - points in red	7.5	≤ 275 g	≤ 2400
Linear Hi Energy - points in green	8.2	≤ 275 g	≤ 2880
Linear Low Energy - points in green	6.0	≤ 180 g	≤ 1300



Concerning the oblique tests, five oblique configurations are introduced with an impact velocity of 8.0 m/s on an inclined anvil set at 45°, employing sandpaper with a P80 friction coefficient. These five obliques configurations aim at inducing rotation around an axis in the x-y planes, as illustrated in Fig. 1, no rotation around the z-axis is proposed. The pass/fail criteria for the peak rotational acceleration (PRA) is 10400 rad/s² and the Brain Injury Criterion (BrIC) [28] calculation to remain below 0.78. Moreover, it is mandatory that the friction coefficient between the helmet and the surrogate head is maintained at 0.3.

$$Eq.2.\ BrIC = \sqrt{\left(\frac{\omega_x}{\omega_{xC}}\right)^2 + \left(\frac{\omega_y}{\omega_{yC}}\right)^2 + \left(\frac{\omega_z}{\omega_{zC}}\right)^2} \quad (2)$$

where ω_x, ω_y and ω_z are maximum angular rates on X, Y, and Z-axis respectively ω_{xC}, ω_{yC} and ω_{zC} are the critical angular velocities in their respective directions: ω_{xC} = 66.25 rad/s ; ω_{yC} = 56.45 rad/s ; ω_{zC} = 42.87 rad/s.

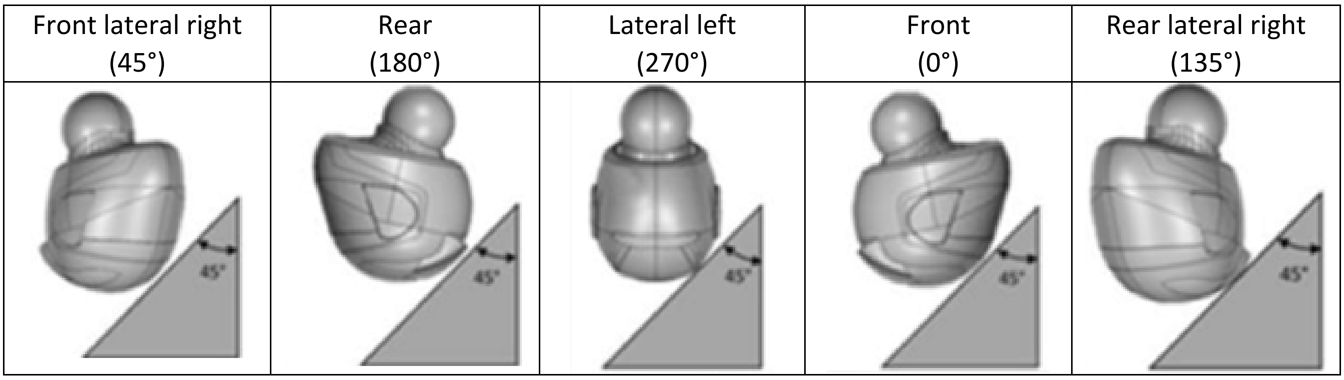


Fig. 1. Illustration of the five-impact configuration for R22-06 [29].

Several motorcycle helmets are now approved according to this new standard. The present paper suggests a comparative evaluation of two groups of helmets, one complying with the UN-ECE-R22-05 standard and the other complying with the UN-ECE-R22-06 standard. This comparative assessment is based on the results of the tests carried out as part of the comparative tests of the Certimoov method, including impacts on horizontal and oblique anvil, in terms of global head kinematic metrics and brain injury risk using model-based brain injury criteria.

II. METHODS

This section proposes a short presentation of the methodology used to compare helmet protection performance between the two groups of helmet models homologated respectively with R22-05 and R22-06 and based on linear and oblique impacts. The motorcycle helmet evaluation method, developed at Strasbourg University and called Certimoov method [30], involves a total of 18 experimental helmet impact tests per helmet model on six helmet samples, followed by the numerical computation of the brain response and the assessment of the brain injury risk for each impact. More precisely the experimental test procedure, illustrated in Fig. 2, consists in three linear impacts against a horizontal flat anvil at a speed of 7.5 m/s (FRONTAL, OCCIPITAL, and LATERAL) and three oblique impacts against an inclined anvil at a 45° angle covered with P40 grit abrasive paper (and not P80 as for the ECE-R22-06) at a speed of 8.0 m/s to induce rotation around the Y-axis (YROT) and two lateral impacts, generating rotation one about the X-axis (XROT) and one about the Z-axis (ZROT). Each helmet received no more than three total impacts. All tests were carried out at room temperature.

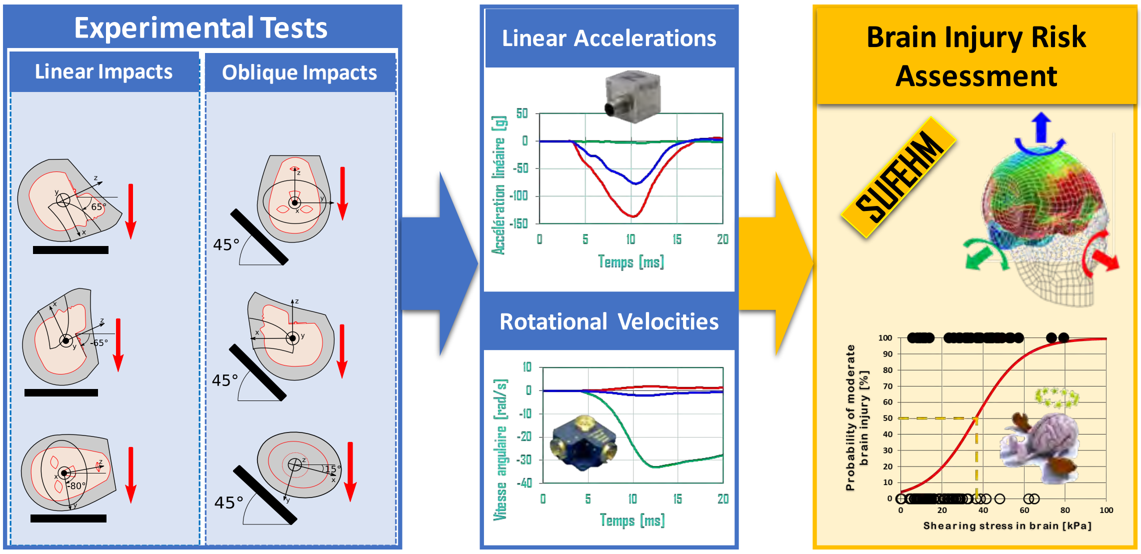


Fig. 2. Illustration of the coupled experimental and numerical test method. The experimental acceleration of the headform is considered as an input condition for the numerical simulation of the head impact followed by the brain injury risk assessment.

In order to control the repeatability of the experiments, each impact configuration is reproduced three times according to the test matrix reported in TABLE II. The 6D kinematics curves are recorded (three linear accelerations and three rotational velocities) for each impact and are implemented into the finite element head model (SUFEHM) to consider tissue level brain injury criteria. This FEM head encompass the main anatomical features such as the skull, brain, brainstem, falx, tentorium, skin, and cerebrospinal fluid. Previous research has detailed the mechanical properties and validation of this model [18, 19, 30, 31]. Additionally, 125 real-world head trauma cases were simulated to establish brain injury criteria, focusing on intracerebral Von Mises stress to predict moderate neurological injuries or short coma. Through extensive statistical analysis, brain Von Mises stress emerged as the most suitable metric for predicting moderate diffuse axonal injuries (mDAI). A brain tolerance limit of 36 kPa for a 50% risk of mDAI was proposed, with the corresponding injury risk curve provided in Fig. 2.

TABLE II. Test matrix for the three linear and three oblique impact tests involving six different helmets.

Impact configurations	Helmet sample ID	First Impact	Second Impact	Third Impact	Impact Velocity
Linear impacts	H1	FRONTAL	OCCIPITAL	LATERAL	7.5 m/s
	H2	LATERAL	FRONTAL	OCCIPITAL	7.5 m/s
	H3	OCCIPITAL	LATERAL	FRONTAL	7.5 m/s
Oblique impacts	H4	YROT	XROT	ZROT	8.0 m/s
	H5	ZROT	YROT	XROT	8.0 m/s
	H6	XROT	ZROT	YROT	8.0 m/s

For all experimental impact tests, we used a more realistic head surrogate, capable of recording linear and rotational loading over time and showing more biofidelic moment of inertia compared to the EN960 headform. Consequently, the EN960 headform used in current standards has been replaced by the instrumented Hybrid III dummy head, with more realistic rotational inertia, with PCB tri-axial linear accelerometer sensors and ATA-type angular velocity sensors. Linear sensors are PCB PIEZOTRONICSinc Accelerometers 356B21, ±500 g with a sensitivity of 10 mV/g, 10.02 mV/g and 10.05 mV/g respectively for x, y and z-axis. The ATA angular velocity sensors are a RS-06 and 06S Triaxial MHD Angular Rate Sensor Arrays with a sensitivity of 50 mV/rad/s for the three channels. The recordings of the sensors were carried out with a sample rate of 25.6 kHz and data were filtered with a CFC 1000 for linear accelerations and with a CFC 180 for the rotational velocities. More details regarding the implemented helmet test protocol are exposed in the certimoov helmet rating platform [30].

For each helmet tested, seven metrics have been considered, peak linear acceleration (PLA), peak rotational velocity (PRV), peak rotational acceleration (PRA), as well as the HIC and BrIC values and finally the tissue level brain injury metric based on SUFEHM were compared for helmets tested to the -05 and -06 versions of the ECE-R22 motorcycle helmet standard. With python scripts, the peak rotational accelerations were calculated by deriving the rotational velocities, HIC and BrIC were computed using equations (1) and (2) respectively.

Thus, a total 47 motorcycle helmet models homologated with R22-05 regulation and 16 more recent helmet models complying to the R22-06 standard were tested under this linear and oblique impacts methodology. All the tested helmet models were selected according to the best sellers and more often used.

We tested 63 motorcycle helmet models (full-face helmets, modular helmets, and open-face helmets), among which 47 were homologated with R22-05 and 16 according to the R22-06 standard. The model names and rating results are available on the certimoov platform (www.certimoov.com) and listed in Table III. The 63 helmet models involved 6 helmet samples subjected to 3 impacts, for a total of 1,134 impacts.

In order to support the claim in this study, a statical analyses were conducted, especially Student T-test using python scripts, to compare the different series of results.

TABLE III. List of tested helmet models with size, regulation and date of experimental tests. In blue helmets homologate with R22-05 and in orange with R22-06.

N°	BRAND	MODELS	SIZE	REG.	DATE	N°	BRAND	MODELS	SIZE	REG.	DATE
1	SHARK	SKWAL	M	R22-05	2018	**33**	DEXTER	PROTON-JOKER	M	R22-05	2021
2	ASTON	MINIJET-RETRO	M	R22-05	2018	**34**	HJC	RPHA70-BALIUS	M	R22-05	2021
3	6DHELMET	ATS-1	M	R22-05	2018	**35**	HJC	RPHA11-BENSPIES	M	R22-05	2021
4	HJC	CS-15	M	R22-05	2018	**36**	ONEAL	CHALLENGER-WINGMAN	M	R22-05	2021
5	HJC	IS-17	M	R22-05	2018	**37**	SHARK	RIDILL-1.2-NELUM	M	R22-05	2021
6	NOLAN	N44-EVO	M	R22-05	2018	**38**	SHOEI	NEOTEC-2-SPLICER	M	R22-05	2021
7	LEATT	GPX-6.5	M	R22-05	2018	**39**	BMW	SYSTEM-7-CARBON	L	R22-05	2021
8	AGV	K3SV	ML	R22-05	2018	**40**	BELL	RACE-STAR-DLX-SOLID	M	R22-05	2021
9	SHOEI	GT-AIR	M	R22-05	2018	**41**	KLIM	KRIOS-PRO-HAPTIK	M	R22-05	2021
10	SHUBERTH	R2	M	R22-05	2018	**42**	LS2	VALLIANT-2-REVO	M	R22-05	2021
11	BELL	QUALIFIER-DLX-MIPS	L	R22-05	2018	**43**	SCHUBERTH	C4-PRO-UNI	M	R22-05	2021
12	SHARK	SPARTAN-CARBON	M	R22-05	2018	**44**	HJC	CS-15	M	R22-05	2022
13	SHARK	SKAWL-2-BLANK-Mat	M	R22-05	2018	**45**	NOX	N961	M	R22-05	2022
14	SCORPION	EXO-510-AIR-SOLID	M	R22-05	2018	**46**	LS2	STREAM-EVO	M	R22-05	2022
15	LS2	BREAKER	M	R22-05	2018	**47**	HELSTON	MORA	M	R22-05	2023
16	SHOEI	NEOTEC	M	R22-05	2018	**1**	NOLAN	N80.8-CLASSIC-N-COM	M	R22-06	2022
17	SCORPION	EXO-920	L	R22-05	2018	**2**	SHOEI	NXR2	M	R22-06	2022
18	LS2	VALIANT	M	R22-05	2018	**3**	ARAI	QUANTIC-wPINLOCK	M	R22-06	2022
19	ARAI	CHASER-X	M	R22-05	2018	**4**	SCHUBERTH	C5	M	R22-06	2022
20	SHARK	EVO-ONE	M	R22-05	2018	**5**	SHARK	SPARTAN-RS	M	R22-06	2022
21	HJC	IS-MAX-II	M	R22-05	2018	**6**	LS2	ADVANT	M	R22-06	2022
22	NOLAN	N87	L	R22-05	2018	**7**	HJC	i100	M	R22-06	2022
23	DEXTER	ADRON	M	R22-05	2019	**8**	LS2	FF811-SPLITTER	M	R22-06	2023
24	DEXTER	CRONOS	M	R22-05	2019	**9**	SCORPION	EXOTECH-EVO-CARBON	M	R22-06	2023
25	ICON	AIRFORM-SOLID-RT	M	R22-05	2019	**10**	SHARK	SKWAL-I3-LINK	M	R22-06	2023
26	HJC	i70	M	R22-05	2019	**11**	HJC	RPHA71-PINNA	M	R22-06	2023
27	SHOEI	GT-AIR-II	M	R22-05	2019	**12**	HJC	RPHA91-COMBUST	M	R22-06	2023
28	ARAI	SZ-R-VAS	M	R22-05	2019	**13**	NOLAN	X552-ULTRA-WAYPOINT	M	R22-06	2023
29	BOXXER	R09	M	R22-05	2019	**14**	NOLAN	N30-4-VP	M	R22-06	2023
30	COPY-ARAI	SZ-R	M	R22-05	2019	**15**	SCHUBERT	S3	M	R22-06	2023
31	ICON	AIRFRAME-PRO-RT	M	R22-05	2019	**16**	DEXTER	ELEVEN	M	R22-06	2023
32	Z1R	SOLARIS-DSK-SIL	M	R22-05	2019						

III. RESULTS

The distributions of the headform responses between R22-05 and R22-06 homologated helmets, reported in TABLE II and represented in Fig. 3, show similar values for the different metrics, especially on linear and rotational accelerations as well as rotational velocities with average values of 162 g, 29 rad/s and 7.6 krad/s² for maximum linear acceleration, rotational velocity and rotational acceleration respectively (Fig. 3).

The range of the peak linear acceleration is from 76 g to 282 g but 95% of the experimental tests report linear acceleration between 98 g and 227 g as illustrated in Fig. 3 with the vertical dashed black lines. Similarly, 95% of the experimental tests show a range on the peak rotational velocity and acceleration of 4.5 rad/s to 53.5 rad/s and 2 krad/s² to 14.8 krad/s² respectively. The proportion given on the y-axis in the Fig. 3 corresponds to the number of helmets in the histogram range divided by the total number of helmets in the corresponding group.

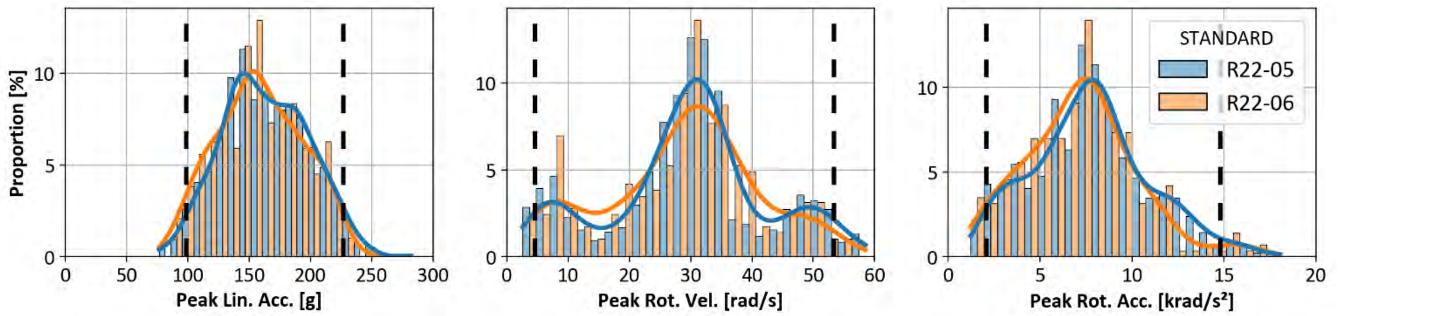


Fig. 3. Distribution of the data in terms of PLA, PRV as well as PRA obtained from all the helmet tests all configurations combined according to standard group.

At first glance, the maximum values of all global kinematic metrics recorded show slightly smaller average values for R22-06 certified helmets group compared to R22-05 certified helmets group, as reported in TABLE IV. Calculation of T-test leads to the PRV of the two groups of helmets have identical average values (pvalue ≥ 0.05) which is not the case for PLA and PRA with pvalue=0.043 and pvalue=0.007 respectively.

TABLE IV. Average of measured parameters extracted from the results on helmet tests using certimoov method for the the two groups of helmets homologated R22-05 and R22-06.

Standards	Impact Counts	Peak Lin. Acc. [g]	Peak Rot. Acc. [krad/s²]	Peak Rot. Vel. [rad/s]
R22-05 helmets group	846	163 ± 35	7.8 ± 3.2	30 ± 13
R22-06 helmets group	288	159 ± 34	7.2 ± 3.0	29 ± 12
All	1134	162 ± 35	7.6 ± 3.2	29 ± 13

Figure 4 shows the distribution of PLA, PRV and PRA according to the six impact configurations for each set of helmets. The horizontal red dashed lines represent the threshold values for linear acceleration at 275 g, defined in R22-05 standard and for the rotational acceleration at 10.4 krad/s² defined in R22-06 standard for oblique impacts. For all six impact configurations, the PLA recorded with "version 6 helmets" are included in the range of distribution of version 05, especially for linear impacts. This shows very similar distribution for helmet family.

For 75% of the tested models, PLA recorded is lower for helmets homologated against R22-06 standard than for those homologated against R22-05 standard regardless of the configurations studied, especially for oblique impact configurations. In the three linear impact configurations, the Student T-test allowed us to confirm our hypothesis that the average values of PLA for the two groups of helmets are very similar with a pvalue ≥ 0.05. The distribution of rotational velocity under FRONTAL impacts is slightly larger for -06 helmets group than for -05 helmets group but slightly lower under LATERAL impact condition. The FRONTAL configuration shows PRV higher for R22-06 homologated helmets group than for R22-05 homologated helmets group (pvalue<0.001) with 29.2 ± 5.1 rad/s and 25.9 ± 5.4 rad/s respectively. Same observation for PRA with 7251 ± 1761 rad/s² and 6434 ± 1534 rad/s² (pvalue<0.006). In contrary, the LATERAL configuration shows lower values for the -06 helmets group for the PRV and PRA (pvalues<0.003). For the OCCIPITAL configuration all the kinematics parameters show similar average with pvalues>0.05.

Under oblique impact configurations, the PLA are lower for the -06 helmets group than for -05 helmets group in the XROT and YROT impact configurations (pvalues<0.007): 153.6 ± 19.3 g vs 145.2 ± 17.5 g for XROT and 142.6 ± 16.5 g vs 134.0 ± 14.6 g for YROT. In contrary, the pvalue>0.05 on XROT and YROT from the Student T-test permitted to confirm us that the difference on PRV were not significant showing similar mean values for the two group of helmets and the improvement is observed under ZROT impact configuration, with a reduction about 3 rad/s from 49.3 ± 4.3 rad/s for -05 helmets group against 46.5 ± 5.4 rad/s for -06 helmets group. The XROT impact configuration from R22-06 homologated helmets show a larger range than those homologated against the R22-05 standard. Under ZROT impact configurations, a slight improvement can be observed as almost 75% of the helmets certified R22-06 standard show PRV lower than 50 rad/s even if this impact condition is not considered in the new regulation (R22-06 standard). The PRA distributions of the R22-06 homologated helmets are slightly lower than those of homologated against R22-05 standard. For the XROT impact configuration, 88% of the R22-06 homologated helmets experimental tests show PRA recorded values lower than the threshold 10.4 krad/s² compared to 90% for R22-05 homologated helmets experimental tests. The median decrease from 1 krad/s² to 4 krad/s² in case of ZROT impact configuration.

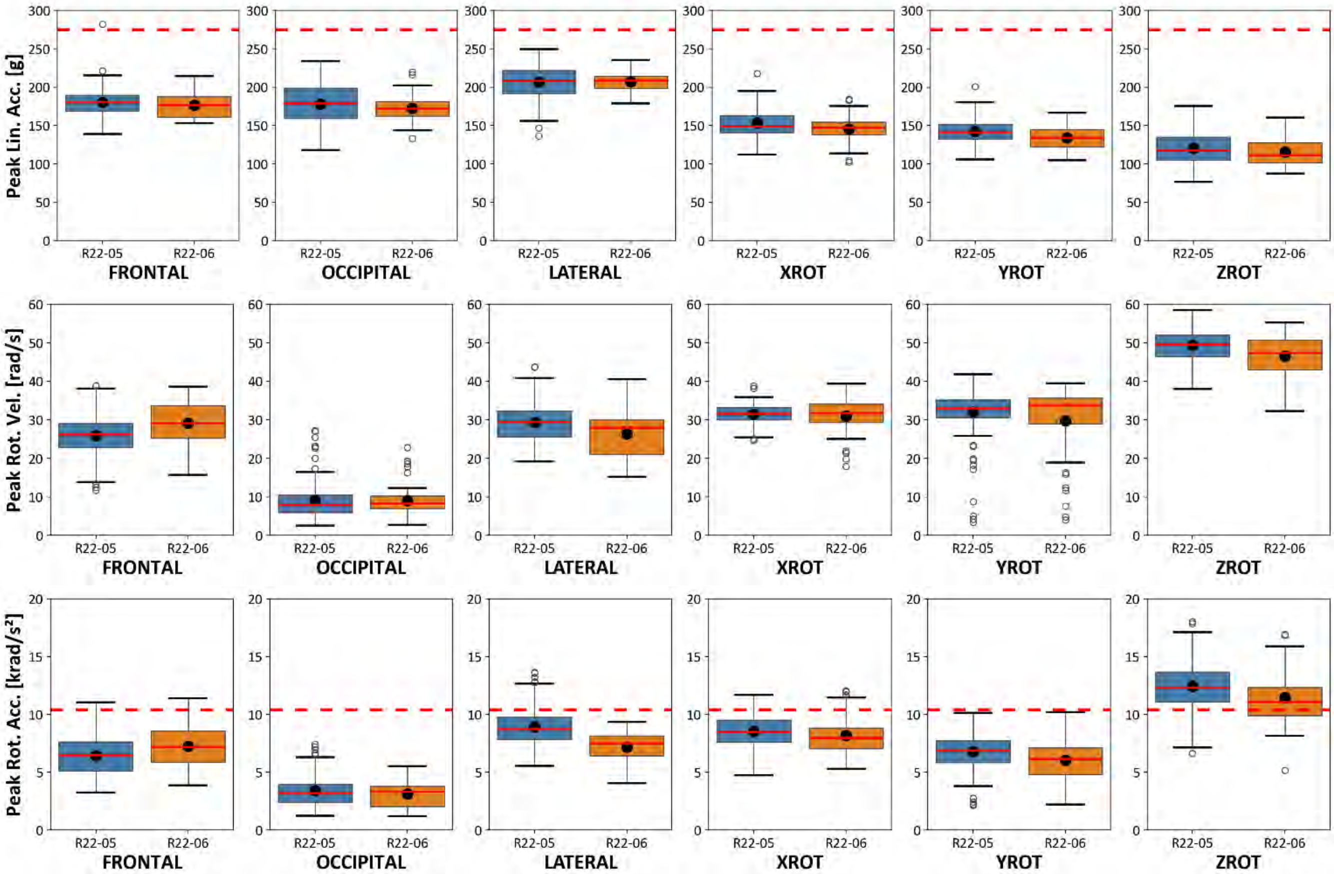


Fig. 4. Distribution of PLA, PRV, PRA for each impact configuration according to R22-05 and R22-06 certification, in terms of boxplot, the outliers are plotted as circles. Blue for R22-05 homologated helmets group; Orange for R22-06 homologated helmets group; black point is the mean value. The red dashed lines represent the threshold values for PLA defined in R22-05 standard and for PRA defined in R22-06 standard.

When considering Head Injury Criterion (HIC) and Brain Injury Criterion (BrIC) metrics, the two groups of helmets (homologated against R22-05 and R22-06 standards) show very similar distribution of results, as illustrated in Fig. 5 which reports distribution of HIC and BrIC values for each impact configuration according to the two helmet regulations. As for linear acceleration and rotational velocity, the distributions of HIC and BrIC values for both groups of helmets show similar results and no relevant improvements. When the differences were statistically significant (pvalues<0.05), the mean values are very similar. Nevertheless, for HIC, a maximum decrease of 11-14% appeared for the XROT and YROT configurations. BrIC values are lower than the threshold defined by R22-06 standard at fixed at 0.78 for XROT and YROT impact configurations but higher for ZROT configuration whatever the helmets group. A statistically significant reduction of 9% on BrIC values can be observed under LATERAL impact configuration (pvalue<0.001) but almost inexistant under oblique impacts.

Regarding the maximum Von Mises stress in the brain extracted from the simulations of SUFEHM for each impact test (SUFEHM VMS), slight improvement can be observed for the OCCIPITAL (pvalue=0.0002), LATERAL (pvalue=0.001), XROT (pvalue=0.02) and ZROT (pvalue<0.0001) configurations. Indeed, results show that the R22-06 homologated helmet models are in the 75% best R22-05 homologated helmets, as illustrated in Fig. 5. The larger reduction of 16% can be observed under ZROT impact configuration from 51.3 ± 11.2 kPa for the -05 helmets group to 43.1 ± 10.8 kPa for the -06 helmets group.

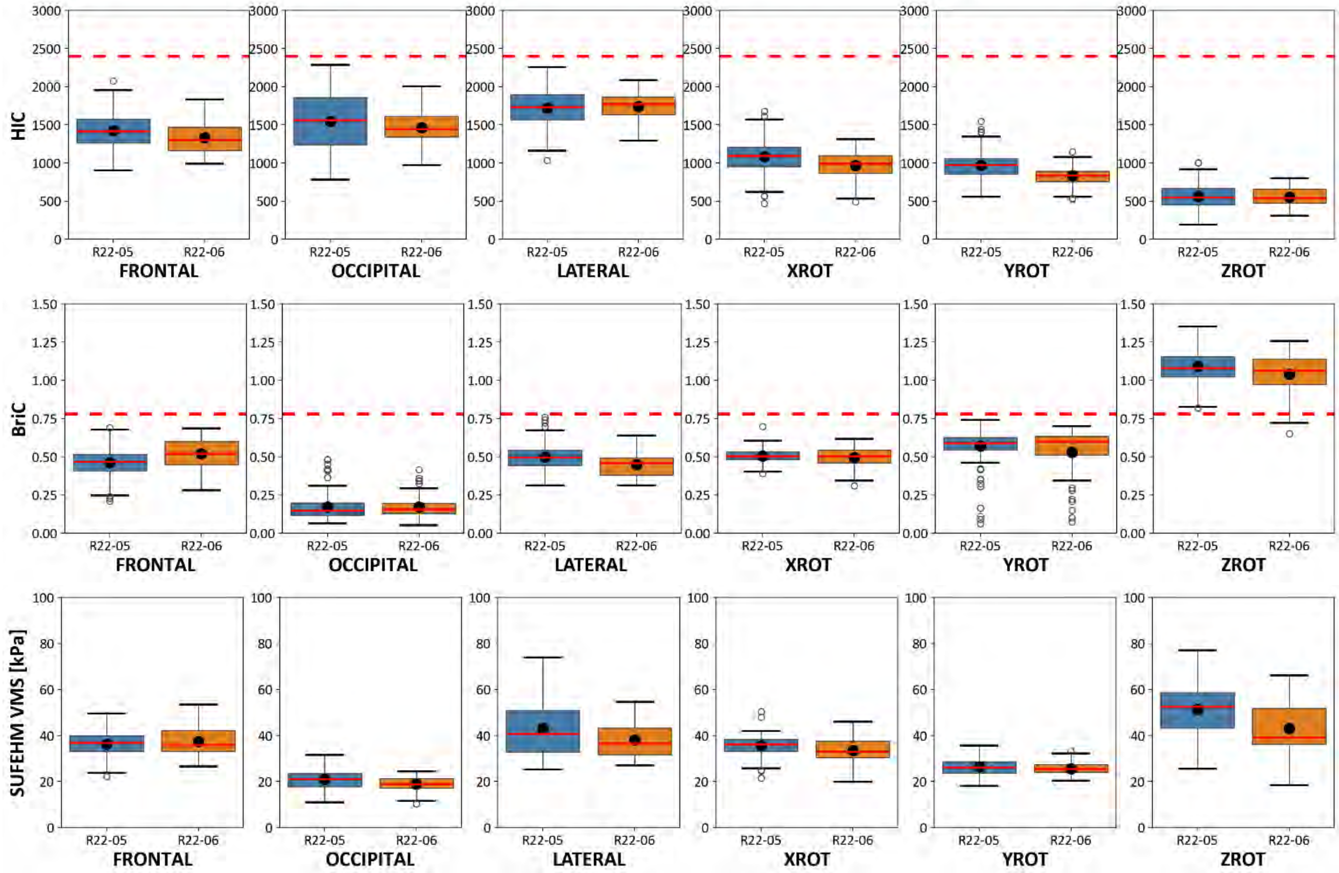


Fig. 5. Distribution of HIC, BrIC and SUFEHM VMS values for each impact configuration according to the certification group, in terms of boxplot: Blue for -05 helmets group; Orange for -06 helmets group; The outliers are plotted as circles; Black point is the mean value. The red dashed lines represent the threshold values for HIC defined in the R22-05 standard and for BrIC defined in R22-06 standard.

Table V synthesizes the mean values for the different parameters extracted from the 1,134 experimental helmet tests according to the two R22 version helmets group. The gray cells correspond to the cases where the difference between the mean values from the two group is significant using Student T-test analysis. Although the statistical analysis allows us to support that there are significant differences between the means of both helmets group, the standard deviations are very large and even exceed the difference between the two averages. This remark is valid for all the parameters studied under all the impacts configurations.

TABLE V. Mean values of the different parameters. Gray cells correspond to a significant difference between means with 95% confidence (pvalue<0.05)

		FRONTAL	OCCIPITAL	LATERAL	XROT	YROT	ZROT
PLA [g]	R22-05	180.5 ± 18.9	178.1 ± 25.7	206.5 ± 21.5	153.6 ± 19.3	142.6 ± 16.5	120.4 ± 21.1
	R22-06	176.4 ± 16.2	172.4 ± 18.1	207.2 ± 13.1	145.2 ± 17.5	134.0 ± 14.6	115.7 ± 19.7
PRV [rad/s]	R22-05	25.9 ± 5.4	9.1 ± 5.2	29.3 ± 5.0	31.5 ± 2.7	32.0 ± 6.2	49.3 ± 4.3
	R22-06	29.2 ± 5.1	9.1 ± 4.5	26.4 ± 5.7	31.1 ± 4.6	29.8 ± 9.5	46.5 ± 5.4
PRA [rad/s²]	R22-05	6434 ± 1534	3423 ± 1310	8941 ± 1813	8553 ± 1376	6789 ± 1501	12435 ± 2132
	R22-06	7251 ± 1761	3137 ± 1110	7202 ± 1334	8202 ± 1672	6055 ± 1865	11472 ± 2525
HIC	R22-05	1422 ± 222	1548 ± 364	1721 ± 236	1082 ± 208	972 ± 167	562 ± 157
	R22-06	1331 ± 194.1	1461 ± 230.6	1740 ± 183.3	967 ± 199.4	835 ± 137.3	551 ± 132.2
BrIC	R22-05	0.46 ± 0.10	0.17 ± 0.09	0.50 ± 0.09	0.51 ± 0.05	0.57 ± 0.11	1.09 ± 0.11
	R22-06	0.52 ± 0.09	0.17 ± 0.08	0.45 ± 0.08	0.50 ± 0.07	0.53 ± 0.17	1.04 ± 0.13
SUFEHM VMS [kPa]	R22-05	36.3 ± 5.6	21.1 ± 4.0	43.1 ± 12.5	35.6 ± 4.1	26.3 ± 3.4	51.3 ± 11.2
	R22-06	37.4 ± 5.9	18.9 ± 3.1	38.1 ± 7.5	33.5 ± 5.9	25.6 ± 2.9	43.1 ± 10.8
SUFEHM Risk [%]	R22-05	50 % ± 12 %	21 % ± 6 %	60 % ± 21 %	48 % ± 9 %	29 % ± 6 %	75 % ± 17 %
	R22-06	52 % ± 12 %	18 % ± 4 %	53 % ± 15 %	44 % ± 12 %	28 % ± 5 %	61 % ± 19 %

IV. DISCUSSION

This study focusses on the comparative evaluation of recent motorcycle helmets compliant with R22-06 standard versus those fulfilling the R22-05 standard and provides insights into advancements in helmet safety standards. By systematically assessing and comparing the performance of the two set of helmets compiling to both regulations, researchers and industrial experts can gauge the effectiveness of the new regulation in enhancing helmet safety. This comparative analysis enables stakeholders to identify potential areas of improvement and innovation, ensuring that motorcycle helmets continue to evolve to better mitigate the risks of head injuries and enhance rider safety on the road. This study focusses on shock absorption under ambient temperature and does not address penetration phenomenon or climate conditioning aspects.

A first limitation of the study is the number of helmet models under consideration. In fact, the number of tested R22-06 homologated helmets are lower than that of tested R22-05 homologated helmets, but the number is sufficient to initiate a comparison the two regulations, especially if no true improvement is noticed. According to the two regulations, impacts are conducted under free fall, neglecting the potential effect of the neck on the head response at the time of impact. In a recent investigation, Feist and Klug [32] conducted a parametric study on neck effect employing the THUMS FE model, while Fahlstedt *et al*. [33] utilised the KTH head-neck FE model for a similar analysis. Their studies demonstrated that the influence of the neck on brain response is minimal, ranging from 10% to 15% depending on the impact conditions.

We used the Hybrid III headform, which presents a higher friction coefficient compared to the magnesium EN960 headform (0.75±0.06 compared to 0.16±0.026 respectively). In 2018, Trotta *et al.* [34] estimated the sliding friction between scalp and liner at 0.29±0.07. Therefore, a new headform (EN17950 [35]) is under developed within CEN TC158-WG11 working group, to implemented it in the coming helmets multi-sport and eventually motorcycle helmets regulations in the coming years.

Nowadays, finite element (FE) head models and related brain injury criteria have emerged. These models surpass the brain injury prediction capacity of metrics like HIC or BrIC values as they consider both, the linear and angular components of the head loading. The literature reports injury metrics based on Maximum Principal Strains as GHBMC FE model [36] or KTH head FE model [5]. For the present study SUFEHM was applied as this model was used for the simulation of 125 meticulously documented head traumas to derive tolerance thresholds for moderate AIS2+ brain injury (Deck *et al*., 2009 [37]). More precisely a 50% risk of occurrence, was established for a brain Von Mises Stress of 37 kPa. Regarding the global brain injury risk computed with the brain shearing stress extracted from SUFEHM in accordance with the presented methodology, slight improvement was observed, as reported in Table IV. Considering the mean value of brain injury risk with a significant difference between the two groups of helmets (pvalues<0.05), values are lower from 3% to 13% of injury risk. These differences should be taken with caution due to a large standard deviation which moderates the results in favor of the new standard. A more observable improvement can be noticed under the ZROT configuration, which is surprising since the new regulation UN R22-06 does not consider this impact configuration. Nevertheless, standard deviation calculated for this configuration is higher than the decrease that is to say 19% of injury risk for the standard deviation compared to 13% of diminution of brain injury risk between -05 helmets group and -06 helmets group.

In the study of Fahlstedt *et al.* [36], in 2022, the authors explored the effectiveness of rotational impact tests in the ECE R22-06 standard by conducting rotational impact tests on three helmet models and linear impact tests on one helmet model according to the regulation procedure. They concluded that the newly ECE R22-06 test standard tends to improve helmets in linear rather than tangential impacts, even though the aim of the new standard was to reduce rotation-induced injuries. The present study shows the same trend, slight improvement under LATERAL impact configurations and no notable improvements on rotational impacts, especially on XROT and YROT configurations if considering mean value of brain injury risk. Another limitation of this study is that only SUFEHM FE model was used to evaluate the head injury risk in terms of AIS 2+. Several other head FE models could be considered as KTH model [5] or GHBMC [37] in the future.

A remark can be done about ZROT configuration results which had not been considered in the new standard. Even if, in the present study, improvement for this configuration in terms of brain injury was calculated between R22-06 and R22-05 standards, the level of brain injury keeps high, more than 60% of AIS2+. If only global parameters are considered, the issue is also observed for this oblique impact with a BrIC value calculated for all ZROT impacts above 0.78, as illustrated in Fig. 5.

V. CONCLUSION

The present research aimed to evaluate the effect of the new ECE R22-06 motorcycle helmet standard on the level of head protection. To do so, recent helmets conforming to version 06 are evaluated comparatively to a set of helmets complying to version 05. Helmet testing involved both, linear and oblique impacts and headform responses are analysed in terms of global and local brain injury metrics. Based on mean values of brain injury risk, the group of helmets conforming to the new standard shows very little improvement with regards to head protection performance. The larger improvement can be observed under ZROT impacts which are not considered in this new standard. But all the results are marred by a large disparity and a significant standard deviation. Thus, the authors conclude that the ECE R22-05 helmets do not look significantly different from R22-06 helmets in terms of head protection.

This comparative analysis represents a crucial step forward in understanding the evolving landscape of motorcycle helmet safety standards and emphasizes the importance of continuous improvements to enhance rider safety on the roads.

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