A comparison of headforms used in rotational impact testing of helmets

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I. INTRODUCTION

Until recently, standards for single-impact helmets have only used peak linear acceleration to assess impact performance. As of 2023, the European certification standard for motorcycle helmets requires helmets to undergo both linear and oblique impacts using a cast magnesium headform (EN 960) [1]. The Fédération Internationale de Motocyclisme (FIM) further requires a silicone-coated EN 960 headform for oblique impacts tests of motorcycle helmets [2]. Recently, oblique testing was also proposed for the European bicycle helmet standard, which will require a new headform, designated EN 17950, that has moments of inertia and a surface coefficient of friction (CoF) representative of the human head [3-4]. The Fédération Equestre Internationale (FEI) has also proposed that equestrian helmets worn during competitions be tested in an oblique impact. Here we sought to compare the kinematics of two newly available EN 17950 headforms during freefall oblique impacts.

II. METHODS

Two EN 17960 headforms were tested (size 570 mm; H: Humanetics, mass=4.32 kg, I_{xx}=189.8 kg-cm^2 I_{yy}=224.2 kg-cm^2 I_{zz}=153.2 kg-cm^2, Farmington Hills, MI, USA; C: Cellbond, mass=4.28 kg, I_{xx}=217.6 kg-cm^2, I_{yy}=239.34 kg-cm^2, kg-cm^2, I_{zz}=159.3 kg-cm^2, Huntingdon, England). The headform surfaces were cleaned according to each manufacturer's protocol and the CoF was measured before and after testing each day [4]. Tipperary Windsor (size L) helmets (Tipperary Equestrian, Woodbridge ON, Canada) were placed on the headforms with 16 mm between the helmet brow and the headform's reference plane. The visor was trimmed to prevent contact with the test assembly during impacts. The ring-fit system was tightened until slight resistance was met, and the chinstrap was adjusted so that 2-3 fingers fit comfortably between the buckled strap and the headform's chin. The headform and helmet were placed on a U-shaped trolley that fell past a 45° anvil covered with 80-grit sandpaper (Mirka, Jeppo, Finland). Three headform orientations were used to produce rotations about the X-, Y-, and Z-axes at target impact speeds of 4.2 and 6.6 m/s. For X-axis rotations (X-rot), the headform was inverted (X- and Y-axes ±1° of horizontal), for Y-axis rotations (Y-rot), the headform was rotated 45° (+Y rotation), and for Z-axis rotations (Z-rot), the headform was rotated 65° (-Y rotation) (Figure 1). A cantilevered arm holding the headform during freefall released prior to impact and a slack tether attached to the headform prevented a secondary impact. Consistent initial headform and helmet positions and orientations were achieved using image overlays for each test condition. Each combination of the 3 impact orientations and 2 speeds was tested 3 times (18 impacts per headform), with each helmet experiencing 3 impacts. All impact sites were separated by at least 135 mm. A 4th impact to the opposite side of a helmet was sometimes used if there were issues with the first X- or Z-rot test. Both headforms were supplied with three 500g (H) or 2000g (C) linear accelerometers, three 8k deg/s angular rate sensors, and an on-board data acquisition system (DTS, Seal Beach, CA, USA). All channels were sampled at 20 kHz and high-speed video was recorded at 1 kHz (Mikrotron, MotionBLITZ EoSens mini2, Gilching, Germany). Each bare headform also experienced 3 X-, Y-, and Z-rot impacts at 3.6 m/s against an MEP pad. Peak resultant linear acceleration (PLA), angular acceleration (PAA) and angular velocity (PAV) were extracted from the filtered data (acceleration: CFC 1000, angular rate: CFC 180). For each dependent variable (PLA, PAA, PAV), we ran a 3-way analysis of variance (ANOVA) to test for the effect of headform (H, C), primary rotation axis (X, Y, Z), and impact speed (low, high). The model included all interaction terms and treated each independent variable as a random effect. Significance was set at $p<0.05$ and all tests were performed using the *anovan* and *multcompare* functions in Matlab (2024b, Mathworks, Natick, MA). We performed pair-wise post-hoc comparisons between headforms at each combination of impact orientation and speed using a Tukey-Kramer test. A pair-wise Student's t-test determined if the pre-and post-test CoF values were significantly different ($p<0.05$, Excel 2025). The percent difference between the C and H bare headform impacts for PLA, PAA, and PAV were determined.

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III. INITIAL FINDINGS

The CoF values varied from 0.25 to 0.35 across both headforms (Table 1). The high impact speeds were 6.51 ± 0.03 m/s and the low impact speeds were 4.11 ± 0.06 m/s. Across all impact orientations, peak kinematics were greater for the high speed tests compared to the low speed tests (Figure 2). At the low speed, PAA and PAV were significantly greater across all orientations for the C headform compared to the H headform. At the high speed, PLA was significantly higher for Y-rot, PAA was significantly higher for all orientations, and PAV was significantly higher for X- and Z-rot for the C headform compared to the H headform. The bare headform impacts (3.67 ± 0.04 m/s) were ≤ 6% different, except for PAA Z-rot (13%) and PAV X-rot (12%).

Figure 1. Headform orientation relative to the oblique anvil.

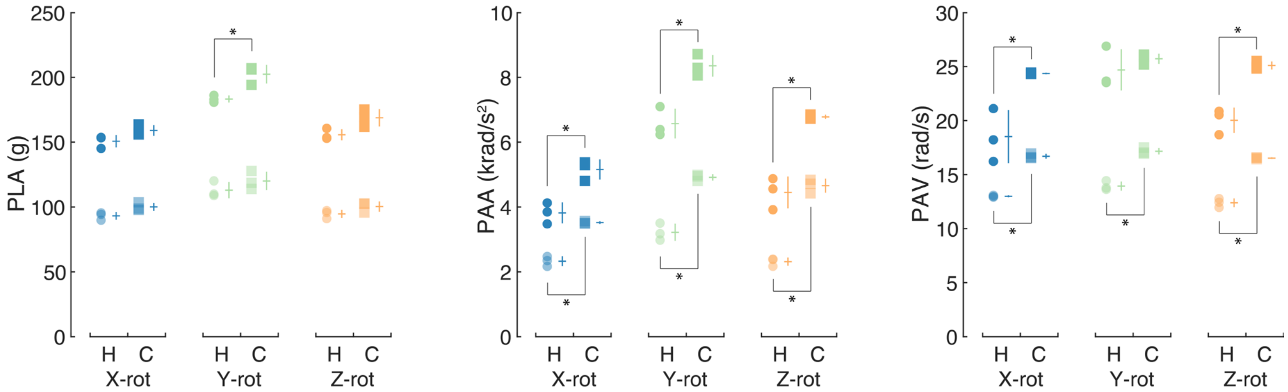

Figure 2. PLA, PAA, and PAV for H (circles) and C (squares) headforms for the low and high impact speeds for each rotation axis (X-rot: blue, Y-rot: green, Z-rot: orange). Significant differences between H and C are indicated by *. The horizontal line to the right of each data set indicates the mean of the three data points and the vertical line is the standard deviation.

IV. DISCUSSION

Overall, our comparison of the peak kinematics between the two EN 17950 headforms showed similar or higher linear and rotational kinematics for the C headform compared to the H headform. These findings may be explained by the higher CoF measured on the C headform (which exceeded the 0.30 ± 0.03 criteria [4]) compared to the H headform (which met the criteria prior to some tests, but was lower than the criteria post-test) rather than differences in inertial properties. Although the proposed standard for oblique tests only considers an impact speed of 6.6 m/s [3], similar impact performance across a range of speeds would make these headforms more useful tools for research and helmet development. Future work comparing these two headforms should explore more helmet types, helmet sizes, impact orientations, anvil angles, and impact speeds to better understand their similarities and differences. Future work should also quantify the repeatability and reproducibility of friction measurements [5], if comfort liner contact affects the headforms' CoF, and if the CoF specified in [4] matches interlaboratory data.

V. REFERENCES

[1] ECE 22.06, 2023 [2] FIM FRHPhe, 2019 [3] prEN 1078, 2025 [4] EN 17950, 2024 [5] ASTM E691-21