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Report: Polo Helmet Rotational Testing

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Background

Present polo helmet testing methods only assess linear acceleration, neglecting the evaluation of a helmet's ability to reduce rotational acceleration. Both linear and rotational accelerations are key predictors of brain injuries. While linear acceleration corresponds to intracranial pressure gradients, rotational acceleration relates to relative brain motion and strain. Understanding these measures is crucial for gauging the risk associated with each helmet. Therefore, the United States Polo Association Safety Committee requested a test series to evaluate current polo helmets under rotational loading conditions.

Methods

Our study aimed to compare the impact performance of 10 polo helmet models under varying linear and rotational loading conditions. We conducted 180 impact tests across these helmet models, using three test systems, two impact speeds, and three impact locations.

The test systems included the NOCSAE drop tower (1), an impact pendulum (2), and an oblique drop tower (3). The NOCSAE drop tower, identical to the system used in the current NOCSAE test standard (4), helped establish baseline values for linear acceleration. However, this system only evaluated the linear acceleration of the headform, which was measured using 3 accelerometers at the headform center of gravity (CG).

The pendulum impactor struck a helmeted NOCSAE headform mounted on a Hybrid III neck and sliding torso mass, measuring both linear and rotational acceleration for direct head impacts. The oblique drop tower, on the other hand, had a helmeted NOCSAE head free-falling onto an angled anvil, measuring both linear and rotational acceleration for oblique angle impacts. For both the pendulum and oblique test systems, the headforms were instrumented with 3 linear accelerometers and a triaxial angular rate sensor at the headform's CG. We evaluated helmets using two different rotational test systems because it is currently unknown which test system best represents the head impacts experienced by polo players, and both impact scenarios are plausible.

We tested two impact speeds - 3.46 m/s and 5.46 m/s, which align with the NOCSAE standard and represent low and high impact severities. The impact locations included the front boss, side, and rear boss, chosen to enable identical impact locations for all three systems (Figure 1).

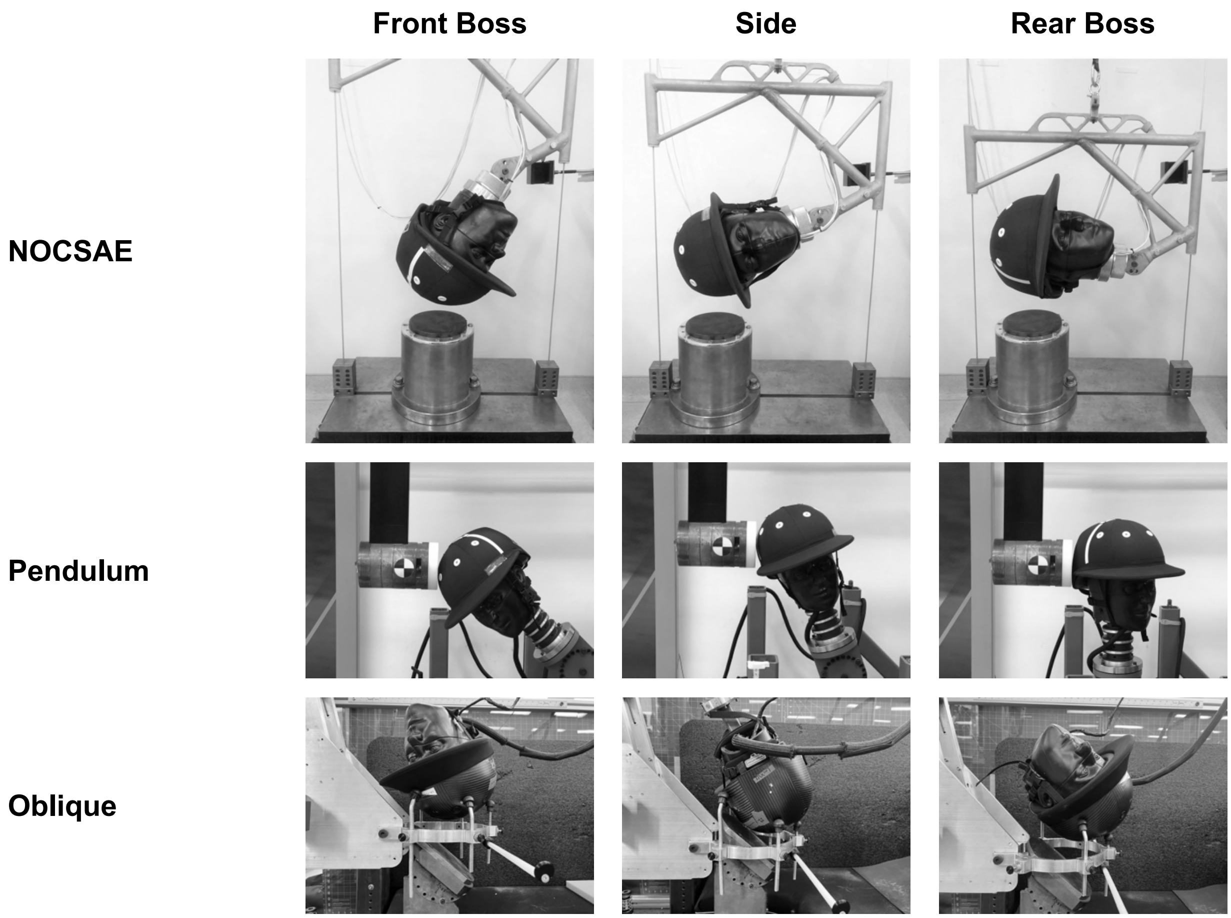

Figure 1: Matched impact locations were tested across the 3 test systems.

Table 1 describes the 10 tested helmets. Four of them comply with the current NOCSAE standard, and one helmet includes MIPS technology.

We sampled data at 20 kHz for all tests. We filtered kinematic signals using a four-pole phaseless digital Butterworth low pass filter in compliance with SAE J211 specifications. We applied a cutoff frequency of 1650 Hz to linear acceleration signals and 300 Hz to angular rate signals.

We computed rotational acceleration by differentiating angular rate signals. We then calculated peak linear and rotational resultant accelerations for each test (PLA and PRA). To determine the overall severity of each impact and present the kinematics in the context of injury risk, we computed concussion risk from peak linear and rotational accelerations (5).

We carried out two types of analyses - a comparison of the kinematics produced by each test system, and an examination of helmet performance across these systems. We compared linear accelerations across all three systems and rotational accelerations between the pendulum and oblique systems. We employed a linear mixed model with a helmet model as a random effect and calculated the least square mean differences between systems. We also explored associations between systems by impact speed, using linear models of each system as a function of the others.

When contrasting kinematics and concussion risk between helmet models, we computed mean values and 95% confidence intervals by impact speed across systems and locations. We calculated Spearman rank correlation coefficients (rho) between test systems for each dependent variable averaged across test systems, impact locations, and impact speeds.

Table 1: The 10 polo helmet models included in this test series.

	Helmet Model	NOCSAE Certified?	MIPS?
	Armis Edge	No	Yes
	Armis Vera	Yes	No
	Casablanca NEU	Yes	No
	Charles Owen Sovereign	Yes	No
	GAP Speed 2x	No	No
	Instinct Askari	Yes	No
	KEP Cromo 2.0	No	No
	Krono Alpha	No	No
	La Martina Windsor	No	No
	La Martina X-Volution	No	No

Results

Test System Comparison

Linear Acceleration

Test system ($p < 0.0001$), impact location ($p < 0.0001$), and impact speed ($p < 0.0001$) all influenced linear acceleration measures (Figure 2). On average, the oblique drop tower produced linear accelerations 52.8 g higher than the pendulum impactor ($p < 0.0001$). The NOCSAE drop tower produced linear accelerations 40.9 g higher than the pendulum impactor ($p < 0.0001$). The oblique drop tower produced linear accelerations 11.9 g higher than the NOCSAE drop tower ($p = 0.0048$).

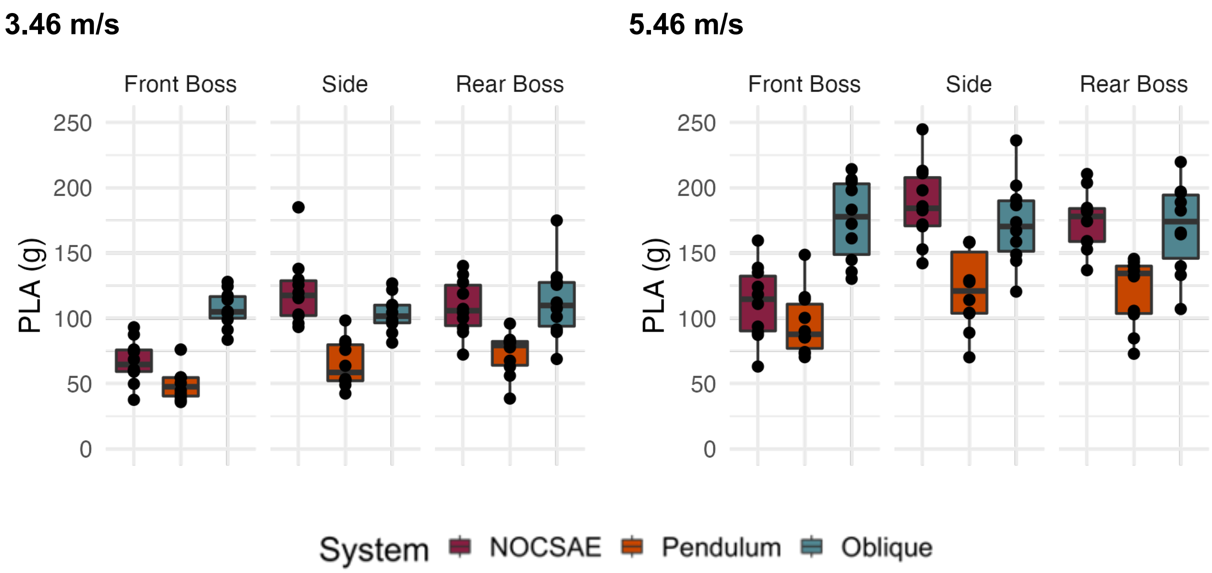

Figure 2: Distributions of linear accelerations between helmet models by test system, impact location, and impact speed.

Table 2: Adjusted R-squared here describes how much of the variance in one system is explained by the other system.

Speed	**Model**	**Adj. R-squared**	**p-value**
3.46 m/s	Oblique ~ Pendulum	0.322	0.0006
	Oblique ~ NOCSAE	0.101	0.0484
	NOCSAE ~ Pendulum	0.515	< 0.0001
5.46 m/s	Oblique ~ Pendulum	0.506	< 0.0001
	Oblique ~ NOCSAE	-0.017	0.4859
	NOCSAE ~ Pendulum	0.120	0.0340

Rotational Acceleration

Test system ($p < 0.1272$), impact location ($p < 0.0001$), and impact speed ($p < 0.0001$) influenced rotational acceleration measures to varying degrees (Figure 3). On average, the oblique drop tower produced rotational accelerations 361 rad/s^2 higher than the pendulum impactor ($p < 0.1272$).

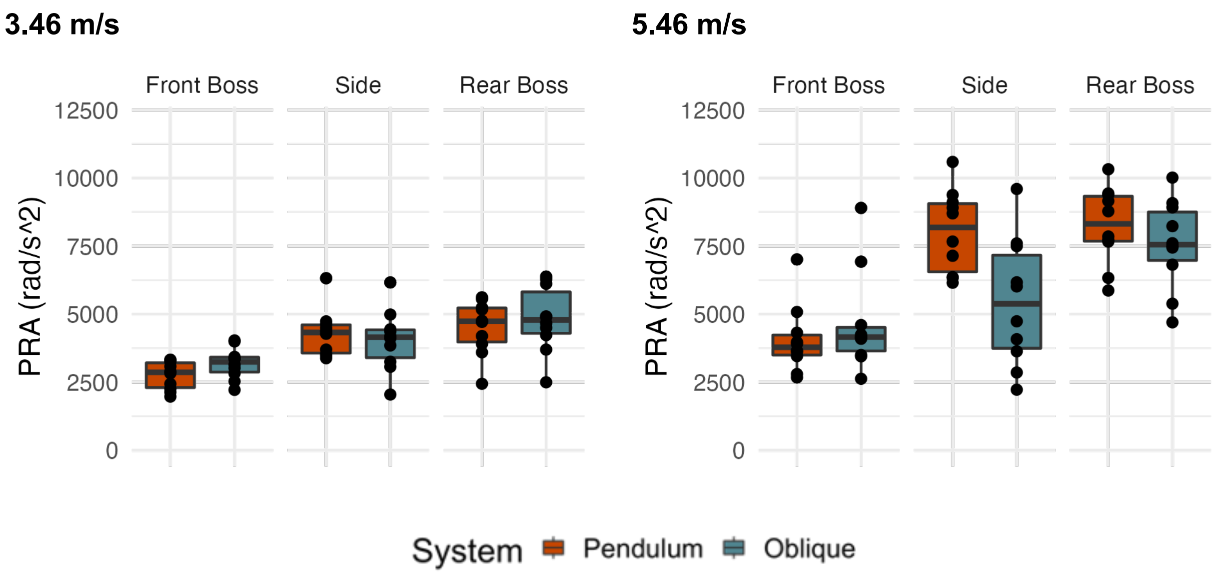

Figure 3: Distributions of rotational accelerations between helmet models by test system, impact location, and impact speed.

Adjusted R-squared values from the linear models of each system as a function of others suggested low or moderate associations between test systems for rotational acceleration (Table 3).

Table 3: Adjusted R-squared here describes how much of the variance in one system is explained by the other system.

Speed	Model	Adj. R-squared	p-value
3.46 m/s	Oblique ~ Pendulum	0.403	< 0.0001
5.46 m/s	Oblique ~ Pendulum	0.208	0.0066

Helmet Model Comparisons

Linear Acceleration

The Charles Owen Sovereign and Casablanca NEU helmets produced the lowest average linear accelerations across all test systems and the La Martina Windsor and Armis Edge helmets produced the highest (Figure 4). Moderate to strong correlations for helmet model rank order were observed between the test systems (Table 4).

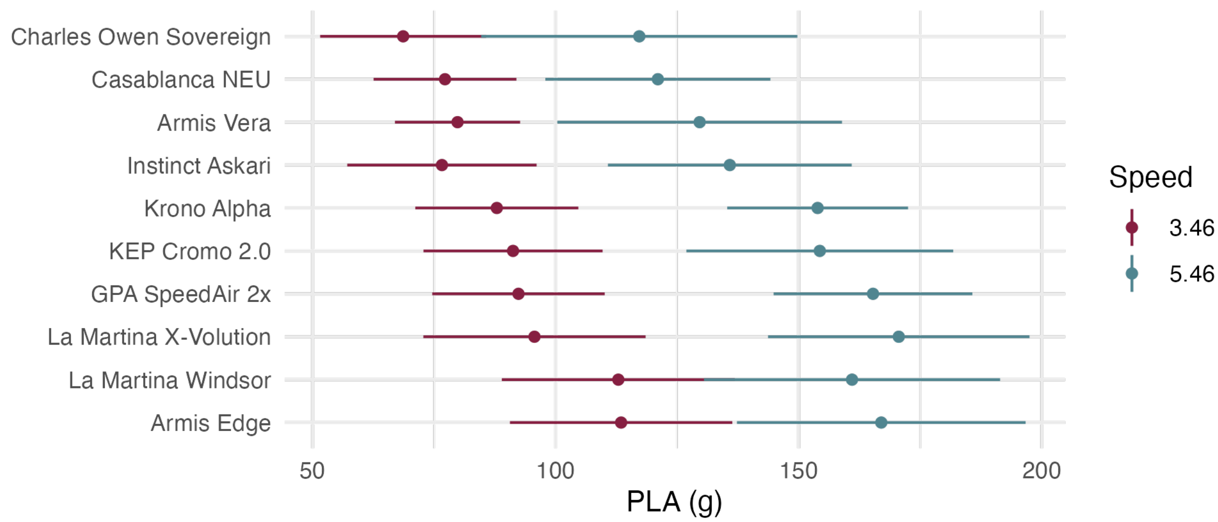

Figure 4: Mean linear accelerations with 95% confidence intervals for each helmet model across test systems by impact speed.

Table 4: Spearman rank correlation coefficients for linear acceleration between test systems.

Model	**rho**	**p-value**
Oblique ~ Pendulum	0.85	0.0035
Oblique ~ NOCSAE	0.75	0.0184
NOCSAE ~ Pendulum	0.62	0.0603

Rotational Acceleration

The Instinct Askari and Charles Owen Sovereign helmets produced the lowest average rotational accelerations across both test systems and the Armis Edge and La Martina X-Volution helmets produced the highest (Figure 5). Helmet model rank order showed a strong correlation between the oblique and pendulum test systems (rho = 0.70, p = 0.0311).

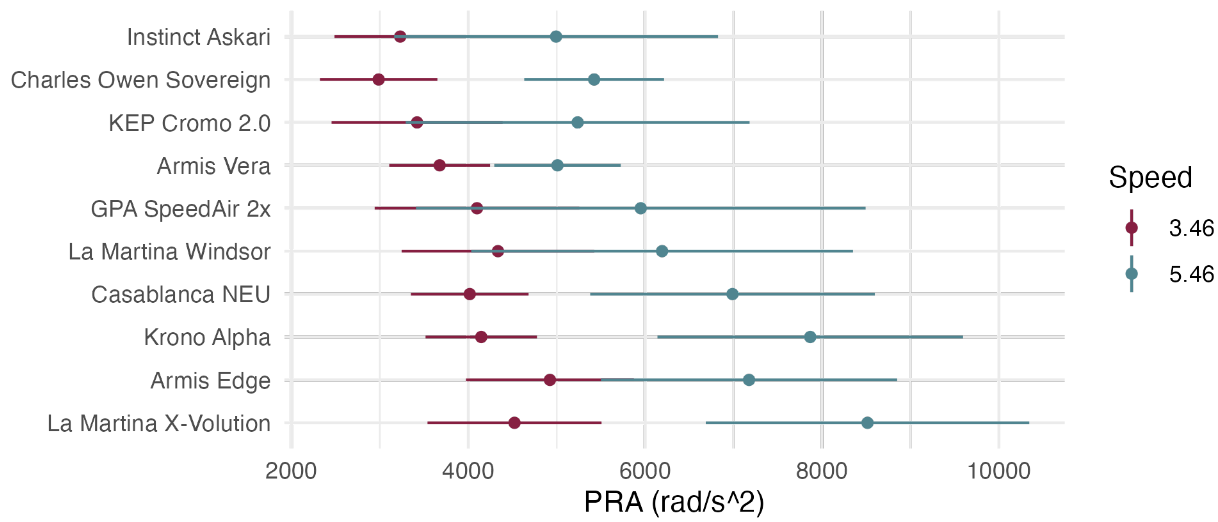

Figure 5: Mean rotational accelerations with 95% confidence intervals for each helmet model across test systems by impact speed.

Concussion Risk

The Charles Owen Sovereign and Armis Vera helmets produced the lowest average concussion risks across both test systems and the Armis Edge and La Martina X-Volution helmets produced the highest (Figure 6). Helmet model rank order showed a strong correlation between the oblique and pendulum test systems (rho = 0.78, p = 0.0117).

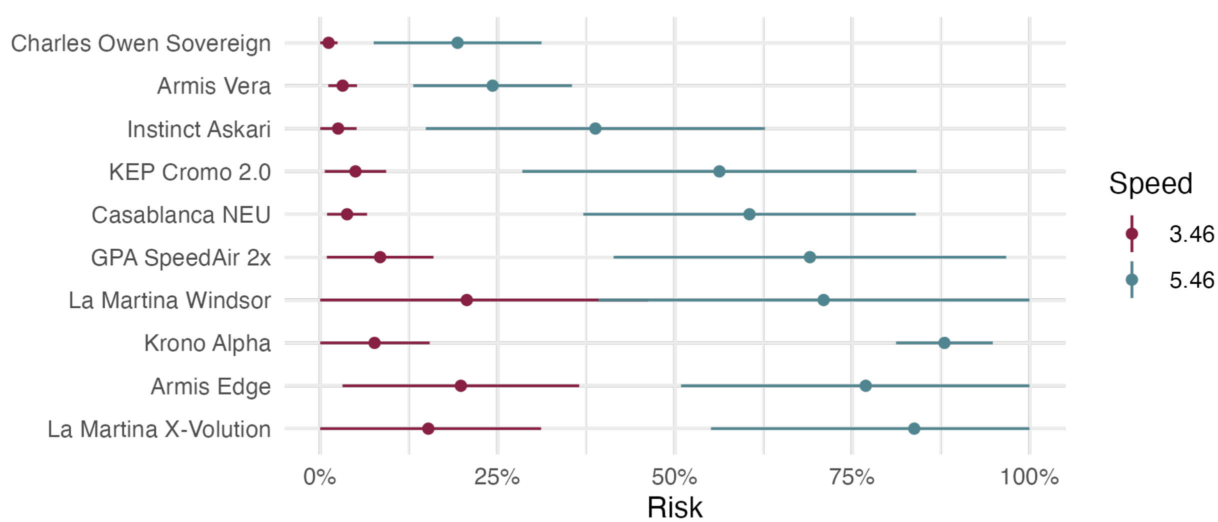

Figure 6: Mean concussion risk with 95% confidence intervals for each helmet model across test systems by impact speed.

Discussion

In our study, we evaluated 10 polo helmet models under varying rotational loading conditions. We found that at matched impact speeds, the impact response varied between test systems. Despite this variance, there was some agreement between test systems in the rank order of helmet models, particularly more for linear than rotational acceleration. The linear and rotational acceleration ranges across different helmet models were substantial, which translated to large differences in concussion risk between helmet models. Notably, both rotational test systems identified the same helmets as the top performers in terms of minimizing concussion risk.

MIPS

Among the tested models, only the Armis Edge included MIPS technology. While we could not robustly compare the effect of MIPS between rotational test systems due to the limited sample, we were able to evaluate this helmet's performance under both test systems for linear and rotational acceleration. For linear acceleration, the oblique system generated accelerations 58.7 [31.9, 85.5] g greater than the pendulum system, which was statistically significant ($p = 0.002$). Additionally, the oblique system produced rotational accelerations 380 [-619, 1352] rad/s^2 higher than the pendulum system (Figure 7), but this difference was not significant ($p = 0.376$). Given the limited comparison, we cannot confidently state that we would not observe a difference if we had the opportunity to test a larger sample of helmet models on both systems.

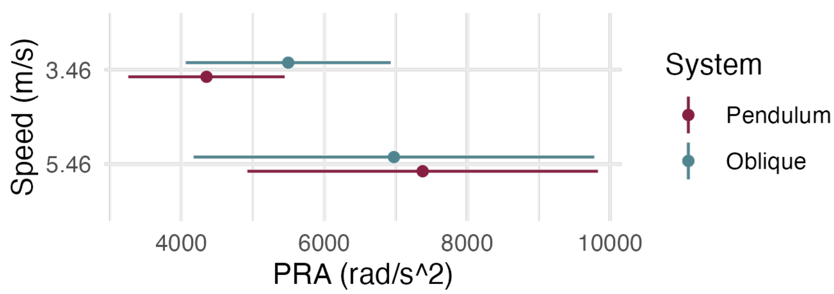

Figure 7: Mean rotational accelerations with 95% confidence intervals for the Armis Edge by test system and impact speed.

NOCSAE Certification

NOCSAE-certified helmets demonstrated superior performance on all test systems, producing lower linear and rotational accelerations than non-NOCSAE-certified helmets. Out of the tested models, four were NOCSAE certified. On average, these helmets generated linear accelerations 29.7 [19.1, 40.3] g lower than their non-certified counterparts, a statistically significant difference ($p = 0.0002$). Additionally, NOCSAE-certified helmets produced rotational accelerations that were 992 [125, 2109] rad/s^2 lower on average than non-certified helmets, although this difference was not statistically significant ($p = 0.0748$). In terms of concussion risk, NOCSAE-certified helmets exhibited a 55% relative risk reduction compared to non-NOCSAE-compliant helmets (Figure 8).

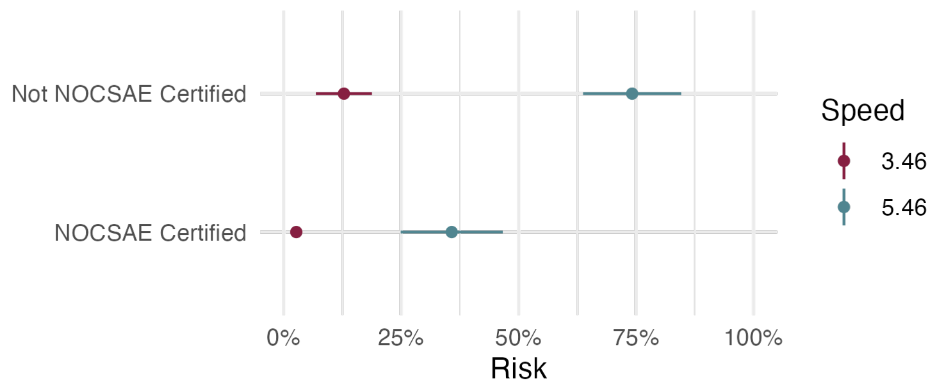

Figure 8: NOCSAE-certified helmets produced lower accelerations that translated into substantially lower concussion risks compared to non-NOCSAE-certified helmets.

Summary

- We evaluated 10 polo helmet models under varying rotational loading conditions.
- At matched impact speeds, impact response differed between test systems.
- While impact response differed, there was some agreement between test systems in rank order of helmet model (more for linear than rotational).
- The acceleration range across helmets was substantial.
- NOCSAE-certified helmets performed better than non-NOCSAE-certified helmets.
- Acceleration differences between helmets translated to larger differences in concussion risk between helmet models.
- Both rotational test systems identified the same helmets as best performers when looking at concussion risk.
- Future work must determine test methods representative of polo head impacts for helmet testing results to be representative of player risk.

References

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