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Assessing Kinematic Variables in Short-Track Speed Skating Helmets: A Comparative Study between Traditional Rigid Foam and Anti-Rotation Designs

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Abstract: Purpose: Short-track speed skating results in high-energy crashes with an elevated risk of head injury. The goal of this study was to evaluate the resulting kinematics of an anti-rotation helmet technology for speed skating. Methods: Two traditional rigid foam speed-skating helmets (*BT* and *ST*) were compared with one anti-rotation speed skating helmet (*MIPS*). Each helmet was impacted with a pneumatic device across three locations. The resulting linear or rotational accelerations (PLA or PRA) and rotational velocities (PRV) were measured with accelerometers placed on a Hybrid III head form. Additionally, the head impact criterion (HIC) was calculated from accelerations and the brain injury criterion (BrIC) was obtained from rotational velocities. Results: *MIPS* showed significantly higher values of accelerations (PLA = 111.24 ± 9.21 g and PRA = 8759.11 ± 2601.81 rad/s^2) compared with the other helmets at all three impact locations ($p < 0.01$, ES = 3.00 to 4.11). However, velocities were lowest, but not significantly different, for the *MIPS* helmet (25.77 ± 1.43 rad/s). Furthermore, all resulting kinematics except peak linear accelerations were significantly different across impact locations. Conclusion: Helmet designs specific to the collision characteristics of speed skating may still be lacking, but would decrease the risk of sport-related concussions.

Keywords: concussion; protective equipment; safety regulations; impact; collisions

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1. Introduction

Short-track speed skating is a fast-paced sport in which athletes can reach velocities of up to 50 km/h [1]. Although short-track speed skating is not a contact sport in the traditional sense, collisions and falls often occur due to the small 111 m oval track and four to eight athletes racing on skates in a tight group. In 1984, the International Skating Union, which governs the safety regulations for the sport, mandated that athletes wear hard-shell helmets and that rinks be fitted with large crash-pads to reduce the incidence of catastrophic injuries [2,3]. Despite these additional safety precautions, head impacts continue to occur in the sport of short-track speed skating, primarily due to crashes [4–6]. There is, however, limited literature on short-track speed skating injury etiology and prevalence, and even less on the rates of head injury and sports-related concussion (SRC) specifically [4,7]. One retrospective injury survey study suggested that 25–31% of short-track athletes sustain contact injuries due to falls and crashes per year [7]. Moreover, the overall season injury prevalence was estimated at 64.2%, with 5.4% of these injuries affecting the head [4].

Currently, helmets for short-track speed skating are tested using the ASTM-F1849 standard, which is a modified road-cycling certification protocol [8]. Results from mechanical impact testing must be below 300 g of resulting linear acceleration in order for short-track speed skating helmets to pass certification [8]. This threshold was advocated as a cut-off to minimize the risk of catastrophic head injury to the speed skaters wearing a helmet (i.e., fractures or intra-cranial bleeding) [9]. However, SRC can still occur below these thresholds in speed skating [10], and less is known about the capacity of current helmets to protect against this injury [11–13]. Although it is currently difficult to predict ensuing SRC from kinematic variables of crashes, rotational kinematics have been shown to be an important contributor to increased risk [9,14,15]. Despite this, measurement of rotational accelerations and velocities is not currently included in the testing standards for speed skating helmets [9]. Therefore, investigating rotational kinematics as a proxy for the risk of SRC is possible [12,16,17] and is currently being included in laboratory-based studies to a greater extent [18–21].

Karton et al. (2014) evaluated the resulting kinematics of two traditional expanded polystyrene (EPS) short-track speed skating helmets compared to a bicycle helmet and an ice hockey helmet [21]. This study used a modified drop tower to collide with a Hybrid III head and neck form at 4 m/s under three impact conditions. They measured the resulting linear and rotational acceleration of the head and found that the short-track speed skating helmets displayed higher rotational acceleration values than both the bicycle and ice hockey helmets, indicating that the tested speed skating helmets might have a lower ability to limit head rotational accelerations.

Newer helmet technologies were developed in a manner specifically designed to reduce rotational movement in cycling [19,22,23] and snow sports [20]. The Multi-directional Impact Protection System (*MIPS*) is one such design, which consists of a liner inside the helmet that can slide independently from the shell, thereby reducing rotational acceleration of the head [22]. Bliven et al. (2019) found that, during impacts from a drop tower at 6.2 m/s onto a 45° anvil, *MIPS* cycling helmets reduced the rotational acceleration of the head by 44% compared to the same cycling helmet with the *MIPS* liner removed [22]. Using a similar experimental setup, Bonin et al. (2022) found that the *MIPS* technology in a cycling helmet also reduced peak rotational acceleration compared to a standard helmet by 23% to 47%, depending on the location of the impact [18]. For a snow sport helmet, the *MIPS* technology reduced head rotational acceleration compared to a control helmet by values ranging from 11% to 66% (drop tower testing at 4.8 m/s and 6.2 m/w onto a 45° anvil, with either frontal, side, or rear impacts) [20].

The *MIPS* technology has now also been integrated into a commercial short-track speed skating helmet; however, laboratory testing evaluating this novel helmet compared to standard short-track speed skating helmets has not been published to date. Therefore, the primary objective of this study was to evaluate the resulting kinematics of an *MIPS* speed skating helmet compared to standard EPS speed skating helmets. Moreover, this study aimed to evaluate the resulting kinematics from impacting the helmets at three different angles.

2. Materials and Methods

2.1. Equipment

The *Bont short-track speed skating* helmet (*BT*; Bont, Mirabel, QC, Canada; 260 g) and *Skate-Tec 010* helmet (*ST*; Skate-Tec, Diever, The Netherlands; 293 g), two standard expanded polystyrene (EPS) foam speed skating helmets, were compared to a *Louis Garneau Vitesse* helmet (*MIPS*; Louis Garneau, Saint-Augustin de Desmaures, QC, Canada; 350 g) with *MIPS* technology. Size S/M *BT* helmets (54–58 cm), size L/XL *ST* helmets (58–61 cm), and size M *MIPS* helmets (56 cm) were used for testing to ensure proper fit on the Hybrid III head form [24]. Five individual helmets of each type were used for each of the two impact speeds, for a total of 30 helmets.

2.2. Experimental Setup

This study employed a pneumatic horizontal linear impactor setup with a Hybrid III B-1846-D 50th percentile head (mass = 4.45 kg) and neck (mass = 1.54 kg) (Figure 1). The pneumatic linear impactor (Cadex, St-Jean-sur-Richelieu, QC, Canada) consisted of a rail-guided, pneumatically pressurized piston that was set at the desired impact velocity [25,26]. This type of testing assembly has shown good reliability (ICC = 0.79–0.88) and validity compared with a standard drop tower impact system (ICC = 0.85–0.95) [27]. The whole impact ram assembly mass was 19.82 kg. The pneumatic ram impact surface was fitted with a flat nylon pad (diameter = 127 mm, thickness = ~38 mm). The head was equipped with nine single-axis Endevco 7264C-2000 accelerometers (PCB Piezotronics, Irvine, CA, USA) with ±2000 g range sampling at 20 kHz, mounted in a 3-2-2-2 orthogonal array, which allowed for the measurement of linear and angular accelerations. The Hybrid III head form is commonly employed to assess this type of head impact, as it is designed to approximate the density of human head and neck components [24].

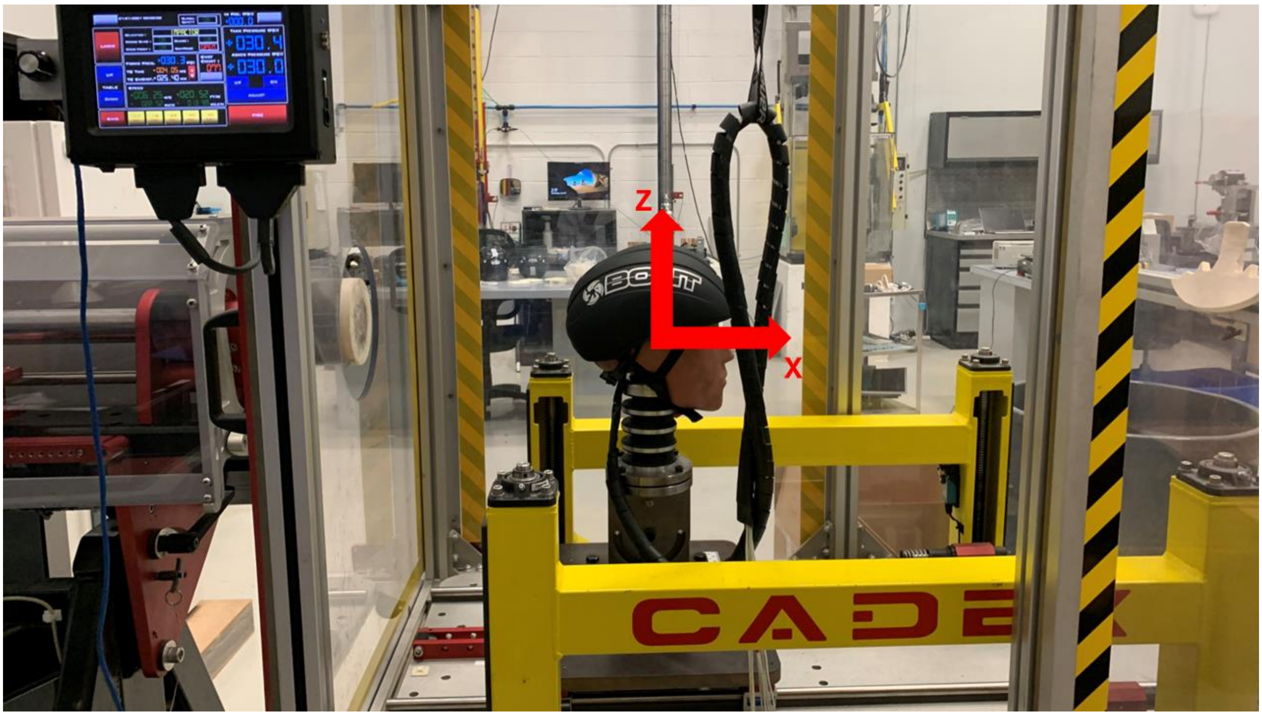

Figure 1. Pneumatic linear impactor with Hybrid III head form set up for posterior impact.

2.3. Impact Conditions—Location and Velocity

Three impact locations were selected based on commonly impacted areas on the head when speed skaters fall and crash into the mats, as reported by expert coaches and medical staff. Further locations may be relevant for assessment by other researchers once more information is available from observational studies. Impact locations included a side impact through the center of mass (CoM) to create a rotation about the antero-posterior axis, a posterior impact through the CoM to create a rotation about the medio-lateral axis, and a rear oblique impact offset from the CoM by 45 degrees in the transverse plane to create rotations about all three axes [21]. The helmets were impacted at two different impact velocities, the same velocities used for the speed skating helmet certification standards, i.e., a low velocity (3.8 m/s) and a high velocity (6.2 m/s) [8,28]. Altogether, this resulted in a total of six impact conditions.

2.4. Data Processing

Data were collected using LabVIEW™ v.2017 (National Instruments Corp., Austin, TX, USA). The filter chain was as follows: low-pass 1.65 kHz hardware filter in the accelerometer condition prior to data acquisition, followed by the software filter CFC1000 (Weisang GmbH, St. Ingbert, Germany) on all nine accelerometer signals [29]. A software filter, CFC180 (Weisang GmbH, St. Ingbert, Germany), was used prior to the calculation of angular acceleration estimates in accordance with the accepted methods [30]. Data were imported and processed in MATLAB™ v.2018b (The MathWorks, Inc., Natick, MA, USA) using the signal processing toolbox and custom written scripts to extract linear acceleration, rotational acceleration, and rotational velocity time series data. Peak resultant linear acceleration (PLA); peak rotational acceleration (PRA); velocity (PRV) about the x-axis for side impact, y-axis for posterior impact, and x- and z-axis for rear oblique impact; head injury criterion (HIC); and brain injury criterion (BrIC) were calculated from the time series data.

The HIC is a measure of head injury that was developed in 1972 by the National Highway Traffic Safety Association (NHTSA). It integrates the resultant linear acceleration for a specified time window, raised to the power of 2.5 [17]:

$$HIC = \left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} adt\right]^{2.5}(t_2 - t_1) \tag{1}$$

where t_1 and t_2 are the initial and final times in milliseconds, and a is the resultant angular acceleration measured in g's. For our study, we chose to calculate HIC over 15 ms (HIC_{15}), in which a maximum value of 700 in automobile crash tests for a 50th percentile male is mandated by the NHTSA for all vehicles [31,32]. The strength of HIC_{15} is the incorporation of both the magnitude and duration of impacts into its results, rather than just reporting the peak linear acceleration value for a given impact.

The BrIC is a measure developed in 2013 that was designed to specifically assess the probability of traumatic brain injury and concussion [33]:

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

where ω_x, ω_y, and ω_z are maximum angular velocities about the X-, Y-, and Z-axes, respectively, and ω_{xC}, ω_{yC}, and ω_{zC} are the critical angular velocities in their respective directions [33]. BrIC is a less universally accepted measure of brain injury, but it does allow researchers the ability to probabilistically calculate brain injury without the use of computer-simulated finite element head modelling [34].

2.5. Statistical Analysis

PLA, PRA, PRV, HIC, and BrIC were obtained for each helmet under both velocities and all three impact location conditions. Before performing the statistical analysis, the normality of the data was verified with a Shapiro–Wilk test within each group of five helmets of the same type. Equal variance of the sample groups was then tested using Levene's test. Given the absence of normality of the datasets, non-parametric Scheirer–Ray–Hare tests were used for each key variable, with the between-factor helmet type (*BT*, *ST*, and *MIPS*) and the within-factors impact location (side, rear oblique, posterior) and speed (low and high velocity) as independent variables [35]. Significant variables (or interaction factors) were then assessed as individual pairs using the Dunn test approach to control for familywise error rates [36]. Effect sizes were reported using Cohen's d with Hedge's correction for small sample sizes. Group differences were interpreted as small (0.20 to 0.49), moderate (0.50 to 0.79), or large (greater than 0.80) [37]. Results were reported as significant at the level of $\alpha = 0.05$. All statistical tests were performed using RStudio (R version 4.1.0, The R Foundation for Statistical Computing). Significance level was set to $p < 0.05$.

3. Results

Individual helmets' mean results for PLA, PRA, PRV, HIC, and BrIC are presented for low- (Table 1) and high-velocity (Table 2) impacts. Time series data for linear acceleration, rotational acceleration, and rotational velocity are found in Figures 2 and 3 for low-velocity and high-velocity impacts, respectively. Impacts recorded with the Endevco accelerometers confirmed that the target velocities were respected for each condition (3.81 ± 0.01 m/s and 6.22 ± 0.01 m/s).

Table 1. Mean results for low-velocity impacts.

3.8 m/s Impacts					
Parameter	**Helmet**	**Side Impact**	**Posterior Impact**	**Rear Oblique Impact**	**Mean by Model**
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
PLA_R [g]	*BT*	92.91 ± 1.76	90.15 ± 1.73	87. 94 ± 1.91	90.33 ± 2.68
	ST	75.38 ± 2.11	85.69 ± 2.18	73.47 ± 3.82	78.18 ± 6.14
	MIPS	122.46 ± 3.88	105.52 ± 2.54	105.73 ± 6.28	111.24 ± 9.21
PRA_R [rad/s^2]	*BT*	9053.01 ± 125.84	3033.54 ± 179.55	8020.13 ± 245.35	6702.23 ± 2726.12
	ST	7633.23 ± 334.95	2651.95 ± 138.92	7472.42 ± 310.44	5919.20 ± 2405.92
	MIPS	12,109.68 ± 337.61	6089.09 ± 382.33	10,169.81 ± 269.75	9456.19 ± 2615.48
PRV_R [rad/s]	*BT*	24.94 ± 0.23	29.19 ± 0.50	25.85 ± 0.55	26.66 ± 1.93
	ST	23.72 ± 0.43	29.25 ± 0.51	25.08 ± 0.43	26.02 ± 2.47
	MIPS	27.30 ± 0.25	24.02 ± 0.54	25.99 ± 0.11	25.77 ± 1.43
HIC 15	*BT*	176.88 ± 4.39	210.61 ± 9.78	164.27 ± 4.68	183.92 ± 21.19
	ST	154.93 ± 2.74	171.85 ± 10.02	145.93 ± 3.98	157.57 ± 12.61
	MIPS	243.47 ± 10.90	260.61 ± 12.30	197.79 ± 16.89	233.96 ± 30.19
BrIC [%]	*BT*	44.18 ± 0.41	51.70 ± 0.88	45.17 ± 0.77	47.02 ± 3.52
	ST	42.01 ± 0.76	51.82 ± 0.90	44.43 ± 0.91	46.09 ± 4.39
	MIPS	48.36 ± 0.45	42.55 ± 0.95	47.40 ± 0.33	46.11 ± 2.70

PLA_R: resulting peak linear acceleration; PRA_R: resulting peak rotational acceleration; PRV_R: resulting peak rotational velocity; HIC: head impact criterion; BrIC: brain injury criterion.

Table 2. Mean results for high-velocity impacts.

6.2 m/s Impacts					
Parameter	**Helmet**	**Side Impact**	**Posterior Impact**	**Rear Oblique Impact**	**Mean by Model**
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
PLA_R [g]	*BT*	162.93 ± 2.69	170.40 ± 3.71	159.30 ± 2.21	164.21 ± 5.50
	ST	139.37 ± 2.08	147.54 ± 6.17	140.00 ± 6.85	142.30 ± 6.35
	MIPS	206.44 ± 9.97	170.50 ± 14.49	184.25 ± 15.70	187.06 ± 19.85
PRA_R [rad/s^2]	*BT*	14,001.45 ± 88.65	7905.05 ± 507.38	13,239.43 ± 226.93	11,715.31 ± 2823.43
	ST	13,739.02 ± 148.27	6224.81 ± 508.32	12,517.17 ± 434.79	10,827.00 ± 3427.42
	MIPS	14,396.52 ± 290.94	10,859.94 ± 402.35	16,572.81 ± 741.63	13,943.09 ± 2483.09
PRV_R [rad/s]	*BT*	37.59 ± 0.20	43.59 ± 0.18	39.41 ± 0.27	40.19 ± 2.61
	ST	38.22 ± 0.56	43.75 ± 0.85	39.30 ± 0.60	40.42 ± 2.56
	MIPS	35.35 ± 1.18	37.70 ± 1.13	42.75 ± 0.68	38.60 ± 3.34
HIC 15	*BT*	643.79 ± 22.02	872.82 ± 30.69	40.42 ± 2.56	712.55 ± 119.84
	ST	543.07 ± 15.54	701.21 ± 55.42	38.60 ± 3.34	594.66 ± 85.12
	MIPS	832.60 ± 73.23	879.53 ± 100.31	724.90 ± 103.68	812.34 ± 109.40
BrIC [%]	*BT*	66.58 ± 0.35	77.22 ± 0.33	70.66 ± 0.35	71.49 ± 4.55
	ST	67.70 ± 1.00	77.51 ± 1.51	70.57 ± 1.68	71.92 ± 4.46
	MIPS	62.61 ± 2.09	66.79 ± 2.00	78.45 ± 1.13	69.29 ± 7.13

PLA_R: resulting peak linear acceleration; PRA_R: resulting peak rotational acceleration; PRV_R: resulting peak rotational velocity; HIC: head impact criterion; BrIC: brain injury criterion.

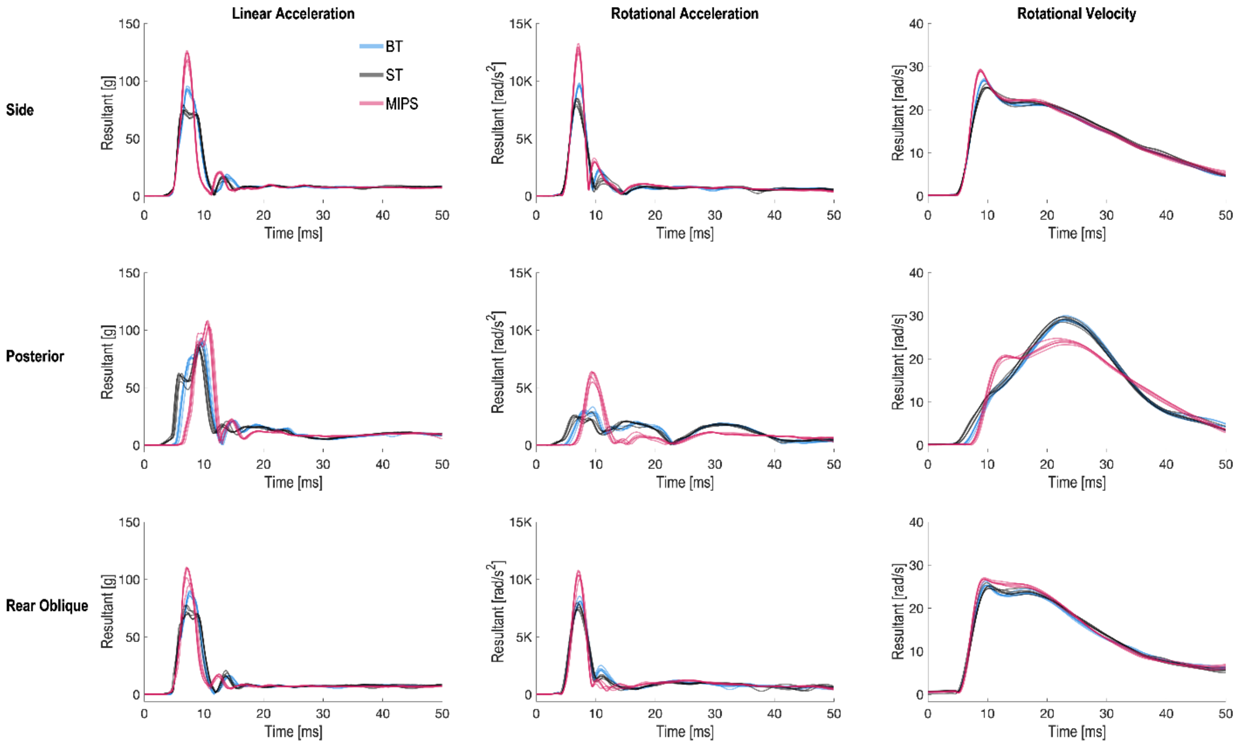

Figure 2. Time series data for linear acceleration, rotational acceleration, and rotational velocity for 3.8 m/s velocity impacts.

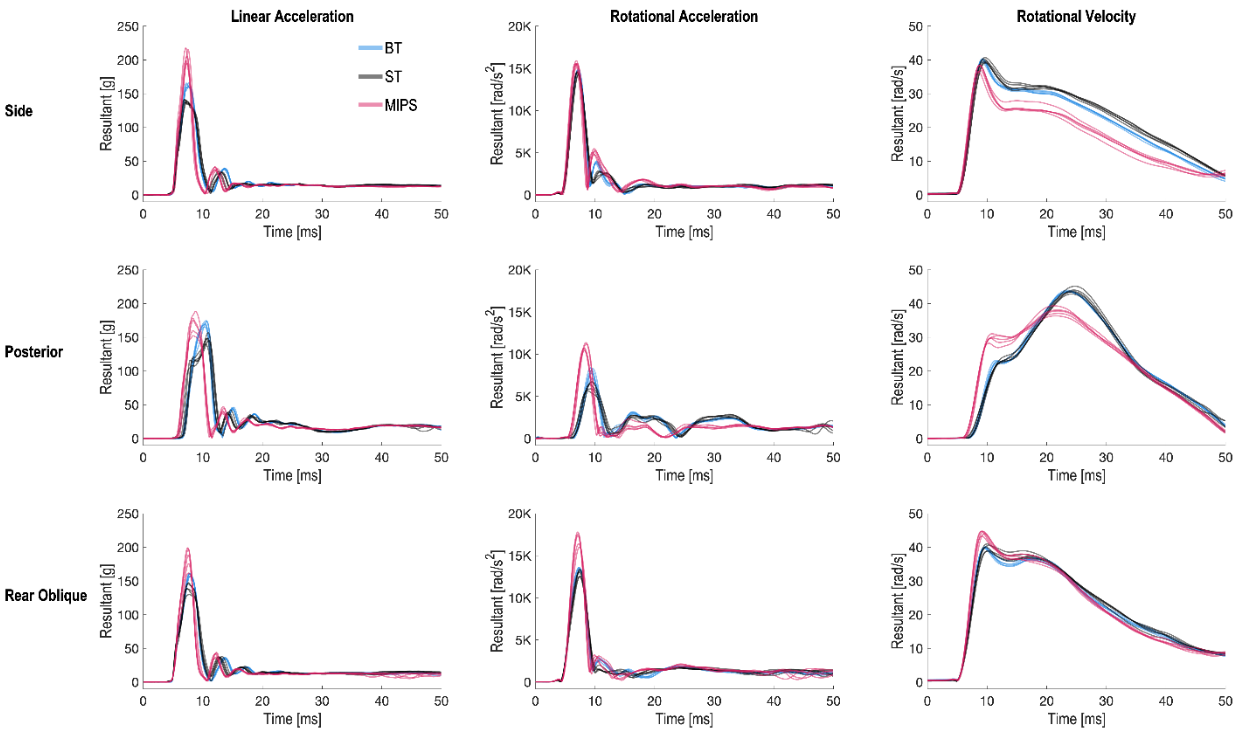

Figure 3. Time series data for linear acceleration, rotational acceleration, and rotational velocity for 6.2 m/s velocity impacts.

3.1. Peak Linear Acceleration

At a slow impact speed, *MIPS* showed the highest value of PLA at 111.24 ± 9.21 g, significantly greater than *ST* and *BT* ($p < 0.01$, ES = 3.00 to 4.11). PLA was not significantly different across impact locations ($p = 0.44$), and there was no interaction between helmet types and impact location on PLA at a slow speed ($p = 0.73$).

At fast impact speeds, *MIPS* showed the highest value of PLA at 187.06 ± 19.85 g, significantly greater than *ST* and *BT* ($p < 0.01$ to 0.03, ES = 1.53 to 2.96). PLA was not significantly different across impact locations ($p = 0.77$), and there was no interaction between helmet type and impact location on PLA at a fast speed ($p = 0.36$).

3.2. Peak Rotational Acceleration

At slow impact speeds, *MIPS* showed the highest value of PRA at 9456.19 ± 2615.48 rad/s^2, significantly greater than *ST* ($p < 0.01$, ES = 1.37), but not *BT* ($p = 0.10$, ES = 1.00). Mean values of PRA were significantly lower for the posterior impact location ($p < 0.01$, ES = 3.09–3.14), but there was no significant interaction between factors ($p = 0.80$).

At fast impact speeds, *MIPS* showed the highest values of PRA at 13,943.09 ± 2483.09 rad/s^2, significantly greater than *ST* ($p < 0.01$, ES = 1.01), but not *BT* ($p = 0.06$, ES = 0.82). Mean values of PRA were significantly lower for the posterior impact location ($p < 0.01$, ES = 2.87–3.82), but there was no significant interaction between factors ($p = 0.56$).

3.3. Peak Rotation Velocities

At slow impact speeds, PRV was lowest for *MIPS,* but this was not significant across helmets (PRV = 25.77 ± 1.43 rad/s, $p = 0.43$). The posterior impacts resulted in the largest PRV at 27.49 ± 2.58 rad/s, and this was significantly greater than the side and boss impacts ($p < 0.01$, ES = 0.92–0.99). There was also a significant interaction between factors ($p < 0.01$).

At fast impact speeds, PRV was lowest for *MIPS,* but this was not significant across helmets (PRV = 38.60 ± 3.34 rad/s, $p = 0.07$). The posterior impacts resulted in the largest PRV at 41.68 ± 3.01 rad/s, and this was significantly greater than the side and rear boss impacts ($p < 0.01$, ES = 0.47–1.90). There was also a significant interaction between factors ($p = 0.01$).

3.4. Head Injury Criterion

At slow impact speeds, *MIPS* showed the highest values of HIC at 233.96 ± 30.19, significantly greater than both *ST* and *BT* ($p < 0.01$, ES = 1.87–3.21). HIC was significantly higher for the posterior impacts (214.36 ± 38.91) than for the rear boss direction ($p < 0.01$, ES = 1.35). There was no significant interaction between factors ($p = 0.99$).

At fast impact speeds, *MIPS* showed the highest values of HIC at 812.34 ± 109.40, significantly greater than *ST* ($p < 0.01$, ES = 2.16) but not *BT* ($p = 0.07$, ES = 0.85). HIC was significantly higher for the posterior impacts (817.85 ± 106.39) than for the rear boss and side directions ($p < 0.01$, ES = 1.18–1.80). There was no significant interaction between factors ($p = 0.61$).

3.5. Brain Injury Criterion

At slow impact speeds, *MIPS* showed a similar BrIC score to the *ST* helmet (46.11 ± 2.70% vs. 46.09 ± 4.39%), but there was no significant difference between helmets. The posterior impacts resulted in significantly higher BrIC scores than the side direction (48.69 ± 4.57%, $p = 0.04$, ES = 0.99). There was also a significant interaction between factors ($p < 0.01$).

At fast impact speeds, *MIPS* showed the lowest BrIC score (69.29 ± 7.13%), but this was not a significant difference from the other two helmets. The side impacts resulted in significantly lower BrIC scores (65.63 ± 2.58%) than the other two directions ($p < 0.01$, ES = 1.90–2.20). There was also a significant interaction between factors ($p < 0.01$).

4. Discussion

This study aimed to compare the resulting kinematics between two commonly used speed skating helmets (*BT* and *ST*) and one helmet (*MIPS*) using an anti-rotation technology. Overall, the *MIPS* helmet (EPS) displayed the highest peak values of accelerations and head injury risk measure (HIC). However, this *MIPS* helmet did not yield the highest values for peak rotational velocity or BrIC probability. Overall, differences in the resulting kinematics were observed between helmet designs, and the impact locations yielded significantly different results across multiple variables.

4.1. Effect of Helmet Technology

The study protocol also allowed us to evaluate the resulting kinematics across three different helmets using two types of technology, namely, EPS and *MIPS*. In terms of acceleration measures (peak linear acceleration, peak rotational acceleration, as well as HIC), the *MIPS* showed the highest values under both testing speeds with large effect sizes. However, the *MIPS* did not yield the highest values for any of the measures based on angular velocity or the resulting BrIC probability. The mechanism of rotation dampening within this *MIPS* helmet is based on allowing the helmet to slide relative to the head. However, additional factors may influence this sliding effect, such as the amount of hair and sweat present under the helmet [18]. Therefore, the exactitude of a Hybrid III model test to represent the function of this helmet outside of the laboratory is uncertain. Furthermore, the BrIC approach to evaluating risk was developed as an alternative to finite element modeling, where angular velocities are assumed to be better predictors of brain injury risk. This *MIPS* may outperform traditional EPS helmets in terms of risk of concussions (as per BrIC criteria), whereas the latter are developed to decrease the risk of catastrophic head injury (as per HIC criteria).

Future studies should investigate the specific kinematics of falls in short-track speed skating to help identify optimal parameters to target peak accelerations and rotational velocities. The current study shows that optimizing the construction of the helmets for the purpose of decreasing one type of resulting kinematic affects the performance of the other.

4.2. Effect of Impact Location

A recent review highlighted the importance of testing helmets under different conditions, as the impacts sustained in sports may not be represented by the typical drop tower-type tests [28]. Previous studies that attempted to impact the helmets in different locations have traditionally tilted the head form on and the anvil below the drop tower [20,22,23]. This setup does not allow for the evaluation of a direct lateral blow to the helmet, which is a common crash collision mechanism in speed skating. Therefore, the experimental design for this study included three separate impact locations where a pneumatic device rammed against the tested helmets. The resulting peak linear accelerations were not significantly different across impact locations. However, all other study variables (PRA, PRV, HIC, BrIC) showed significant differences between impact locations at both slow (3.8 m/s) and at fast speeds (6.2 m/s). Altogether, these findings suggest that testing regimens based on multiple impact directions stresses different characteristics of the helmets [9]. Thus, the single axial loads produced by a drop tower test may be insufficient to evaluate the helmet's tolerance to sport-specific crashes [28]. Reducing linear forces may decrease catastrophic brain injury risk, but SRC appears to be more likely when rotational acceleration mechanisms are at play, which are better observed when varying the impact directions [12,38,39].

4.3. Resulting Kinematic Findings

In 2004, Zhang et al. proposed thresholds for risk of mild traumatic brain injury after reproducing impacts in a laboratory setting based on video footage of football contacts known to result or not result in a brain injury [40]. Their model extrapolated that athletes were at an 80% risk of brain injury when sustaining peak linear accelerations above 106 g or rotational accelerations above 7900 rad/s^2. In the current study, the 3.8 m/s testing conditions yielded peak linear accelerations below this threshold in all three impact locations (89.05–96.91 g). However, peak rotational accelerations were above the 80% risk threshold for both side and rear boss impacts (8554.12 and 9598.64 rad/s^2). At 6.2 m/s, all testing conditions yielded linear and rotational accelerations above the 80% threshold risks across all helmets and all three impact locations. Considering that peak racing speeds are nearly twice as fast as the testing conditions (e.g., 14 m/s), it appears that most existing short-track helmet technologies would be inadequate to prevent SRC if the athletes collided their heads with a hard surface at this speed [21]. This may simply reflect that helmets are first designed to prevent catastrophic head injury, and future technologies more suitable for protecting against concussion-threshold impacts should not come at the cost of losing this fundamental purpose [28]. Alternatively, the thresholds proposed by Zhang et al. (2004) may not be transferable to the resulting kinematics obtained from experimental setups that do not calculate finite models [40].

4.4. Strengths and Limitations

This study employed a testing apparatus that diverges from the traditional drop towers employed for helmet safety regulations. Notably, the helmet with anti-rotational technology did not show superior capacity in reducing rotational accelerations, unlike what was observed in previous settings [20,22,23]. This difference may be due in part to the variation in experimental setup. However, we hypothesize that the impact locations chosen and the ability to strike the helmets with a pneumatic device allowed for a more ecological reproduction of speed skating crash collisions. The absence of a torso in the experimental setup, however, cannot inform us regarding the way this would affect accelerations in different planes. Using finite modeling approaches that consider additional variables such as neck muscles, tendons, and ligaments could refine the analysis of the measurements obtained in this study. Moreover, evaluation of the MIPS technology itself for the LG helmet would require an experimental setup where the components of that helmet are tested separately, such as what was achieved by Bonin et al. (2022) [18].

Investigations of the energy-reducing capacities of helmets are not practical to perform in live participants, and unfortunately, the Hybrid III model is not a perfect replica of a human. The dissipation of energy through the materials does not replicate that through human tissues perfectly, which can lead to inconsistent findings. Difficulties with the rebounding effect of the materials was noted by previous researchers and may have affected the results in the current study [19]. Moreover, the coefficient of friction can change based on the surface of the model, such as when athletes wearing helmets have short or long hair, wet or dry skin, etc. Additionally, the strapping tightness of the helmet under the chin may vary between participants, leading to additional potential differences in the resulting kinematics in live crashes on ice.

5. Conclusions

This study showed that an experimental setup with a pneumatic ram allowed for the reproduction of more ecological impacts on the Hybrid III head form. The experiment demonstrated that, although the *MIPS* helmet was less successful at reducing peak linear and rotational accelerations, it proved satisfactory at reducing angular velocities compared to the two traditional EPS helmets. Future research should evaluate the ability of these helmets to tolerate repeated impacts and investigate their durability after repeated crashes, such as those seen in short-track speed skating. Increasing knowledge about the kinematic and kinetic characteristics of collisions in short-track speed skating will further improve the ability of helmet designers to create better solutions for this sport.

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