Evaluating Youth Hockey Helmet Performance and Design Characteristics

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Abstract

Hockey has the second-highest concussion rate in youth sports (1.20 concussions per 1,000 athletic exposures), yet youth helmets are designed to meet adult certification standards that do not reflect youth-specific impacts. This study evaluated 22 commercially available youth hockey helmets under youth-specific impact conditions using a pendulum impactor. Peak linear acceleration (PLA) and peak rotational acceleration (PRA) were recorded at four impact locations and three speeds, and concussion risk was calculated. Liner thickness and shell construction were documented for each helmet. A linear mixed effects model quantified the effects of these design features, along with impact speed and location, on PLA, PRA, and concussion risk. Acceleration attenuation varied widely across helmets. Differences in peak head kinematics and concussion risk were most significant during high-speed impacts, with notable variations also at medium-speed impacts. Liner thickness had no effect on peak accelerations or concussion risk, while shell construction influenced PRA and concussion risk but not PLA. These findings suggest that youth hockey helmets could benefit from padding designs tailored to youth-specific impacts. The development of youth-specific testing protocols will encourage manufacturers to create helmets optimised for youth safety.

Keywords Concussion, Helmet Testing, Hockey Helmets, Youth Hockey,

I. INTRODUCTION

Ice hockey is a popular youth sport with over 800,000 children registered in the U.S. and Canada in the 2022-2023 season [1], [2]. Across Europe, the total number of youth ice hockey players is nearly 275,000 as of 2024 [3]. Despite its popularity, hockey reports the second-highest concussion rate amongst youth sports, with an incidence rate of 1.20 concussions per 1000 athletic exposures (AE) [4]. Compared to the adult population, youth athletes are also more susceptible to concussions due to their increased head-body ratio and weaker neck musculature that limits their ability to reduce resultant head accelerations due to collisions or falls [5], [6], [7], [8], [9]. Concussions may also have a more serious effect on youth athletes since youth athletes who sustain a concussion experience memory deficit symptoms and require a longer recovery period than adults [10]. Also, adolescents who report having a concussion within the past 12 months are 25% more likely to be in poor academic standing than those without a concussion [11]. These factors combined make concussion prevention in youth hockey critical.

Certain injury prevention strategies such as helmet use, protective padding, and rule changes, have been implemented to try to reduce the number of head injuries. To improve player safety, bodychecking in ages 13 and under has been banned since 2011 in the U.S. and 2013 in Canada. Although several studies have shown that concussion rates are lower in age groups where body checking is banned, both compared to pre-rule change data and to older age groups, concussions remain one of the most common injuries at all youth levels [12], [13], [14], [15], [16], [17], [18], [19], [20]. Some leagues have also introduced a fair play policy (FPP) that can increase a team's standings by having fewer penalties. While the FPP resulted in a significantly lower number of penalties than games not played under the FPP, there are conflicting results on its ability to decrease head injury rates, demonstrating the need for further protections such as helmets to reduce head injury risk [21], [22], [23].

While helmets can offer some head injury protection, youth-specific hockey helmets are tested using the same certification standard as adult hockey helmets, which may not be representative of youth head impact conditions experienced in practice or gameplay [24]. In Europe, helmets must pass the Conformité Européenne (CE) certification, which verifies the helmet upholds safety, health, and environmental protection requirements [25].

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Both U.S. and Canadian hockey helmet standards impact helmets at 4.5 m/s [26], [27]. Comparing this to on-ice data which, on-average, youth hockey head impacts range from 2.05 - 2.76 m/s [28]. However, helmet testing protocols assess impact higher speed impacts that reflect the upper percentile of on-ice data indicative of high-risk impacts [29]. On-ice studies of youth hockey head impacts have reported 95th percentile PLA ranging from 27.8 to 45.6 g and PRA from 2147 to 4058 rad/s^2 [28], [30], [31], [32] and reported impacts as high as 90 g and 10000 rad/s^2,[30], [32] indicating that severe impacts can occur in youth hockey. Helmets that are tested to impact conditions not-representative of real-world scenarios fail to perform as intended, emphasizing the need for sport-specific helmet testing [33]. Additionally, the U.S. and Canadian hockey helmet standards certify helmets using linear acceleration head injury metrics, despite all real-world head impacts containing a linear and rotational component which both contribute to concussion risk [34], [35], [36], [37]. To understand their real-world protective abilities, youth hockey helmets need to be tested at youth-specific impact conditions informed by game play and practice data.

Several studies have characterised the ability of adult ice hockey helmets to mitigate impact energies under sport-specific impact conditions [38], [39], [40], [41], [42]. However, research on youth hockey helmet performance under youth specific impact conditions is limited. Post *et al.* compared adult and youth hockey helmets under two separate impact scenarios (falls and collisions) and found that falling events produce higher head kinematics and brain strains than collisions in youth ice hockey players [43]. Hoshizaki *et al.* compared ice hockey, alpine, and cycling helmets for general use in winter activities and found that ice hockey helmets were the most protective at low-velocity impacts (2 – 8 m/s) [44]. However, this study aimed to compare the impact performance of helmets from three different sports and did not examine youth hockey helmets under sport-specific conditions.

Additionally, Butterfield *et al.* reconstructed youth hockey head impacts captured on video in a laboratory setting and related the impact severity results to the frequency of the head impact event [45]. While this study tested youth hockey helmets under realistic impact conditions, only one helmet model was used, which may not represent the range of helmet models available and their respective performances. Additionally, several studies have demonstrated that there is an association between hockey helmet design characteristics such as liner material and thickness on the measured head impact response [46], [47], [48], [49]. A study by Rousseau *et al.* and Koncan *et al.* examined how expanded polypropylene (EPP) and vinyl nitrile (VN) liners affected head kinematics in adult and youth hockey helmets, respectively, and both found that VN liners were better at managing rotational accelerations whereas EPP was better at managing linear accelerations [46], [47]. Additionally, a study by Clark *et al.* examined how liner and shell thickness affected hockey goalie helmet performance and found that liner thickness had no clinical significance on peak linear acceleration during falls [49]. More work needs to be done to understand how helmet design characteristics affect youth hockey helmet performance so that informed design decisions that improve athletes' head protection can be made.

This study aims to evaluate youth hockey helmet performance under youth-specific impact conditions by measuring peak head kinematics and calculating concussion risk. A variety of helmets were chosen to represent the diverse range of products available on the market at the time of the study, including many helmet manufacturers and price points. Impact locations and velocities were selected to try and encompass the range of head impacts a youth hockey player may sustain during a season. Design characteristics such as liner thickness and helmet shell composition were evaluated to determine their effects on helmet performance. The results from this study will identify the current top-performing youth hockey helmets and can help guide helmet manufacturers to create hockey helmet designs specifically intended for youth players.

II. METHODS

Pendulum Impact Testing

A pendulum impactor was used to perform all impact tests (Fig. 1) [29]. The pendulum arm measured 190.5 cm long, with a total mass of 36.3 kg and a 16.3 kg impacting mass at the end. The pendulum arm's moment of inertia was 72 kg·m^{2}and a flat, rigid nylon impactor face with a 12.7 cm diameter was used to maximise repeatability and reproducibility of tests [29]. A rigid impacting face was chosen to isolate helmet performance and simulate the rigid surfaces in hockey including the ice, boards, and helmets.

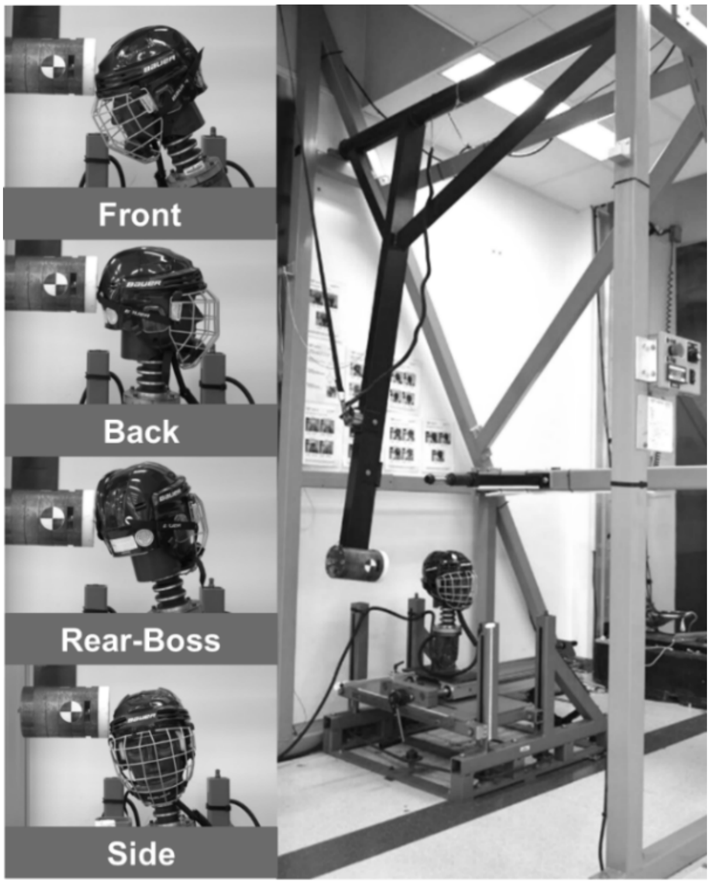

Figure 1. Pendulum impactor and locations tested for youth hockey helmets.

The pendulum impacted a helmeted small NOCSAE headform weighing 4.9 kg that was modified to fit a 5th percentile female Hybrid III neck. The head and neck assembly were attached to an 8 kg sliding mass on an adjustable table intended to simulate the effective mass of the torso upon impact (Biokinetics, Ottawa, Ontario, Canada). This combination of head, neck, and torso has been shown to represent the 50th percentile 10 to 12-year-old boy [29]. The NOCSAE headform was instrumented with three linear accelerometers and a triaxial angular rate sensor (ARS) at its center of gravity to measure linear and rotational impact kinematics. Each helmet was tested at three impact speeds (2.3, 3.4, and 4.9 m/s) and four impact locations (front, back, side, and rear boss), totaling twelve testing conditions. Impact locations were chosen based on previous research that determined the helmet's most hit locations during both practice and gameplay [38], [50]. Impact speeds were based on characteristics of other youth sports [28], [29]. Each helmet was tested once per location and speed, totaling 48 tests per helmet model and 1056 total impact tests. We ensured a proper helmet fit by following manufacturer guidelines, which specified adjustment of the chinstrap to allow for two fingers to be inserted comfortably between the chin and the chinstrap.

Helmet Characteristics

Twenty-two youth hockey helmets were chosen to be tested as a representation of available brands and helmets on the market at the time this study was conducted (2023-2024) (Fig. 2, Table 1). Helmet size was determined based on the circumference of the small NOCSAE headform (53.4 cm). Some helmet models were specifically marketed for youth hockey players as indicated by naming conventions with “youth” or similar terminology. Other helmets were smaller versions of commercially available models that were sized to fit the small NOCSAE headform.

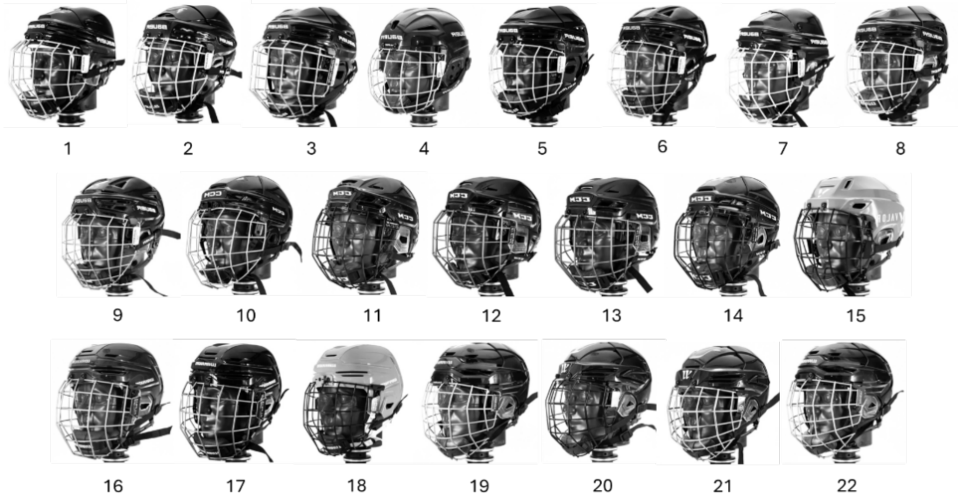

Figure 2. Available helmet models during the time of testing. Numbers relate to Table 1.

Table 1. Helmet models selected for testing, their number of shell pieces, their mass with facemasks included, and their average liner thickness [mean ± standard deviation] across impact locations.

	Helmet	Number of shell pieces	Liner thickness (mm)	Mass (g)
1	Bauer 4500	2	28.0 ± 5.9	822
2	Bauer 5100	2	37.4 ± 6.0	796
3	Bauer IMS 5.0	2	29.3 ± 2.7	818
4	Bauer Lil'Sport	1	42.1 ± 3.1	556
5	Bauer Prodigy	2	30.7 ± 5.2	650
6	Bauer RE-AKT 65	2	39.1 ± 12.0	692
7	Bauer RE-AKT 85	2	51.1 ± 8.7	756
8	Bauer RE-AKT 100 Youth	2	23.9 ± 6.9	696
9	Bauer RE-AKT 150	2	44.0 ± 8.2	754
10	CCM Tacks 70	2	28.0 ± 2.1	714
11	CCM Tacks 210	1	30.5 ± 9.9	810
12	CCM Tacks 310	2	36.3 ± 5.4	776
13	CCM Tacks 710	2	34.9 ± 7.7	760
14	CCM Tacks 910	2	32.2 ± 3.4	836
15	Valor Axiom	1	52.0 ± 5.1	940
16	Warrior Alpha One	1	52.3 ± 8.0	834
17	Warrior Alpha One Pro	1	38.7 ± 4.4	762
18	Warrior Alpha One Youth	1	46.0 ± 1.7	674
19	Warrior Covert CF100	2	40.0 ± 8.0	801
20	Warrior Covert PX2	2	28.4 ± 4.9	730
21	Warrior Covert PX +	2	48.6 ± 10.9	798
22	Warrior Covert RS Pro	2	29.1 ± 4.5	818

A conical impactor face with the apex in the center was used to determine each impact location's center on all twenty-two helmet models. A drill was used to create a hole through the helmet shell and liner, and then the liner was removed from the helmet to be measured using calipers (Table 1). Shell configuration was also noted, and helmets were characterised as having a one- or two-piece shell (Fig. 3).

Figure 3. Characterization of shell type (1 or 2 pieces) and measurement of liner thickness was measured at each impact location with calipers.

Analysis

Data were sampled at 20,000 Hz and filtered using a 4-pole Butterworth low pass filter with a cutoff frequency of 1650 Hz for accelerometer data (SAE J211) and 300 Hz for ARS data [51]. Angular acceleration was obtained by differentiating the angular velocity data using a five-point central difference method as outlined by SAE J1727. The resultant peak linear acceleration (PLA) and peak rotational acceleration (PRA) were reported for each impact test.

Risk of concussion was assessed using a youth-specific risk function (YGAMBIT, Equation 1) [29]. This risk function relates PLA and PRA into a single metric [29]. This risk function was developed from head impact data collected from youth football players who sustained a concussion and was designed to be used to assess the risk of single head impacts [29]. Conclusion risk was calculated by relating the average CDF to YGAMBIT using the log-normal distribution fit with $\mu = 0.967$ and $\sigma = 0.331$ [29].

$$YGAMBIT = \sqrt{\left(\frac{PLA}{62.4}\right)^2 + \left(\frac{PRA}{2609}\right)^2} \quad (1)$$

where PLA is the Peak linear acceleration (g), PRA is the peak rotational acceleration (rad/s^2).

A linear mixed effects model (lmerTest Package) with helmet model as a random effect was conducted in R (Version 4.4.0, RStudio; Boston, Massachusetts, USA) to quantify the effects of shell type, average liner thickness, helmet mass, impact speed, and impact location on PLA, PRA, and concussion risk [52]. A significance level of $\alpha < 0.05$ was selected, and post hoc comparisons were completed using least squares means (lmerTest Package [52]).

III. RESULTS

Helmet Comparison

Across the 22 helmet models tested, PLA, PRA, and concussion risk responses varied (Fig. 4). The worst-performing helmet, the Warrior Alpha One Pro, had a 32% concussion risk for medium-speed impacts and 83% for high-speed impacts (Fig. 4.). In contrast, the best-performing helmet, the Warrior Covert RS Pro, exhibited an 8% concussion risk for medium-speed impacts and 50% for high-speed impacts. This highlights the differences in concussion risk among helmets available in the market. Notably, even the top helmet still demonstrated a significant concussion risk of 50% for high impacts.

Impact speed and impact location affected PLA, PRA, and concussion risk ($p < 0.001$) (Table 2, Fig. 5). Based on location, the side and front impact locations were on average associated with high PLAs and PRAs across impact speeds (Fig. 5). At the low impact speed concussion risk across helmet models was similar at all impact locations and had a range 95% CI range of 0% to 5% risk. Comparing medium and high energy impacts, we found there were large differences in concussion risk between helmets, where the 95% CI of risk at the medium impact speed was 1% to 47% and at the high impact speed was 29% to 99%.

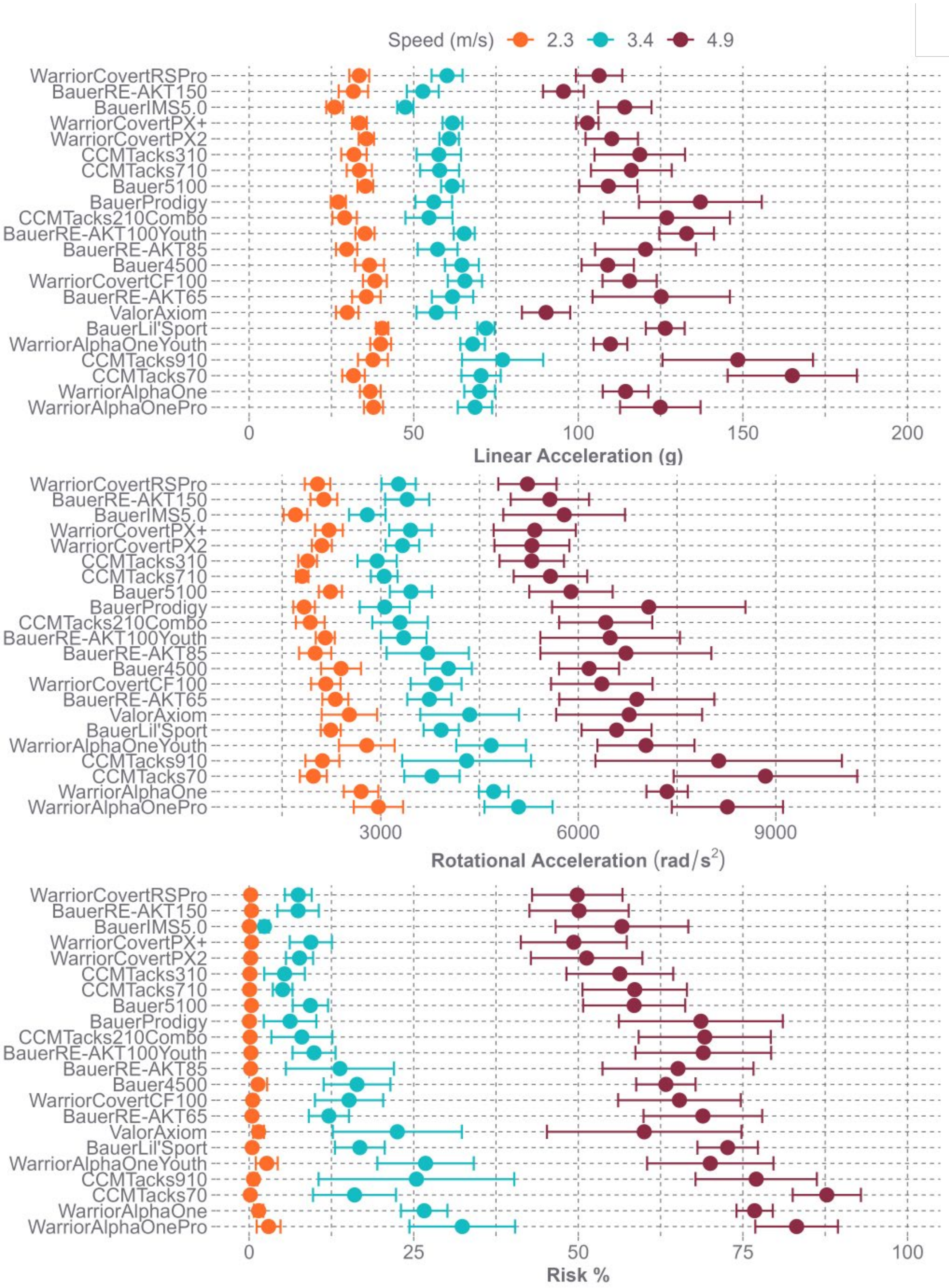

Figure 4: Peak linear acceleration (g), peak rotational acceleration (rad/s^2), and concussion risk (Risk %) mean and 95% confidence interval for each helmet model across all impact locations by impact speed. Ordered from lowest average risk to highest average risk.

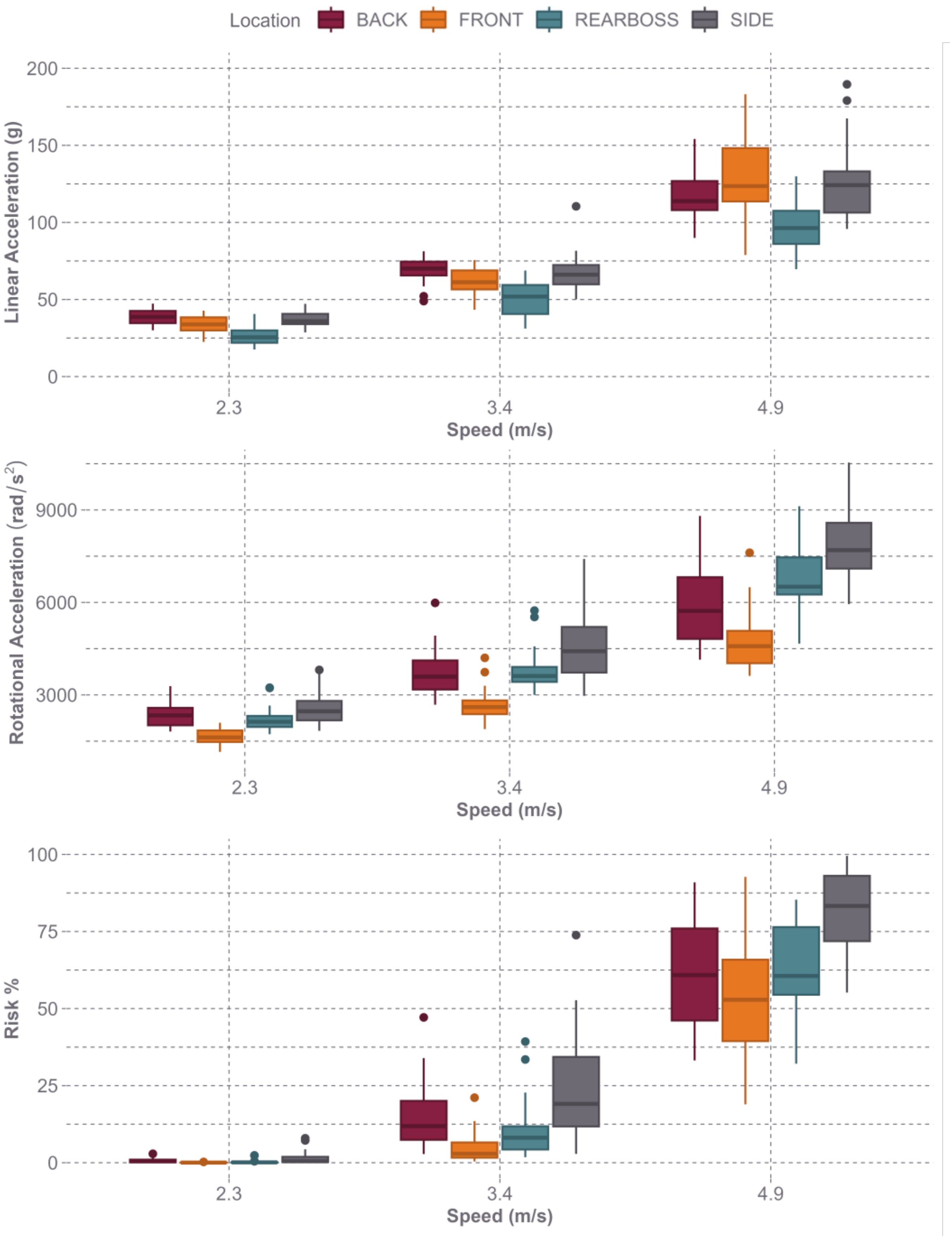

Figure 5: Peak linear acceleration (g), peak rotational acceleration (rad/s^2), and concussion risk (Risk %) across all helmets by impact location and speed (m/s).

Table 2. The average peak head kinematics for all helmet models by impact velocity. [Mean (95% CI)]

Impact Speed (m/s)	PLA (g)	PRA (rad/s^2)
2.3	33.9 (18.8, 49.0)	2192 (1261, 3547)
3.4	62.2 (36.5, 84.2)	3707 (2050, 5949)
4.9	119.0 (72.7 190.9)	6502 (3708, 12141)

Helmet Characteristics

Neither shell construction (p = 0.854), helmet mass (p = 0.061), nor liner thickness (p = 0.179) influenced the PLA (Fig. 6). While liner thickness (p = 0.140) and helmet mass (p = 0.988) did not have a notable effect on, we saw that two-piece shells were associated with an average reduction in PRA by 776 rad/s^2 (p = 0.005, 95% CI 300, 1252 rad/s^2) (Fig. 6). This effect varied by speed where at the low speed two-piece shells were associated with an average reduction in PRA by 915 rad/s^2 (p = 0.012, 95% CI 258, 1573 rad/s^2) compared to high speed with a reduction of 682 rad/s^2 (p = 0.022, 95% CI 140, 1225 rad/s^2). The average decrease associated with the two-piece shells for PRA correlated to the 7.7% risk reduction (p = 0.005, 95% CI 2.7, 12.5%). In low-speed impacts, the reduction from these shells for PRA indicated an 11.2% risk decrease (p = 0.006, 95% CI 3.8, 18.6%). For high-speed impacts, the reduction related to the two-piece shells for PRA demonstrated a 6.6% risk decrease (p = 0.041, 95% CI 0.3, 12.8%). Liner thickness (p = 0.850) and helmet mass (p = 0.605) did not affect concussion risk.

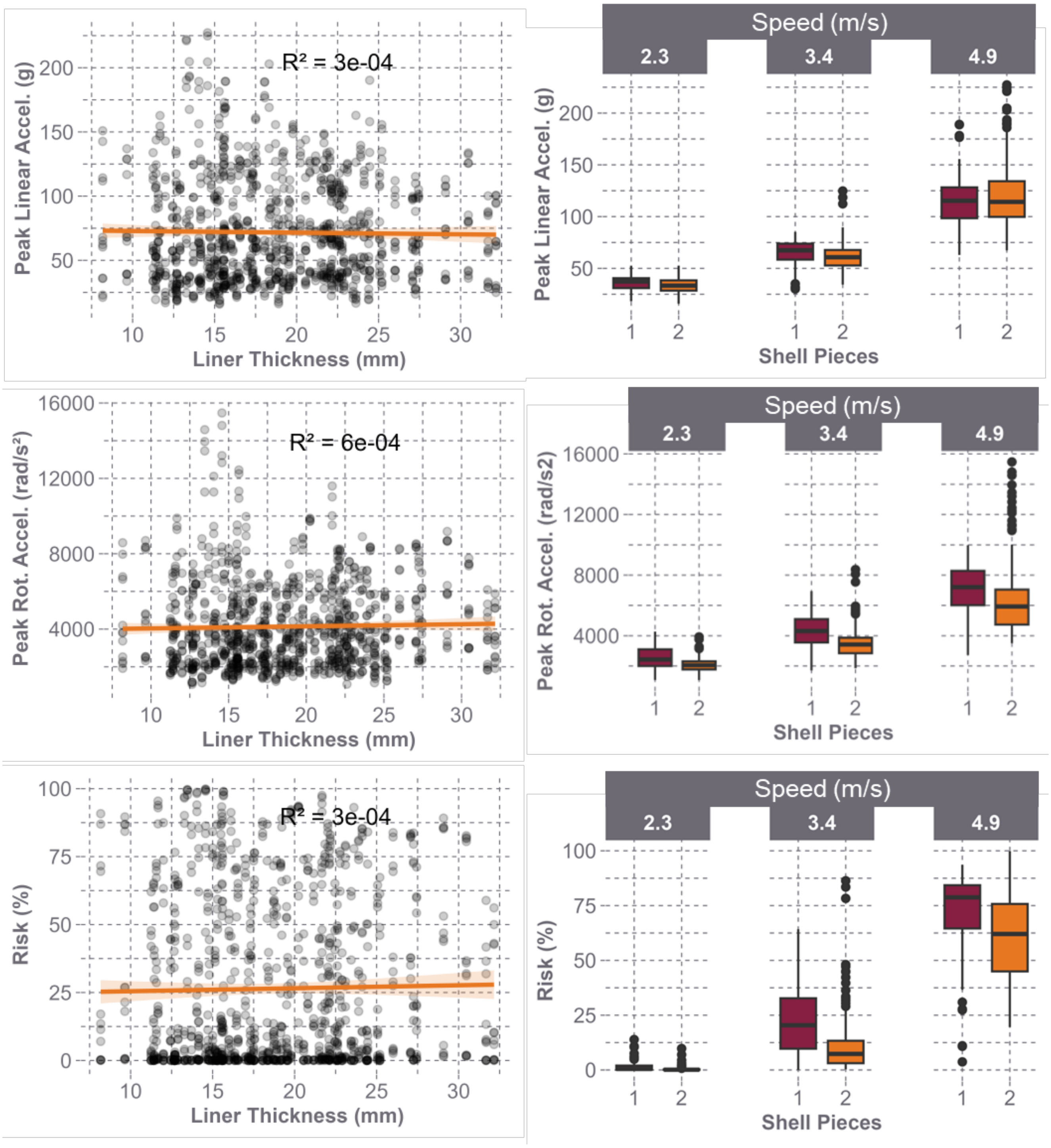

Figure 6: Liner thickness and shell pieces comparison for peak linear acceleration (PLA), peak rotational acceleration (PRA), and percent concussion risk (% Risk). Linear thickness had no effect on PLA, PRA, or % Risk. Two-piece shells reduced PRA and concurrently reduced % Risk.

IV. DISCUSSION

This study assessed the performance of 22 commercially available youth hockey helmets under impact conditions representative of youth play using a youth-specific concussion risk equation. Impact attenuation, measured by both PLA and PRA, varied across helmet models. While all helmets meet the standard testing threshold, remaining below 275 g at 4.5 m/s and 215 g—concussion risk varied substantially [26], [27]. At the low impact speed, concussion risk ranged from 0% to 3%. However, a larger range in performance was observed at medium impact speeds, where the worst helmet had a concussion risk 6.4 times higher than the best-performing helmet. At the high impact speed, concussion risk ranged from 50% to 88% across helmet models, with the worst-performing helmet exhibiting a 1.76 times higher concussion risk compared to the best-performing helmet. Notably, the range in concussion risk reduced with high-impact speed and the best-performing helmet exhibited a 50% concussion risk at the high impact speed, underscoring the need for improvements in helmet design to better protect youth hockey athletes.

Studies on adult ice hockey helmets under sport-specific impact conditions have demonstrated variation in PLA and PRA across different helmet models [41], [42]. Similarly, other studies have reported differences in concussion risk among helmet designs [38], [39], [40]. Our study on youth hockey helmets also found large variations in PLA, PRA, and concussion risk across helmet models. When compared to previous research on youth hockey helmets, our findings align with prior results. Hoshizaki *et al.* examined youth ice hockey, alpine, and cycling helmets at impact speeds ranging from 2 to 8 m/s [44]. They reported a front impact PLA of 34.9 ± 2.6 g at 2 m/s and 152.4 ± 3.4 g at 6 m/s, which falls within the range observed in our study of 22.5 to 204.5 g for front impacts at 2.3 to 4.9 m/s. Similarly, their reported PRA values of 1,426 ± 182 rad/s² at 2 m/s and 6,500 ± 474 rad/s² at 6 m/s were consistent with our front impact results, which ranged from 1,154 to 6,492 rad/s² for impact speeds of 2.3 to 4.9 m/s. For side impacts, our PLA values were similar to Hoshizaki *et al.*, but our PRA values were higher. This discrepancy is likely due to differences in testing methodologies, as our study evaluated multiple helmet models, whereas Hoshizaki *et al.* tested only one. Comparing our results to those of Post *et al.*'s youth data, who used a pendulum impactor at 3.0 m/s, we observed higher PLA and PRA values [43]. Post et al. showed PLA and PRA values at 14.7 g and 1269 rad/s^2 at 3 m/s, compared to our 22.5 g and 1154 rad/s^2 and 204.5 g and 6492 rad/s^2 in impacts at 2.3 m/s and 4.9 m/s, respectively. However, their linear impactor adult collision showed PLA and PRA values of 32.5 g and 2661.4 rad/s^2 at impacts of 6.5 m/s [43]. This difference can be attributed to variations in impactor design, as Post *et al.* employed a more compliant impactor face made of vinyl nitrile foam. Meanwhile, Champoux et al. showed PLA and PRA values of 24.0 - 38.0 g and 1334 - 3698 rad/s^2 in 45-degree drop tower testing between 3 different locations at 3 m/s. For 4.5 m/s, these values increased to 42.6 - 68.9 g and 1660 - 6613 rad/s^2 [42]. Previous studies on youth hockey helmets have only assessed one helmet model, while our study compared 22 models, providing a broader perspective on helmet performance and the current youth hockey helmet market.

This study also examined the influence of helmet characteristics on impact attenuation, finding that liner thickness had no meaningful effect on helmet performance. The absence of a clear relationship between liner thickness and head kinematics suggests there remains potential to enhance youth hockey helmet safety through improved optimization of liner composition. However, the number of shell pieces (one or two) influenced PRA and, consequently, concussion risk, while having no effect on PLA. This was evident in the best-performing helmet, which had two shell pieces, whereas the worst-performing helmet had only one. Our findings on liner thickness align with previous studies, which also concluded that liner thickness does not meaningfully impact head impact kinematics [49]. However, a limitation of this study is that we did not assess the effect of liner material composition on impact response and several studies have shown a relationship between liner material and head impact kinematics [46], [47], [48], [49]. Understanding how helmet design characteristics influence head impact response can help manufacturers make informed design choices to reduce concussion risk and better protect youth hockey athletes

While this study provides insight into youth hockey helmet performance, impact speeds, and locations were informed by field data but not exclusively determined by them. A combination of on-ice data from both adult and youth hockey determined the impact locations and impact speeds were determined from youth other youth sports. Mihalik *et al.* collected head impact data during youth hockey practices and games, finding the 95th percentile PLA of 45.6 g and PRA of 4150 rad/s² [50]. Comparing these data, the 2.3 m/s impact speed produced impacts that were on average PLA of 33.9 g (95% CI 18.8, 49.0 g) and PRA of 2192 rad/s^2 (1261, 3547 rad/s^2) and 3.4 m/s impacts resulted in an average PLA of 62.2 g (36.5, 84. 2 g) and PRA of 3707 rad/s^2 (2050, 5949 rad/s^2), which covered the 95th percentile impacts reported by Mihalik *et al.* It is important to note that Mihalik *et al.* used a singular helmet model that was not evaluated in this study, and that the impacts were not verified through video or direct observation, which could lead to an overestimation of head impacts [53], [54]. Other studies on youth hockey have reported 95th percentile PLA ranging from 27.8 to 45.6 g and PRA from 2147 to 4058 rad/s^2 [28], [30], [31], [32]. The 95th percentile acceleration was similar to the results from the 2.3 m/s impact condition for PLA and PRA, and the upper end of the reported 95th percentile range was also covered in the 3.4 m/s impact condition. Two studies reported the highest accelerations recorded from on-ice data, 191.5 g, 13262.9 rad/s^2, and above 90 g and 11000 rad/s^2 [30], [32]. Though infrequent, this indicates that severe impacts can occur in youth hockey, and these high-severity impacts were best represented with the 4.9 m/s impact condition. Further, the impact speeds used over a reasonable range of concussion risk where, on average, the low-speed impact represents an under 1% concussion risk, the medium-speed impact represents a 10% concussion risk, and high-speed represents around a 60% concussion risk. Another study limitation is considering the impact surfaces; youth hockey athletes experience a variety of head impacts, including board, ice surface, and other athletes [32]. Future work should consider the different contact types when evaluating youth hockey helmets. Moreover, this study only evaluated 22 youth hockey helmet models and did not examine every helmet model on the market. However, this study comprises the largest helmet comparison for youth hockey to date.

V. CONCLUSION

This study evaluated a large sample of youth hockey helmets under youth-specific impact conditions, comparing peak head kinematics and concussion risk to identify the top-performing models. Key design features, such as padding thickness and shell construction, were analyzed to assess their influence on impact attenuation. Despite the variety of helmet designs available, many youth models are scaled-down versions of adult hockey helmets rather than being tailored for the unique impact conditions in youth play. These findings emphasise the importance of developing youth-specific testing protocols to help manufacturers optimise helmet designs for young athletes. By advancing youth-specific hockey helmet testing protocols, manufacturers can be encouraged to develop helmets specifically engineered for the impact conditions youth hockey players face. This could further enhance impact attenuation and overall protection, ultimately improving athlete safety and reducing concussion risk.

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