INVESTIGATING THE PERFORMANCE OF CYCLING AND HOCKEY HELMET LINER MATERIALS IN MITIGATING IMPACTS AT LOWER SPEEDS DURING FREE FALLS

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This study examined the performance of helmets made of expanded polystyrene (EPS) and expanded propylene (EPP) in mitigating linear impacts over three consecutive drop trials at 16 impact speeds ranging from 0.93 to 3.96 m/s. It was found that EPS, a liner material used in cycling helmets, had lower capacity of mitigating linear impact acceleration and captured a larger compressed area of impact than the EPPs, liner materials used for hockey helmets. EPS and EPPs all experienced some degrees of loss in their capacities to mitigate acceleration after the initial impact. All tested materials had no statistically significant difference in their peak resultant linear acceleration (PRLA) between the first and third impacts, and the second and third impacts. This study also found strong and positive correlations between ellipse area and PRLA.

KEYWORDS: Helmets, linear acceleration, expanded polystyrene, expanded propylene.

INTRODUCTION: Cycling is a popular form of human transportation and leisure activity (Harlos & Rowson, 2021). Unfortunately, with this popularity comes an increase in cycling-related head injuries, due to falling or collisions with motor vehicles (Lustenberger et al., 2010). Impacts to the head during cycling collisions were found to most frequently occur in the front, top, and back regions of the head (Depreitere et al., 2004). Cycling helmets provide a means to reduce the risk of head injuries (Harlos & Rowson, 2021). Conventional cycling helmets are made of expanded polystyrene (EPS) foams that are housed in a plastic hard shell. These helmets are designed to dampen and reduce impact forces known to cause concussions (McIntosh et al., 2013). However, EPS is brittle in nature and recommended for single impact performance (Shuaeib et al., 2007). As an unrecoverable foam, EPS has the advantages of higher energy absorption capacity and lower cost when compared with expanded propylene (EPP), a recoverable liner material commonly used in hockey helmets (Razaghi et al., 2018). Schweitzer and Thali (2016) inspected one EPS helmet after its wearer suffered a minor fall and found that the EPS foam fractured, although the wearer had not had any noticeable head and neck injuries. Asuke et al. (2018) drop-tested, from a height of 1.5 m or at an impact speed of 5.4 m/s, three cycling helmets consisting of an outer shell made of polycarbonate, an internal liner of polystyrene foam, plus a pad made of soft polyurethane foam. They found that the maximum resultant accelerations and head injury criterion (HIC) values were markedly higher after the second drop when compared with those after the first drop. Additionally, they noted no macroscopic damage on the outer shell after the first impact (Asuke et al. 2018).

There is a gap in the literature, however, in investigating EPS and EPP liners in low impact velocity as most studies have tested helmets under certification conditions such as those by Consumer Product Safety Commission (CPSC, 2012) which requires an impact speed of 4.8 m/s. Therefore, the first purpose of this study was to compare the performance of EPS and EPP over three consecutive impacts in low impact speeds ranging from 0.93 m/s to 3.96 m/s. The researchers hypothesized that there would be an interaction effect between helmet materials (EPP and EPS) and consecutive impact trials for measures of peak resultant linear acceleration (PRLA) and compressed area of impact represented by a 95-confidence ellipse. The 95-confidence ellipse is the smallest ellipse that covers 95% of the center-of-pressure points measured by an electronic force plate at impact. Conducting virtual autopsy (Schweitzer and Thali, 2016) to determine the damages, if any, on a helmet would have been impractical. Therefore, the researchers selected the 95-confidence ellipse as a measure of the compressed area of the liner. The second purpose was to investigate the relationship between the compressed area of the liner material, PRLA and risk of head injury represented by the Gadd severity index (GSI) and HIC, which includes the duration of the impact. The researchers hypothesized that the ellipse area would be correlated to PRLA, GSI and HIC.

METHODS: A medium-sized National Operating Committee on Standards for Athletic Equipment (NOCSAE) headform instrumented with linear accelerometers was used to simulate dynamic impacts to the back of the head during vertical collisions. The NOCSAE headform was connected to a mechanical neckform. The researchers set the strength of the neck by adjusting the stiffness of the neckform with a torque of 1.356 N·m (or 12 in·lb), which represents the 50th percentile of adult neck stiffness (Rousseau et al, 2009). The neckform, headform, and helmet assembly was attached to a drop carriage mounted on a dual rail vertical drop system. The drop carriage was raised to a desired height by a 110-volt AC winch prior to each impact. An electronic controller then de-energized the magnetic plate causing the drop carriage to fall freely onto an American Mechanical Technology Incorporated (AMTI®) Force Plate to measure the impact forces and moments to compute the ellipse area of the liners. Each helmet was dropped from 16 different heights, resulting in impact velocities ranging from 0.93 to 3.96 m/s. For each height, the helmet was dropped three times consecutively, for a total of 48 impacts on each helmet. Three different types of helmets were drop-tested, one cycling helmet with EPS as the liner and two different hockey helmets with EPP liners.

The measures used in the study included PRLA, GSI, HIC, and the area of the 95-confidence ellipse. The GSI was computed using Equation 1 (Gadd, 1966).

$$\mathrm{GSI} = \int_0^{\tau} a(t)^{2.5} dt \qquad (1)$$

where $a(t)$ is the resultant linear acceleration measured in g (9.81 m/s^2) and sampled at a frequency of 20 kHz and τ (in seconds) represents the impact duration. The HIC was computed using Equation 2 (Rousseau et al., 2009).

$$\mathrm{HIC} = \max_{t_1,t_2}\left\{(t_2 - t_1)\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}\right\} \qquad (2)$$

where t_1 and t_2, in seconds, present the time intervals for integration. For brevity, the computation of the ellipse area (Schubert & Kirchner, 2014) is not repeated here.

The researchers conducted mixed-factorial ANOVAs for 3 liner material types (EPS, EPP_1 and EPP_2) × 3 consecutive impact drop tests (drop test 1, drop test 2 and drop test 3) on the measures of PRLA and ellipse area to address the first hypothesis. Subsequently, the researchers conducted correlation analyses among ellipse area, PRLA, GSI and HIC for each of the drop tests to address the second hypothesis of the study.

RESULTS: The researchers conducted mixed-factorial ANOVAs to address the first hypothesis. The results revealed no significant interaction effect between helmet type and impact drop test for the measures of PRLA. There was, however, a significant main effect for helmet type: F (2,45) = 8.728, $p < .001$, $\eta^2 = 0.279$. The Tukey's honest significance difference (HSD) for pair mean comparison tests showed statistically significant mean difference between EPS and EPP_1 (MD = 45.8321 g, $p = .039$), but no significant mean difference between EPS and EPP_2, and between EPPs. Descriptive statistics in Table 1 show that the EPS experienced the highest PRLA across all drop tests, compared with the EPPs. There was also a statistically significant main effect for drop test on measures of PRLA: F (2,90) = 5.182, $p = .007$, $\eta^2 = .103$. Bonferroni post-hoc tests showed that drop test 2 had statistically significantly higher PRLA (M = 107.806 g, SD = 7.716) when compared with drop test 1 (M = 98.506 g, SD = 7.425, $p = .006$). However, there was no statistically significant difference between drop tests 1 and 3, and 2 and 3. Across all drop tests, EPP_1 and EPP_2 saw, respectively, 34.6% and 32.0% of reduction in PRLA when compared with the EPS.

The results also revealed no significant interaction effect between helmet type and impact drop test for measures of ellipse area. There was a statistically significant main effect of helmet type on measures of ellipse area: F (2,45) = 3.967, $p = .026$, $\eta^2 = 0.150$. The Tukey's HSD tests showed a significant mean difference between EPS and EPP_1 (MD = 36.98 cm^2,

p = .004) and between EPS and EPP_2 (mean difference = 40.79 cm^2, p = .001), but no significant mean difference between EPPs. The descriptive statistics for ellipse area are given in Table 2. It can be seen that EPS had the greatest ellipse area across all drop tests, when compared with the EPPs. There was also a significant main effect of drop tests on ellipse area, F (2,90) = 4.175, p = .018, η^2 = .085. Bonferroni post-hoc tests showed that drop test 2 had significantly higher value of area (M = 58.31 cm^2, SD = 37.52) when compared with drop test 3 (M = 49.83 cm^2, SD = 32.82, p = .007); but there was no significant difference between drop tests 1 and 2, and 1 and 3. For drop test 2, EPP_1 and EPP_2 had reductions in ellipse area of 49.9% and 51.6%, respectively, when compared with EPS.

The researchers subsequently conducted correlation analyses to address the second hypothesis of the study. The Pearson correlation coefficients (PCCs) and corresponding 95% confifence intervals (CIs) are given in Table 3 where all the PCCs were significant at the .01 level (2-tailed). While the strong correlations between PRLA and GSI, PRLA and HIC, and GSI and HIC were as expected, the correlations between ellipse area and PRLA, GSI, and HIC, respectively, were found to be strong, to a moderate degree. It was also noted that the PCCs between ellipse area and GSI were higher than those between ellipse area and PRLA, and ellipse area and HIC; and all the PCCs were positive.

Table 1: Descriptive statistics of PRLA (in g = 9.81 m/s^2).

Liner Material	N	drop test 1		drop test 2		drop test 3	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
EPS (cycling)	16	125.266	67.778	139.644	69.322	132.705	57.114
EPP 1 (hockey)	16	84.297	39.186	88.417	41.602	87.406	42.106
EPP 2 (hockey)	16	85.955	42.533	95.357	45.133	89.913	45.815

Table 2: Descriptive statistics of ellipse area (in cm^2)

Liner Material	N	drop test 1		drop test 2		drop test 3	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
EPS (cycling)	16	827.500	564.701	881.250	499.077	711.875	447.991
EPP 1 (hockey)	16	449.375	272.433	441.875	180.858	420.000	224.143
EPP 2 (hockey)	16	407.500	129.280	426.250	130.429	363.125	108.917

Table 3: Pearson correlation coefficients and 95% Confidence Intervals

drop test 1	Ellipse Area	PRLA	GSI	HIC
Ellipse Area	-	.634	.655	.575
PRLA	CI [0.427, 0.778]	-	.912	.849
GSI	CI [0.445, 0.792]	CI [0.848, 0.950]	-	.978
HIC	CI [0.348, 0.739]	CI [0.744, 0.913]	CI [0.960, 0.987]	-
drop test 2	Ellipse Area	PRLA	GSI	HIC
Ellipse Area	-	.614	.669	.600
PRLA	CI [0.400, 0.765]	-	.919	.878
GSI	CI [0.475, 0.801]	CI [0.858, 0.954]	-	.987
HIC	CI [0.380, 0.755]	CI [0.792, 0.930]	CI [0.976, 0.993]	-
drop test 3	Ellipse Area	PRLA	GSI	HIC
Ellipse Area	-	.558	.691	.672
PRLA	CI [0.325, 0.727]	-	.933	.901
GSI	CI [0.507, 0.815]	CI [0.884, 0.962]	-	.989
HIC	CI [0.479, 0.803]	CI [0.830, 0.944]	CI [0.980, 0.994]	-

DISCUSSION: The location of impact examined in this study was the back of the head. The back region of the head is amongst the most frequent head impact locations during collisions in cycling (Attewell et al., 2001; Depreitere et al., 2004). Cycling helmets made of EPS are designed for single impact and tested at the impact speed of 4.8 m/s to be certified. In this study, the impact speeds were lower. It was found that, for all liner materials investigated, EPS or EPP, the ability to mitigate PRLA deteriorated when they were impacted the second time. This trend, however, did not seem to continue with either EPS or EPP, as the ANOVA on PRLA revealed that there was no statistically significant difference between drop tests 1 and 3, and 2 and 3. It was expected that EPPs did not deteriorate further since EPP is a recoverable material (Razaghi et al., 2018). On the contrary, EPS is a brittle, unrecoverable foam (Shuaeib et al., 2005). The findings of this study did not indicate EPS had statistically significant loss in mitigation after the second impact. This may be due to the low impact speeds in this study.

However, both EPPs had statistically significantly smaller ellipse areas compared with EPS. Considering the positive significant PCCs between ellipse area and GSI, PRLA and HIC, respectively, the smaller areas with the EPPs can be associated with lower risk of head injuries, and possibly better performance of the liner materials in mitigating linear impacts to the back of the head.

CONCLUSION: This study examined the performances in mitigating linear impacts of helmet liners made of EPS and EPPs over three consecutive impacts to the back of the head at lower speeds. The EPS was found to have lower capacity of mitigating linear impacts than the EPPs. EPS and EPPs all seemed to experience loss to some degrees of capacity to mitigate after the initial impact. Yet all materials saw no statistically significant difference in their mean PRLAs between the first and third impacts, and between the second and third impacts. Furthermore, the EPPs had statistically significantly smaller ellipse areas compared with EPS. This information seems to provide another avenue to assess helmet performance using measures of ellipse area to better understand helmet capacity to prevent risk of concussion.

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