

EVALUATING THE COMBINED EFFECT OF NECK MUSCLE STRENGTH AND HOCKEY GOALTENDER HELMET LINERS IN MITIGATING CONCUSSION RISK DURING SIMULATED HORIZONTAL HEAD IMPACTS

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Concussions represent the second most common injury for ice hockey goaltenders. This study examined the combined effect of neck strength level and helmet liner type in mitigating concussion risk for ice hockey goaltenders. The researchers tested each helmet liner material statically for energy absorption capacity of the liner material, and dynamically by recreating concussion-causing events via head impact simulations for the risk of head injury criterion (HIC). The thermoplastic polyurethane (TPU) liner outperformed the standard vinyl nitrite (VN) liner during static testing and significantly reduced the HIC for high levels of neck strength (in newtons) during the repeated impact testing at the front, side, and back locations of the helmet. This information may facilitate the development of helmet liners composed of TPU and VN material across a range of neck strength levels to mitigate concussion risk for goaltenders.

KEYWORDS: Head injury criterion, thermoplastic polyurethane, vinyl nitrite.

INTRODUCTION: Concussions or mild traumatic brain injuries (mTBI) represent the second most common injury for ice hockey goaltenders (Clark et al., 2020). These concussion injuries are prevalent for ice hockey goaltenders due to the number of head collisions that they are exposed to while playing the sport. The most common causes of head injury that result in a concussion are the speed of the puck striking the goaltender's head, the speed and size of other players during head impacts, unpredictable rapid changes in the direction of play, and head collisions with ice surfaces. Since goaltenders' primary objective is to prevent pucks from entering the net, the goaltenders are more susceptible to mechanisms of injury produced by impacts from pucks and other players (Clark et al., 2020). Recent improvements in equipment technology have led to increased skating velocity, faster shots with the ice hockey pucks, and, consequently, more collisions while playing the sport (Clark et al., 2020; Meaney & Smith, 2011). These technological improvements have increased the occurrence of concussions and the need to improve the protective capacity of goaltenders' helmet to mitigate concussion risk. Two strategies can be adopted to mitigate the occurrence of concussions in the sport of ice hockey for goaltenders. The first strategy is to increase the goaltender's cervical muscle strength. Increased neck strength can decrease the risk of concussion for a given impact (Mihalik et al., 2011). The second strategy is to increase the protective capabilities of goaltenders' hockey helmets. The use of TPU liner material in the helmet may offer an avenue to increase helmet protective capabilities as it is found to dissipate impact forces more reliably than VN liners due to the structure of the material (Qi & Boyce, 2005). The TPU material contains large cells to store air within a diameter ranging between 300 and 500 μm (Ramirez & Gupta, 2018). As stress increases on the TPU material due to a force impact, the large cells collapse, forcing the air to escape through the perforations of the TPU material. Since the air escape rate cannot catch up with the loading stress applied to the material, some of the cells stiffen and deform slowly (Ramirez & Gupta, 2018). This property of the TPU allows energy to dissipate by the dynamic bending, twisting, and rotation of the cell walls, similar to VN foam material but in a more reliable manner. Other research finding indicate that TPU can potentially reduce linear impact accelerations to the goaltender's head more effectively than the standard VN helmet liners used in current goaltender helmets (Gimbel & Hoshizaki, 2008; McGillivray et al., 2022). There is, however, a need to examine the effect of TPU material in combination with cervical neck strength to reduce concussion risk. Based on these concerns, the researchers of this study compared the energy absorption capacity per kilogram mass of the TPU

and VN liners. The researchers hypothesized that the helmets with the TPU liner would have lower levels of concussion risk than those with the VN liner when impacted at the front, side and back locations, respectively, for low and high levels of neck strength.

METHODS: The researchers conducted static and dynamic testing on the TPU and VN liners to address the hypothesis of this study. For the static testing, the TPU and VN liners were compared based on the capacity to absorb energy per kilogram mass. Each sample was compressed and decompressed 5 mm at a rate of 25 mm for 15 cycles by the Chatillion® TCD1100 force tester into the American Mechanical Technology Incorporated (AMTI®) Force Plate. Four variations of the TPU design were created and compared to respective sections of the VN standard goaltender helmet liner (headband, upper head, side and back) for measures of compressive, shear and total specific energy absorption (J/kg). The researchers computed the specific energy absorption for each helmet liner type (TPU and VN) during static testing across the 15 cycles. This computation entailed dividing the compressive, shear, and total energy absorbed (in J) by the mass of the material in kilograms. The researchers used the mean values and standard deviations across cycles 2 through 15 to compare the helmet liner materials on specific energy absorption. For the dynamic testing, the researchers tested the helmet liners by using a modified version of the NOCSAE pneumatic ram test method for protective headgear and face guards (NOCSAE, 2018). A NOCSAE headform was attached to a mechanical neckform, which was positioned on the impacting mechanism of a pneumatic air driven horizontal impactor to strike the front, rear, and side impact locations of each helmet according to the NOCSAE protocol (NOCSAE, 2018). The researchers tensioned the mechanical neckform to accommodate four neck strength levels, which included the 30th (66.83 N) and 50th (76.01 N) percentiles for females, and the 50th (185.75 N) and 80th (225.23 N) percentiles for males. The female and male neck strength values implemented in this study were secondary data obtained from the studies conducted by Pennock et al., (2021) and Broennle (2011), respectively. LabChart® computer software was used to collect linear accelerations in the X, Y, and Z directions at a frequency of 20 kHz for each impact via the accelerometers positioned at the CoM (center-of-mass) of the NOCSAE headform. The resultant linear acceleration (RLA) was calculated within the LabChart® software. The RLA was subsequently used for the computation of HIC to assess concussion risk. To obtain the maximum HIC value for each set of data as a measure of concussion risk, a MATLAB® script was used to determine which time duration t_2-t_1 resulted in the largest HIC value. The HIC was computed using Equation 1 (Rousseau et al., 2009).

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

where t_1 and t_2 , in seconds, represent the time interval for integration, and $a(t)$ is the RLA. To address the hypothesis of this study, mixed factorial ANOVAs were conducted with neck strength levels as an independent factor and helmet liner types as a repeated factor on the HIC measures across 18 different impact velocities ranging from 2.01 to 5.13 m/s for each helmet location separately. Bonferroni corrections were implemented for the multiple comparisons across helmet locations.

RESULTS: The TPU liner design and VN liner sample varied in shape, structure, and density but were identical in overall length, width, and height. Table 1 outlines the specific energy absorbed per kilogram mass, of the TPU and VN samples that the researchers tested during the static testing. The means results indicate that the TPU material outperformed the VN standard liner in terms of compression, shear, and overall (or total) specific energy absorption for all locations tested.

Table 1: Percentage (%) of energy absorption (mean and standard deviation)

Locations	TPU Means and Standard Deviations			VN Means and Standard Deviations		
	Compression	Shear	Total	Compression	Shear	Total
Headband	65.8 (5.3)	41.5 (3.4)	91.8 (7.4)	5.5 (0.2)	4.1 (0.1)	8.6 (0.3)
Upper Head	41.1 (4.1)	32.1 (3.3)	64.5 (6.6)	7.1 (0.3)	5.3 (0.2)	10.8 (0.4)
Back	70.9 (5.9)	43.8 (4.1)	97.9 (8.6)	5.9 (0.2)	4.1 (0.1)	8.7 (0.3)
Side	59.3 (4.7)	36.8 (3.4)	82.1 (7.7)	4.7 (0.2)	3.8 (0.1)	7.1 (0.3)

The mixed factorial ANOVAS were conducted to address the interaction effect between neck strength level and helmet liner type for measures of HIC. The mixed factorial ANOVAS were conducted for front, side, and back locations, respectively.

For the front location, the mixed factorial ANOVA results revealed a statistically significant interaction effect between neck strength level and helmet liner type for measures of HIC, $F(3, 68) = 4.213$, $p < .001$, $\eta^2 = 0.157$ (large effect). When examining the interaction effect, the t -tests for repeated measures revealed statistically significant differences between the TPU liner ($M = 191.06$, $SD = 114.77$) and the VN standard liner ($M = 232.16$, $SD = 158.28$) for the 80th percentile male neck strength level, $t(17) = -3.17$, $p = .006$, $d = -0.75$ (medium effect), $CI = [-1.26, 0.214]$.

For the side location, the results of the mixed factorial ANOVA revealed again a statistically significant interaction effect between neck strength level and helmet liner type for measures of HIC, $F(3, 68) = 3.961$, $p = .012$, $\eta^2 = 0.149$ (large effect). Statistically significant differences were found between the TPU liner ($M = 181.25$, $SD = 155.25$) and the VN liner ($M = 144.72$, $SD = 156.76$) for the 50th percentile female neck strength, $t(17) = 2.03$, $p = .05$, $d = 0.48$ (medium effect), $CI = [-0.018, 0.96]$.

For the back location, the mixed factorial ANOVA results indicated also a statistically significant interaction effect between neck strength level and helmet liner type for measures of HIC, $F(3, 68) = 9.285$, $p < .001$, $\eta^2 = 0.291$ (large effect). When examining the interaction effect, statistically significant differences were found between the TPU liner ($M = 314.99$, $SD = 223.32$) and VN liner ($M = 264.57$, $SD = 196.15$) for the neck strength level of the 50th percentile male, $t(17) = 6.127$, $p < .001$, $d = 1.44$ (large effect), $CI = [0.77, 2.10]$. The results also revealed statistically significant differences between the TPU liner ($M = 312.28$, $SD = 270.19$) and VN liner ($M = 270.19$, $SD = 224.04$) for the 50th percentile female neck strength level, $t(17) = 6.90$, $p < .001$, $d = 1.63$ (large effect), $CI = [0.90, 2.33]$. Lastly, the results revealed a statistically significant differences between the TPU liner ($M = 286.38$, $SD = 233.64$) and standard VN liner ($M = 248.76$, $SD = 191.80$) for the neck strength level of the 30th percentile female, $t(17) = 2.61$, $p = .018$, $d = 0.62$ (medium effect), $CI = [0.10, 1.13]$.

DISCUSSION: The current study examined the TPU and VN liner materials and compared them in terms of their specific capacity to absorb energy as measured in J/kg when loaded with compressive and shear forces. Although the TPU liner absorbed more specific compressive, shear, and total energy per kilogram mass than the VN liner, it turned out to be less compliant. It required approximately 10 times more force than the VN liner to be compressed 5 mm. This result indicated that the VN liner would saturate and cease to absorb energy under less force than the TPU liner. In terms of helmet liner technology, it means that once the liner material saturates, it does not absorb more force, and consequently, more force and energy are transferred to the goaltender's head (Ouckama & Pearsall, 2018). This result supports the use of TPU as a potential goaltender helmet liner material based on Ouckama and Pearsall (2018), who found that stiffer liners mitigated impact forces more effectively than softer liners at high impact velocities that can cause concussions.

According to Mane et al. (2017), materials can behave differently when loaded statically as compared to dynamically under different strain rates. Based on this notion, the researchers

used RLA to compute the HIC to assess the effectiveness of the helmet liners to reduce the risk of injury. Although peak RLA is a measure currently used for the certification process of ice hockey goaltender helmets (Clark et al., 2020), this measure alone does not take into consideration the strain rate, or the time aspect of dynamic loading, which was important in the current study to assess the reduction of concussion risk. The findings of the present study suggest that the TPU liner mitigated HIC more effectively for the 80th percentile male neck strength level, which was the strongest neck strength level in this study. The standard VN liner, however mitigated HIC more effectively for the 30th percentile female neck strength level, which was the weakest neck strength level in this study. These findings highlight the need to develop new helmet testing protocols by including athletes' levels of neck strength. The findings also highlight the need to combine helmet liner technologies for the reduction of concussion risk for ice hockey goaltenders.

CONCLUSION: The researchers hypothesized that the helmets with the TPU liner would have lower levels of concussion risk than those with the VN liner when impacted at the front, side and back locations, respectively, for low and high levels of neck strength. The researchers rejected this hypothesis as the TPU liner was found to be more effective only for higher levels of neck strength at the front location. The current study, however, provided a better understanding of the risk of head injury when wearing a goalie helmet and highlighted possible strategies to develop more effective helmet liners with a combination of TPU and VN materials. This approach can function as a prevention strategy for ice hockey goaltenders during horizontal head collisions for specific neck strength levels. The data from the current study also provide insight into the need to create more standardized measures of neck strength levels for male and female populations when examining concussions for ice hockey goaltenders.

REFERENCES

- Broennle, M. (2011). *The Relationship Between Maximal Isometric and Isotonic Neck Strength of Hockey Players and Wrestlers*. (M.Sc. thesis, Lakehead University). Available from <http://knowledgecommons.lakeheadu.ca/handle/2453/144>
- Clark, J. M., Hoshizaki, T. B., & Gilchrist, M. D. (2020). Event-specific impact test protocol for ice hockey goaltender masks. *Sports Biomechanics*, 20(4), 510–531.
- Gimbel, G.M., & Hoshizaki, T.B. (2008). Compressive properties of helmet materials subjected to dynamic impact loading of various energies. *European Journal of Sport Science*, 8(6), 341–349.
- Mane, J., Chandra, S., Sharma, S., Ali, H., Chavan, V., Patel, R. (2017). Mechanical property evaluation of polyurethane foam under quasi-static and dynamic strain rates. *Procedia Engineering*, 173, 726-731.
- McGillivray, K., Przystucha, E., Sanzo, P., Liu, M., & Zerpa, C. (2022). Comparison of hockey helmet lining technologies in mitigating concussion risk during simulated horizontal head collisions. *International Journal of Extreme Automation and Connectivity in Healthcare*, 4(1). DOI:10.4018/IJEACH.316134
- Mihalik, J. P., Guskiewicz, K. M., Marshall, S. W., Greenwald, R. M., Blackburn, J. T., & Cantu, R. C. (2011). Does cervical muscle strength in youth ice hockey players affect head impact biomechanics? *Clinical Journal of Sport Medicine*, 21(5), 416–421.
- NOCSAE (2018). Standard Pneumatic Ram Test Method and Equipment Used in Evaluating the Performance Characterizes of Protective Headgear and Face Guards.
- Ouckama, R., & Pearsall, D. J. (2014). Projectile impact testing of ice hockey helmets: Headform kinematics and dynamic measurement of localized pressure distribution. 2014 IRCOBI Conference Proceedings - International Research Council on the Biomechanics of Injury.
- Pennock, B., Kivi, D., & Zerpa, C. (2021). The effect of neck strength on simulated head impacts falls in female ice hockey players. *International Journal of Exercise Science*, 14(1), 446-461.
- Rousseau, P., Post, A., & Hoshizaki, T. B. (2009). The effects of impact management materials in ice hockey helmets on head injury criteria. *Journal of Sports Engineering and Technology*, 223(4), 159–165.